Solving for Pattern

An operational-level model to redesign engineering education for sustainability

A Thesis

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by

Geetanjali Date

Homi Bhabha Centre for Science Education

Tata Institute of Fundamental Research

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DECLARATION

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

The work was done under the guidance of Professor Sanjay Chandrasekharan, at the Tata Institute of Fundamental Research, Mumbai.

[Geetanjali Date]

In my capacity as supervisor of the candidate's thesis, I certify that the above statements are true to the best of my knowledge.

[Sanjay Chandrasekharan]

Date: July 31, 2019

Dedicated

With love

To my dear mother,

Anjali Anil Talegaonkar

Acknowledgements

This research project drew a lot of inspiration from the path-finder engineers I know personally -

Firstly, my father Anil Ramachandra Talegaonkar, an engineering designer to his core, who always appreciated an elegant design, and was engrossed in design plans till his last breath. His passion for making and building probably permeated the air I breathed, growing up.

And, secondly, Rajesh, Ashish, Neelesh, Santosh, and Ajit, whose careers demonstrate a courage and commitment to solving problems of the society through their engineering enterprise. These close friends gave me the confidence that it is possible to be the kind of engineers I argue for.

It is my hope that this thesis is a small tribute to them all!

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My mother, Anjali Talegaonkar, a science educator and researcher, showed me the way. To her I humbly dedicate this thesis.

Abstract

The practice of building novel structures and artifacts is central to human adaptation. Engineering is the modern version of this adaptive practice. However, this adaptive trait is now in runaway mode, as building activity has damaged the planet significantly. Changes in our current approach to engineering and design are thus critically needed to address the changing face of global climate, and the sustenance of our biosphere, while also addressing the current and future requirements of society.

One of the areas to initiate this change is engineering education (EE). However, an integrated understanding of how building is related to society and nature is lacking in EE, and sustainability values and ethics remain on the periphery of engineering curricula. An analysis of current reforms to EE, based on a wider literature on technology and society, suggests that the reforms are limited, and a successful pedagogy for sustainability engineering cannot be built around canonical models of EE. Further, the mainstream engineering practice does not offer any alternate models of sustainability engineering for EE.

A promising approach to develop an operational-level model of sustainability engineering is the systematic study of successful cases that demonstrate sustainability. Following this reasoning, I undertook a study of innovators working at the grassroots, who generate sustainable technology designs 'in the wild'[1]. The objective of the study was to understand, and make explicit, the problem-solving practices, knowledge, skills, and values involved in such design. To do this, I first developed an empirically driven characterization of

1 Hutchins, *Cognition in the Wild*, 1995a, p xii-xiv. The term 'in the wild' is borrowed from Edwin Hutchins, in the sense he uses it to distinguish between the lab and the real/everyday world. He explains it in the context of cognition as, "The phrase "cognition in the wild" refers to human cognition in its natural habitat - that is, to naturally occurring culturally constituted human activity. .. I have in mind the distinction between the laboratory, where cognition is studied in captivity, and the everyday world, where human cognition adapts to its natural surroundings."

non-formal grassroots innovation, as well as formal (non-mainstream) sustainable technology design practice, in the Indian context. The findings from this study were then abstracted, to develop two core design principles (Plasticity of the Socio-Technical Connection, Technology to sustain local livelihoods). These were then brought together to develop a wider design perspective, termed Solving for Pattern, inspired by Wendell Berry's discussion on this topic. The intervention directions based on these principles are applicable more widely to engineering education.

However, given the emphasis on formal structures (engineering sciences and mathematics) in the current engineering curricula, it is unclear how engineering students could be trained to make these design principles a part of their design thinking and approach. To understand this, an analysis of the cognitive processes involved in engineering design was developed, particularly to examine the role played by formal structures in the design process. This analysis showed that imagination (mental simulation of structure and dynamics) is the core cognitive process in engineering design, and formal structures play only a supporting role. Imagination as the core cognitive process of design supports the inclusion of the design principles identified by the first analysis.

Extending the findings from the above studies and analyses, I develop two specific policy recommendations to redesign engineering education for sustainability. Bringing these policy recommendations together, I propose an implementation-level recommendation. I conclude with a discussion of the wider implications of these findings, particularly for research, practice, pedagogy, and policy.

A characterization project

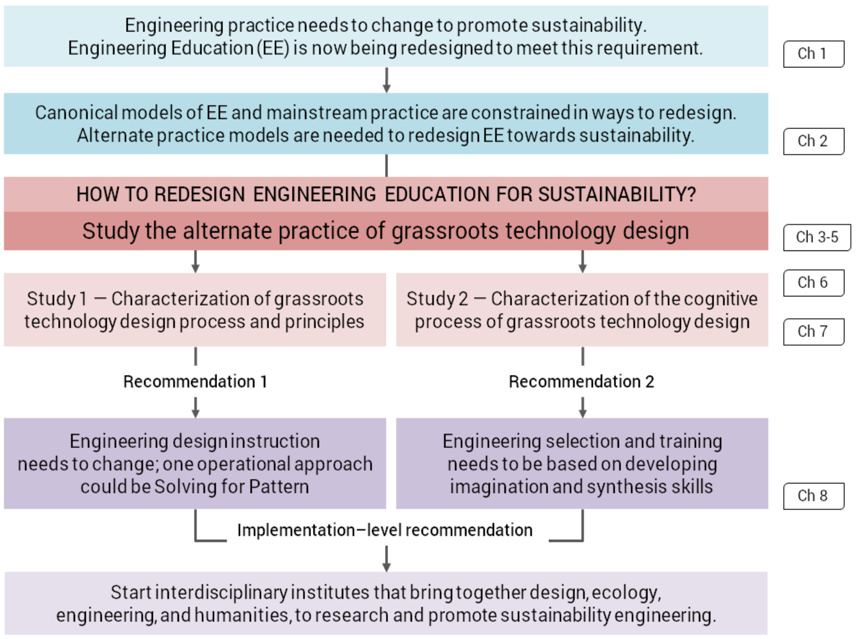

Fig. 1. The research problem, work done, recommendations.

A graphical summary

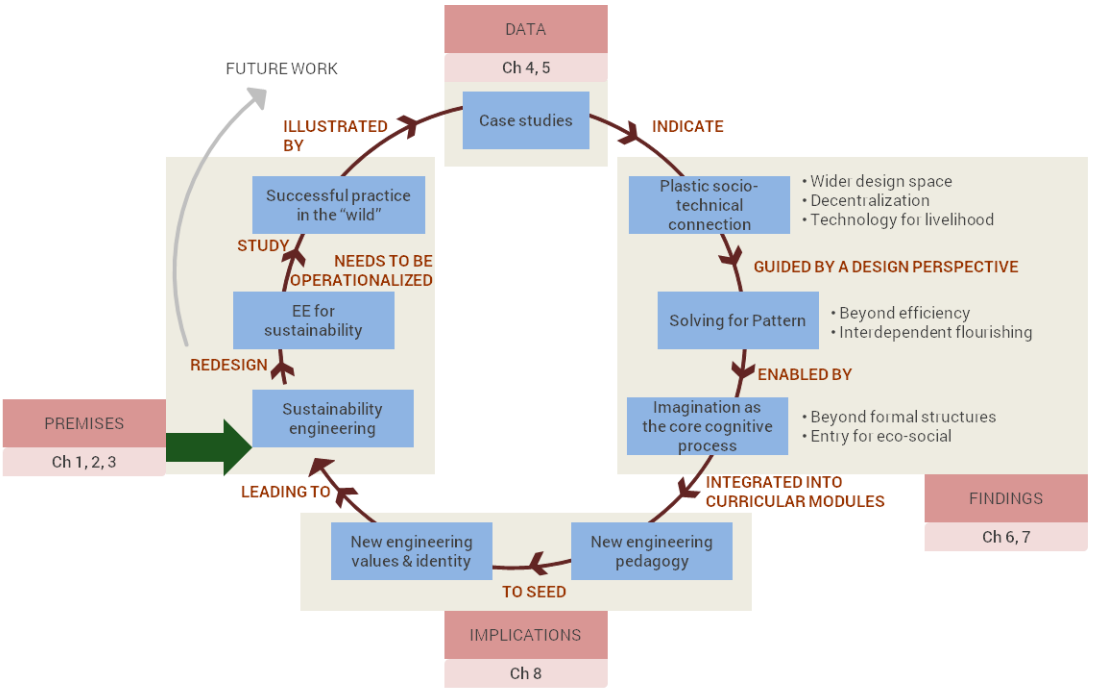

Fig. 2. A graphical summary of the thesis process and argument.

Publications based on this thesis

Journal papers

1. Date, G., & Chandrasekharan, S. (2017). Beyond Efficiency: Engineering for Sustainability Requires Solving for Pattern. *Engineering Studies*, 1-26. DOI:10.1080/19378629.2017.1410160

2. Date, G., Dutta, D., & Chandrasekharan, S. (In press). Solving for pattern: a model of technology beyond efficiency. *Journal of Environmental Values*.

Refereed conference papers

1. Date, G., Agrawal, H., & Chandrasekharan, S. (2018). Probing 'design thinking' through simulation tasks: A novel tool to elicit thinking strategies and principles in grassroots engineering design. *Proceedings of epiSTEME 7: International Conference to Review Research on Science, Technology and Mathematics Education*. Mumbai: Cinnamonteal.

2. Date, G. R., & Chandrasekharan, S. (2016). The Socio-Technical Connection is Plastic, but Only When Design Starts from Need Formulation. In *Proceedings of the 2016 ASEE Annual Conference & Exposition, New Orleans, Louisiana.* 10.18260/p.27019.

3. Date, G., Chandrasekharan. S. (2014). Beyond interfaces: Understanding the process of designing grassroots technologies, to develop sustainability case studies for engineering education. In *Proceedings of the 6th IEEE International Conference on Technology for Education, Kerala, India*. DOI 10.1109/T4E.2014.16

Refereed conference abstracts

1. Date, G. & Chandrasekharan, S. (2017). What role do formal structures play in the design process? Presented in the special track 'Artefacts, Design Practices, and Engineering Knowledge', at the *20th conference of the Society for Philosophy and Technology, June 14-17, 2017 – Darmstadt, Germany*.

2. Date, G. (2016). Learning from grassroots innovation: Case studies for a socially engaged engineering education. Poster presented at the *ASEE Engineering Education Graduate Research Consortium, New Orleans, Louisiana, USA*.

3. Date, G. & Chandrasekharan, S. (2016). *Teaching for socially-engaged engineering and innovation: a case study of grassroots design*. Paper presented at the Second Graduate Seminar, School of Public Policy & Governance, TISS, Hyderabad, India.
4. Date, G., Chandrasekharan. S. (2015). *Characterizing the grassroots innovation process, to develop value-driven case studies for engineering pedagogy*. Abstract book of the 3rd International Conference on Creativity and Innovations at Grassroots, Ahmedabad, India.

Contents

Table of Contents

List of Tables

List of Figures

Clarification of Terms

Table 1: Clarification of concepts and terms used in the document

Term	Meaning
Calibration	Demarcation/measurement of performance parameters against known standards.
Consensus	Agreement on the course of building action or design decision within a team or stakeholders.
Coordination	Communication, distribution, collaboration, and synchronization of design and building work.
Eco-social	Ecological/environmental and social/socio-cultural.
Formal structures	Theory, equations, formulas, calculations, graphs, charts, models and other representations based on engineering sciences or mathematics.
Grassroots	The base of the societal pyramid; the large lowest-income strata of society.
Grassroots innovation	The practice of designing innovative solutions to address the unmet needs at the base of the societal pyramid, by individuals or groups from the unorganized sector, who are 'not formally trained' in science and engineering. Such technical/non-technical innovations are being scouted out from the remote interiors of India by the Honey Bee Network. Such innovations are rewarded, recognized, and given further business and Intellectual Property protection support through the National Innovation Foundation, an autonomous body under the Department of Science and Technology, Government of India. See NIF, HBN, SRISHTI, GIAN websites.
Grassroots technology design (as used in this thesis)	Designing of innovative technological solutions to address grassroots needs (unmet by mainstream engineering industry), by individuals or groups, who are non-formally or formally trained.
Idealization	Removing or making abstract parts of a design problem. This is done so that formal structures can be used to generate a model of the design problem.
Imagination	The process of mentally simulating (i.e. activating in working memory) physical structures and their activity/dynamics.
Micro hydro power (MHP)	Electricity generated from flowing water, in the range of 1-100 kW.
Modularization	Separation or isolation of various component assemblies or sub-systems in a technical product or system, for the convenience of design.
Plasticity of socio-technical connection	The connection between society’s needs and the functions provided by technology is fluid or plastic, and thus amenable to redesign or reconfiguring. Recognizing this expands the innovation space, generating multiple novel designs/business models.
Solving for Pattern	A process of solving problems, proposed by American farmer and writer Wendell Berry,[2] where the larger sustainable eco-social patterns within which the design problem is embedded are not adversely disturbed by the design solution.

2 Berry, *The Gift of Good Land: Further Essays Cultural and Agricultural*, 1981.

Analytical index of chapters

The analytical index presents the argument of this thesis, and its respective chapter structure in brief. It may be understood as an executive summary of the thesis.

Premise and motivation (Ch 1)

The need for a new pedagogy for sustainability engineering

Building is a key adaptive capability of the human species, and engineering is the modern version of this adaptive practice. However, our building activity is now damaging the planet. Engineering practice thus needs to change, to design and build systems that enable a sustainable way of life. One way to do this is through engineering education. Sustainability requires training for a new kind of engineering, but it is not clear how traditional engineering education – in India and across the globe – could be redesigned for this. A possible approach is to study the process of sustainable technology design practice, 'in the wild'.

Review of literature (Ch 2)

Limitations of the canonical approach to sustainability engineering

The engineering education research (EER) literature identifies some key challenges to training students for sustainability. On the one hand is the overall challenge of broadening the knowledge/skill-base, by fitting more (sustainability content) into an overcrowded curriculum, and integrating this with the core disciplinary knowledge. Furthermore, the multi-disciplinary knowledge needs to be integrated for sustainability, while ethics, humanities, and social sciences need to be more central to EE. On the other hand, the standard instructor-led learning model is pedagogically not sufficient for developing students as sustainability engineering professionals.

The broader literature (across engineering education, sociology, philosophy and politics of technology, as well as design studies) further points out that EE trains for textbook problems rather than real-world workplace problems, where the problem framing is limited to the techno-commercial, while largely excluding the socio-technical nature of the engineering practice. The contemporary EE is based on a canonical approach to technology and engineering, which considers engineering to be value-neutral and technology-driven, while implicitly prioritizing values of instrumentality and efficiency. Moreover, design is a situated activity rather than mere technical problem-solving. The emphasis in EE on engineering sciences and mathematics as core technological knowledge, and a purely techno-economic focus in the design process, perpetuates a societal disengagement among students, and students' engineering identities develop based on techno-scientific rationality/instrumental thinking alone.

EE reforms to address these issues are segmented and isolated at the level of both curricula and pedagogies, and thus cannot achieve success in integrally addressing the messy complexity of sustainability problems, where the competencies required are still unclear. The current EE approach is thus inadequate to develop an engineering for sustainability.

Research approach (Ch 3)

Studying practice 'in the wild' - an approach to redesigning EE pedagogy for sustainability engineering

Since mainstream practice does not offer any alternate models to the structure identified above, a satisfactory, and evidence-based, way to redesign EE pedagogy for sustainability engineering needs exploring successful cases of sustainability engineering design in the wild. Such cases are hitherto unexplored from the sustainability engineering and

EE perspectives, and research is required to characterize these cases well to contribute to these perspectives.

The thesis project sought to address the above research gap, by exploring successful cases of sustainable technology design practice in the wild. In the Indian context, grassroots innovation[3] is one such practice. The project's objective was to characterize such grassroots technology design well, extract their underlying design principles and cognitive processes, both non-formal and formal, and then use these to develop a new pedagogic approach to support engineering for sustainability. In other domains, similar studies of practice, examining both traditional (medicine, agriculture) and modern (bio-medical engineering)[4] practices, have provided evidence-based ways to design education systems. Following these approaches, a new engineering pedagogy for sustainability could be developed based on studies of sustainable grassroots technology designs, which have not been explored from this perspective.

Research design (Ch 4) and case studies (Ch 5)

Multiple case study - qualitative cross analysis

Grassroots innovation is a unique practice, spread across a wide range of problems and contexts. Given this variety, the case study method was identified as the appropriate method to study this practice. Cases were purposively selected, based on the contribution they could make to engineering education. The case of Micro Hydro Power (MHP) generation systems was chosen as a focus area, as the technology is part of mainstream

3 Grassroots innovators are individuals, 'not formally trained' in science and engineering, who have been recognized (through National Innovation foundation) for designing technology to address their needs unmet by the formal engineering industry.

4 Nersessian, *Creating scientific concepts,* 2008; Nersessian et al., “Research laboratories as evolving distributed cognitive systems,” 2003; Nersessian & Newstetter, “Interdisciplinarity in engineering research and learning,” 2014.

engineering, and it is sufficiently complex in terms of design process and thinking. Further cases were then selected to provide more generality to the study of this core practice, through comparison and validation. (See Fig. 3).

The empirical data for the core cases included primary sources (interviews, observation, artifacts, simulation data), as well as secondary sources (photos, videos, and reports, including brochures and news articles). To probe design thinking across both formally and non-formally trained designers in a controlled fashion, a computational simulation of MHP systems, with visual and numeric modes, was developed. Data on the designers' interactions with this simulation provided a different perspective on their design processes.

The data from all these sources were integrated, and qualitatively analyzed using cognitive historical analysis[5] and thematic analysis,[6] to develop a comprehensive understanding of the design practices and their underlying cognitive processes. (See Fig. 6). Distributed cognition[7] was the primary theoretical framework used for studying the cognitive process of design.

Findings 1 - Design practice (Ch 6)

The socio-technical connection is plastic; sustainable technology aims at empowering people and sustaining their local livelihoods

A thematic analysis of the core cases – non-formal and formal practice while designing MHP systems – provided insights into the process and principles of designing for sustainability. Additional cases were selected for a comparison with the core cases, to explore

5 Nersessian, "How do engineering scientists think? Model-based simulation in biomedical engineering research laboratories," 2009; Nersessian, *Creating scientific concepts*, 2008.
6 Braun & Clarke, "Using thematic analysis in psychology," 2006.
7 Hollan et al., "Distributed cognition: toward a new foundation for human-computer interaction research," 2000; Hutchins, *Cognition in the Wild*, 1995a.

if other grassroots cases demonstrate similar characteristics, and whether the other cases could add to the understanding of alternate practice. A comparison with the canonical design process was done to identify generic findings that cut across the empirical cases.

The characterization of the practice of grassroots technology design showed that such design worked by reconfiguring the socio-technical connection, which was found to be very plastic and capable of generating multiple novel designs, but only when the designer started from problem formulation. Further, technology developed for grassroots was found to be aimed at empowering people and sustaining local livelihoods, which is a socio-technical design principle that is wider than the standard model of technology lowering drudgery/cost.

Findings 2 - Cognitive process of design (Ch 7)

Imagination and synthesis are the core cognitive processes in engineering design; formal structures play only subsidiary roles

As current engineering education (EE) focuses on formal structures, and the formal structures mainly support only the Detailed design stage in the design process, it is unclear how the design principles and processes, identified in the previous study (Ch 6), could be integrated into EE. To understand how engineering students can start thinking like the designers of sustainable technology, in order to implement sustainable design process and principles, a cognitive historical analysis of the core cases (non-formal and formal design process for the MHP system), was done, to understand the cognitive processes involved in designing such systems, particularly the role played by formal structures. Additional cases were then selected for comparison and a wider characterization. A comparison with the canonical training process allowed for some generalization of the findings, across the results from the empirical cases and the additional cases.

This analysis demonstrated that imagination (mental simulation of material structure and dynamics) and synthesis, are the core cognitive processes in engineering design, and the role of formal structures is mostly supportive/supplementary to these core processes. As imagination and synthesis are general cognitive processes, they can include the sustainability engineering principles identified by the earlier analysis, and these can thus be part of EE.

Discussion and implications (Ch 8)

Solving for Pattern is a promising process approach to design technology for sustainability. Implementing this design approach requires setting up of interdisciplinary institutes that bring together design, ecology, engineering, and humanities, to research and promote sustainability engineering

Integrating the findings, an overarching guiding perspective for engineering design for sustainability is developed, borrowing from Wendell Berry's idea of 'Solving for Pattern', a design perspective that goes beyond the standard efficiency approach to design. The findings from the studies also indicate that grassroots technology design can provide interesting insights towards developing a new engineering pedagogy for sustainability.

Based on these findings, I develop two policy recommendations to redesign engineering education for sustainability - a) engineering design instruction needs to change, and one operational approach could be Solving for Pattern, and b) engineering selection and training needs to be based on developing imagination and synthesis skills. Bringing these policy recommendations together, I propose an implementation-level recommendation, suggesting the creation of interdisciplinary institutes that bring together ecology, design, engineering, and humanities, to research and promote sustainability engineering. Wider implications of these findings, particularly for research, engineering practice, and pedagogy (particularly case-study-based learning, grassroots projects, and internships), are also discussed.

Chapter 1: Introduction

The need for a new pedagogy for sustainability engineering

"Our current world view, or paradigm, has led us to our current unsustainable state of affairs. Much of our current attempts toward sustainability are doomed to failure as they do not address fundamental flaws in our world views."[8]

In this chapter
Building is a key adaptive capability of the human species, and engineering is the modern version of this adaptive practice. But this building activity is now damaging the planet. Engineering practice needs to change, to design and build systems that enable a sustainable way of life. One way to do this is through engineering education. Sustainability requires training for a new kind of engineering, but it is not clear how traditional engineering education – in India and across the globe – could be redesigned for this. A possible approach is to draw on sustainable technology design practice 'in the wild'.

Introduction

The practice of building novel structures and artifacts is central to human adaptation. Engineering is the modern version of this adaptive practice. Engineers make artifacts, real or virtual. They design, build, and maintain products, processes, and systems. Essentially they create the artificial or human-made part of the world around us. Over the last few centuries, the making of artifacts and in turn the knowledge and education of the makers has changed in significant ways. While there have been many benefits from the new ways, the world is also facing several challenges, some attributed to the creations by engineers, while others still awaiting solutions from engineers. It has become clear recently that this adaptive trait of building is now in runaway mode, as human activity, primarily based on building, has damaged the planet significantly, and has thus pushed every species towards

8 Lau, "Sustainable design: A new paradigm for engineering education," 2010, p 252.

extinction. In the words of philosopher Hans Jonas, modern technology's ‘syndrome of self-proliferation’[9] has made human the ‘prime agent in the threatening disposition of things'.[10]

From the larger Indian intellectual tradition, the life, work, and writings (many in vernacular) of many recent/contemporary Indian thinkers, teachers, and activists, such as, Anil Agarwal, S. A. Dabholkar, Manibai Desai, M. K. (Mahatma) Gandhi, Prakash Gole, Sharad Joshi, J. C. Kumarappa, Vilasrao Salunkhe, are valuable to understanding nuances of the development-environment debate, indirectly touching upon engineering and technology design in the Indian context.

Changes in our current approach to engineering and design are thus critically needed. Problems and technological needs across the globe make it imperative that engineering activity now delivers technology that enables a sustainable way of life, by – 1) limiting the damage to the environment including global warming, 2) bridging the disparity in the world, between the developed and the marginalized/developing.

One way to address this challenge is through engineering education, by developing the competencies of engineers. Organizations of practicing engineers as well as engineering educators have engaged with this expectation, by way of educational interventions and research studies in order to find ways to fulfill it. Education of 21st century engineers, such that they design technology for a sustainable way of life on Earth, is thus a crucial area where change is being initiated.

9 Jonas, “Toward a philosophy of technology,” 1979, p38. “This syndrome of self-proliferation-by no means a linear chain but an intricate web of reciprocity-has been part of modern technology ever since. To generalize, technology exponentially increases man's drain on nature's resources (of substances and of energy), not only through the multiplication of the final goods for consumption, but also, and perhaps more so, through the production and operation of its own mechanical means.”

10 Jonas, “Toward a philosophy of technology,” 1979, p41. “This would summon man's duty to his cause even if the jeopardy were not of his own making. But it is, and, in addition to his ageless obligation to meet the threat of things, he bears for the first time the responsibility of prime agent in the threatening disposition of things.”

In this chapter, I start with a short overview of engineering education in India, its history, current scenario, and vision, to provide a backdrop and a context to the discussion that follows, about the future challenges and reforms in engineering education (Section 1). I then present in brief the diverse aspects of a felt need across the world, including India, to focus on sustainability in Engineering Education (EE). I report some key engineering education reforms towards sustainability, and discuss their limitations. I also touch upon the critique from a wider literature briefly (reported in detail in the Literature Review Ch 2), as that has a bearing on the educational reforms (Section 2). Against this background, I argue that EE needs an integrated solution to address such limitations, and discuss how this constitutes a research problem (Section 4). I then briefly present one way to address it, through the operationalization of this research study (Section 5).

1.1 Engineering Education (EE) in India

1.1.1 The historical backdrop

Modern engineering education started in India during the British rule, with a small surveying school in Chennai in 1794. Engineering colleges were then established at Roorkee (1847), Pune (1854), and Kolkata (1856), to provide trained surveyors and civil engineers for Public Works Department (PWD), as well as military engineers. Over the course of time, these engineering colleges offered limited degree programs in civil, mechanical, and electrical engineering, to cater to government jobs in the departments of Railways, Electricity, Telecommunications, Irrigation, etc. A demand for the expansion of engineering education then started building up, as educated Indians felt the need for employment and industrialization. “The Indian National Congress in its third Session held at Madras in 1887 passed a resolution that having regard for poverty of the people, it is desirable that the Government be moved to elaborate a system of technical education."[11] While the government was slow in responding, private initiative gave rise to IISc (1908) and BHU engineering college (1919). In 1945, N. R. Sarkar committee recommended the establishment of at least four higher technical institutions, on the lines of MIT, USA, to train 'creative scientist engineers' (As envisioned by William Rogers, MIT engineers were to be inventors, men who would use their knowledge of scientific principles to improve on existing processes[12]). Towards this, All India Council for Technical Education (AICTE) was established in 1945 to plan and coordinate the growth of technical education in India.

With the Nehruvian emphasis on Science and Technology for development of the newly independent India, another recommendation from the Sarkar committee was implemented, and five Indian Institutes of Technology (IITs) were established, at Kharagpur (1951), Bombay (1958), Madras (1959), Kanpur (1960), and Delhi (1961).[13] Four of these, except IIT Kharagpur, received mentoring from a developed country each, the USSR, Germany, USA, and UK respectively. Over the years, more IITs were instituted, and presently there are 16 operational and five upcoming IITs in the country. The Government of India also established Regional Engineering Colleges, now known as National Institutes of Technology (NITs),[14] apart from state-level engineering colleges and private colleges. The IITs and NITs have a more autonomous status, to enable them to meet international standards.

11 Singh, cf Biswas et al., "Profile of engineering education in India: Status, concerns and recommendations," 2010, p. 11.
12 Bassett, "MIT-trained swadeshis: MIT and Indian nationalism, 1880–1947," 2009, p 215.
13 Kakodkar Committee. "Taking IITs to Excellence and Greater Relevance," 2011; Subramanian, "Engineering Education in India: A Comprehensive Overview," 2015.
14 Mashelkar Committee Report, 1998, cf Subramanian, "Engineering Education in India: A Comprehensive Overview," 2015.

Many committees were constituted from time to time, in order to review the status of engineering education and recommend roadmaps for improvement. Radhakrishnan Commission (1949), Thacker Committee (1959), Kothari Commission (1964), Nayudamma Committee (1978), Rama Rao Committee (1995 & 2004), Mashelkar Committee (1998), Rao Committee (2003), Joshi Committee and Anandakrishnan Committee (2006), and Kakodkar Committee (2011) are some of the landmark reports in this context (See Banerjee & Muley, 2007, p 3 for a tabulated summary).[15]

1.1.2 Current scenario and the identified challenges

Currently, there may be more than 2300 government and private engineering education institutes in India, with an intake capacity to cater to more than 8,00,000 students.[16] The IITs are reputed to have produced engineers of world class training. However, many students have found the IITs to be a stepping stone for emigrating abroad. The Indian tax-payers' investment in training engineers at IITs didn’t reap a large enough return, in terms of the graduating engineers addressing the country's technological needs.

On the other hand, while it was suggested that the new IITs need not follow the model of the early IITs, generally the 'engineering science' orientation of IIT curricula has been aspired to by all engineering education institutions in the country, be they government or private. The quality of academic engagement and infrastructural facilities at these institutes is uneven across the country, and catering to a vast population of aspiring students continues to pose immense challenges to engineering education in India. Particularly, as Pradeep Kumar Choudhury analyzes, “… this massive expansion of engineering education has not been able

15 Banerjee & Muley, “Engineering education in India,” 2007.
16 Biswas et al., “Profile of engineering education in India: Status, concerns and recommendations,” 2010, p 91.

to provide access to the disadvantaged groups, namely women, scheduled castes and scheduled tribes."[17]

Furthermore, the focus on training for engineering sciences leaves out the training for professional skills emphasized in industrial job interviews. Struggling to teach both these aspects, EE fails to produce students that meet industrial job requirements, which themselves are changing at a much faster pace than education in the current times.

> *"According to India Skills Report 2017, jointly sponsored by Confederation of Indian Industry (CII), United Nations Development Programme (UNDP), Association of Indian Universities (AIU) and All India Council of Technical Education (AICTE), only 40.4% of the students passing out of the Indian higher education system are deemed employable. Going hand in hand with employability is the availability of employment: by 2020 India would be graduating six engineers for every engineering job available."*[18]

All India Council of Technical Education (AICTE) lays down the standards for EE, and the National Board of Accreditation (NBA) is responsible for the evaluation of technical training institutions. Established in 1994, NBA revised the accreditation norms in 2009, in line with the international standards of the Washington Accord. In 2014, India became the 17th permanent member of the Washington Accord, in order to have an equivalence of its EE qualifications with other signatory countries. On the one hand, this will enable better mobility for India-trained engineers across the member countries. On the other, it will also ensure a minimum quality of education for the engineers from the accredited tier-I colleges.

1.1.3 EE vision and future challenges

Vision for EE in India mainly aims at converting its demographic 'dividend' to an advantage, by providing a workforce for global industry. "If we take the right steps and make rapid progress in quality technical education, we can provide a well-trained, innovative

17 Choudhury, "Growth of Engineering Education in India: Status, Issues and Challenges," 2016, p 93.
18 TIFAC. "Technology Vision 2035: Technology Roadmap Education," 2017, p 19.

workforce not only to India but possibly other countries."[19] Most recommendations for improving EE focus on the quality of faculty, infrastructure, and linkages with industry and top R&D establishments. This may be achieved through-

> *"... total autonomy, independent, empowered Board of Governors, an outstanding academic as head, liberal funding by the government supplemented by private donations, good faculty with some stars, high-quality students and good infrastructure."*[20]

Similarly, improvements to curricula focus on current needs of industry, while the pedagogical suggestions support educational technology more than opportunities of experiential and active learning.[21]

A comprehensive study by Biswas and colleagues goes deeper to discuss many challenges in detail and suggest international-quality solutions/approaches to address these. Apart from access and equity, the major challenges for Indian EE are recognized to be,

> *"… competence development of existing teachers, attracting through suitable incentives a larger number of engineering graduates and post-graduates to a teaching and research career, synergizing the innovation efforts and potential of educational institutions, research laboratories and industry, and above all a change in the mindset of educational managers and policy planners in removing barricades to achieving excellence."*[22]

Even though the reports highlight "the need for well-trained, motivated teachers and researchers; innovative research for societal needs and new products",[23] they do not emphasize a training of students for independent or entrepreneurial work, beyond the current and default model of industry, and severely limit EE to the vision of industry, rather than the broader problems of the society and the planet. Nevertheless, Banerjee and Muley comment

19 Subbarao, "India's higher engineering education: opportunities and tough choices," 2013, p 56.
20 Subbarao, "India's higher engineering education: opportunities and tough choices," 2013, p 65.
21 Subbarao, "India's higher engineering education: opportunities and tough choices," 2013.
22 Biswas et al., "Profile of engineering education in India: Status, concerns and recommendations," 2010, p 59.
23 Subbarao, "India's higher engineering education: opportunities and tough choices," 2013, p 57.

that, “The linkage and commitment of engineering institutions to the nation’s development is essential before the engineering colleges can aspire to make a global impact.”[24]

India’s Technology Vision for 2035, as presented by the think tank TIFAC, calls for “the presence of industry on academic campuses to provide hands-on learning opportunities for learners in research translation”,[25] and counts educational institutions as a principal actor in realizing the vision through participation in the innovation ecosystem along with industry.

> *“This is necessary because education is the fountainhead of young human resource and that must be oriented and prepared to be effective in strengthening Indian innovation and technological capability.”*[26]

1.2 Sustainability in global Engineering Education

Struggling to address these diverse challenges, engineering education (EE) across most engineering training institutions in India, as well as the world, is only barely acknowledging that sustainability is one of the greatest challenges for engineering and EE today, and it is far from addressing this challenge effectively. In this section, I present in brief the diverse aspects of a felt need across the world, including India, for a sustainability focus in Engineering Education (EE). I report some key engineering education reforms towards sustainability, and discuss their limitations. I also touch upon the critique from a wider literature briefly (reported in detail in the Literature Review Ch 2), as it has a bearing on the educational reforms.

1.2.1 Need for a sustainability focus in EE

Nevertheless, scholars across the world have identified the need to address this situation, and argued for engaging with sustainability concerns through EE. Broadly, these

24 Banerjee & Muley, “Engineering education in India,” 2007, p 108.
25 TIFAC. “Technology Vision 2035: Technology Roadmap Education,” 2017, p 110.
26 TIFAC. “Technology Vision 2035,” 2015, p 95.

concerns are understood in terms of environmental damage and degradation, and socio-economic deprivation and disparity.

1.2.1.1 Engineering training to limit the environmental damage

Of global magnitudes and long-term consequences are the serious problems of pollution of natural environment and resource depletion. Modern technology has brought on critical concerns about the sustainability of the current ‘modern’ way of life. Stephen Petrina comments that, “When we design, and teach design and technological problem solving, however, we invariably neglect the interconnectedness of products, streams, and wakes”.[27]

Engineering has started addressing some of these challenges through design approaches guided by systems engineering, industrial ecology, and product life cycle management. Nevertheless, designing every artifact for reuse, recycling, dissembling, and deconstruction is still not integral to engineering practice. The engineering education scenario is no better in this respect. Chandrasekharan and Tovey[28] point out the need to train engineers for these.

> *“... most of our universities have engineering schools that are focused on assembling and manufacturing complex artifacts, a valued and respected activity. A plausible institutional change would be to develop deconstruction/re-usability engineering departments within these engineering departments...”*

Furthermore, discipline-based engineering to the exclusion of ethical aspects appears to leave an engineer's training incomplete and insufficient to handle the sustainability (including equity) challenges. Engineering curricula, in trying to accommodate an ever-expanding body of disciplinary engineering knowledge, have consequently relegated the historically included disciplines of humanities and social sciences to the periphery.

27 Petrina, “The Political Ecology of Design and Technology Education: An Inquiry into Methods,” 2000, p 208.
28 Chandrasekharan & Tovey, “Sum, Quorum, Tether,” 2012, p 474.

Engineers need a broad vision to handle the deliverable specifications for social and ecological sustainability. It may be said that the broader challenge of social and ecological sustainability actually encompasses all the other challenges. Based on studies of engineering work, Stevens, Johri, and O'Connor anticipate that the nature of engineering work in the 21st century may be a great deal different from that before.

> *"Engineering is clearly implicated in solving some of the planet's biggest problems including sustainable energy, climate change, and famine. These are problems that call for a full-scale recognition of heterogeneous engineering and its artful practice...".*[29]

The Indian Technology Vision for 2035 also emphasizes the need for sustainability engineering.

> *"Since the early 1990s, those thinking about engineering education have felt the need to develop a more holistic approach that revises the objectives of engineering education from controlling nature to participation with nature. .. The societal goals of sustainable development will require the rapid institutionalisation of ecosystems thinking, exemplified in the emergence of fields such as Earth Systems Engineering (ESE)."*[30]

1.2.1.2 Engineering training to address unmet needs of the underserved

Global challenges for development are perhaps all the more pressing and ill-structured problems, fitting the category of 'wicked'[31] problems. UNESCO report now seeks to redefine the role of engineers in order to meet the development goals across the world. Gerard van Oortmerssen (President, International Council of Academies of Engineering and Technological Sciences, 2008) warns that,

> *"Realization of the United Nations Millennium Development Goals will require significant effort by engineers, but also creativity because the contexts of developing countries often requires new ways of doing things or the rediscovery of traditional techniques".*[32]

29 Stevens et al., "Professional Engineering Work," 2014, p 130.
30 TIFAC. "Technology Vision 2035: Technology Roadmap Education," 2017, p 154.
31 Rittel & Weber, "Wicked problems," 1974.
32 van Oortmerssen, "UNESCO Report," 2010, p 7.

The report adds that,

“Resolving these issues will require tremendous innovation and ingenuity by engineers, working alongside other technical and non-technical disciplines. It requires the engineer’s ability to synthesize solutions and not simply their ability to analyse problems”.[33]

Claude Alvares underlines the same challenge.

“The skills and ingenuity of engineers and technologists are needed in each economic area and the task is no easier whether the area is economically advanced or not.”[34]

Drawing attention to the 70% rural population, report of the Working Group on Engineering Education of India's National Knowledge Commission also highlights that,

“... equitable growth within the country is not possible as long as this sector remains in a neglected state. Along with the requisite of knowledge and skills to work in this area, the incentives to motivate scientists and engineers are an issue that needs to be addressed”.[35]

Often the engineering solutions in a location, culture, or ecology do not fit 'as is' to another, and there is a need for continuous innovation or customization of solutions that may have worked in the developed countries, when they are 'applied' to the developing ones. Shuman et al.[36] point out that the current engineering curricula are not sufficiently geared to build an awareness of the nature of such problems specific to developing communities as water provision and purification, sanitation, health, power production, shelter, site planning, infrastructure, food production and distribution, and communication.

Milind Sohoni[37] defines good engineering as 'societal problem solving' and suggests that it is best taught as a partnership between ambient society and the budding professional. According to him, “The bottom line of good engineering is the solution of the problem posed

33 Jowitt, “UNESCO Report,” 2010, p 39.
34 Alvares, *Decolonizing history: technology and culture in India, China and the West 1492 to the present day*. 1991, p 236.
35 National Knowledge Commission, “Report of Working Group on Engineering Education,” 2008, p 15.
36 Shuman et al., “The ABET “professional skills” – Can they be taught? Can they be assessed?,” 2005.
37 Sohoni, “Engineering teaching and research in IITs and its impact on India,” 2012.

by the end-user in society.” At a time when this was taught in India, such good engineering included, along with the technical knowledge of the engineering domains also the knowledge and skills to observe, model, and parameterize societal problems, and then design and deploy solutions. With the adoption of abstract engineering curricula at the Indian Institutes of Technology (IITs), however, the focus shifted to the technical ability to solve well-posed problems. This shift led engineers to neglect the societal problems, to an extent, that Sohoni derides whether,

> *“Perhaps we doubt if the 'drinking water problem' is really technical at all... Or that 'drinking water' is indeed a technical problem, but it is for other 'lower' Indian institutions to address”.*[38]

Sohoni summarizes this as, “... a great deficit in courses on societal modeling and a great surfeit in the technical and scientific domain”. Students are thus exposed mainly to textbook problems, in a sense 'toy-problems'. As a result, students having abilities to solve only well-posed problems, and aspiring for the best jobs to do so, choose jobs at companies that focus on well-posed problems of the developed countries, rather than the developing countries like their own. Sohoni stresses the irony of this education model, where the best students learn engineering but are unable to solve problems of their own people. He criticizes that the curricula do not teach protocols which start from the society and end at it.

Scientists, engineers, as well as faculty and students remain disconnected from the societal problems. Moreover, students are not introduced to the historical or contemporary technological solutions developed for and by the people themselves. Anil Gupta, who founded Honey Bee Network, brings to light technology that untrained and marginalized

38 Sohoni, “Engineering teaching and research in IITs and its impact on India,” 2012, p 1512.

people innovated because trained engineers in the society did not address their needs, and points out that,

> *"... the pedagogy and curriculum in the educational institutions seldom require interaction among the students and the disadvantaged sections of society. Further, the innovation by common people almost never becomes part of the curriculum or textbooks at any level from primary education to the higher education level".*[39]

It is clear that the outcomes expected out of engineering education as yet do not place these problems at the center. Even engineering firms vying for global business require their engineers to be sensitive to diverse societal contexts.

> *"In the future, industries that cannot compete in the international market are unlikely to survive in the domestic market. Succeeding internationally requires cultural and economic understanding no less than technological expertise."*[40]

It is not enough to specialize in a discipline, as engineers need to work in interdisciplinary teams and problem situations. Human activity, driven by science and technology, has built a new artificial world, and brought comforts to many. But it leaves unmet the needs of many more, in the process also significantly damaging the planet's ecosystem. Systemic changes resulting from this activity, such as global climate change and poverty, are now central concerns while designing future policies and technologies that promote equity and sustainability.

Meeting these core challenges to enable a sustainable way of life on the planet requires that current education of engineers is reformed accordingly.

39 Gupta, "Innovations for the poor by the poor," 2012, p 34.
40 Felder et al., "The Future Of Engineering Education I. A Vision For A New Century," 2000, p 3.

1.2.1.3 Engineering training to address the critique from a wider literature

Engineering practice now requires the ability to work in interdisciplinary teams across globally diverse cultures and task contexts, and this change is getting reflected in EE. However, this is a narrow change, applicable only to the sphere of well-defined problems. This change is does not capture the wider nature of the sustainability engineering problem, which requires engineering students in developed countries to understand the ill-structured problems related to development. The best students in developing countries, though aware of the problems of the marginalized, are groomed by the EE curricula to serve only the developed.[41] Students are thus not trained for sustainability problems, which are arguably the most ‘wicked’ of all.

Critique of engineering education, from a wider scholarly literature, indicates that EE assumes technological knowledge to be limited to engineering sciences and mathematics, and technology is considered to be value-neutral. Design is limited to making techno-scientific calculations, while hands-on components are mostly missing. Students acquire technical rationality and social disengagement as key aspects of their engineering identity, while lacking a sense of the real nature of engineering practice, and the nature and role of technology. (See Ch 2 Literature Review for more).

1.2.2 Need for engineering education reforms

Educators have recognized the new challenges in engineers' work, and acknowledged the corresponding need to bring changes to engineering education. In response, several educational reforms have been suggested and instituted across the world.

41 Gupta, “Innovations for the poor by the poor,” 2012; Shuman et al., “The ABET “professional skills” – Can they be taught? Can they be assessed?,” 2005; Sohoni, “Engineering teaching and research in IITs and its impact on India,” 2012.

These range from undergraduate programs dedicated to sustainability in engineering, to initiatives for training of professional skills such as teamwork and communication. The expected outcomes, curricula, and pedagogy, especially related to sustainability, are reported in this section.

Revision of accreditation requirements in some countries reflect nation-wide effort and commitment to such reforms. In the USA, the focus shifted from 'credits completed' to 'outcomes achieved'. ABET[42] 'conducted national-level rounds of review of its baccalaureate accreditation requirements. Its revision EC2000 included a new set of 11 outcomes. Relevant among the Criterion 3 - Student outcomes for engineering education are:

‘(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability’, and

‘(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context’.

Institution of Engineers, Australia, updated the procedure for accreditation of the engineering baccalaureate to ensure inclusion of sustainability learning[43].

In the Indian engineering education context, the National Accreditation Board (NBA) prescribes a set of individually assessable outcomes for competence in undergraduate students. Among other outcomes, the Graduate Attributes emphasize, under ‘Environment and sustainability’, that students:

42 ABET, “Criteria for accrediting engineering programs,” 2017, p 4-5.
43 Carew & Mitchell, “Characterizing undergraduate engineering students' understanding of sustainability,” 2002.

> *"Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development."*[44]

In correspondence with these, various curricular reforms and pedagogical approaches, especially courses related to sustainability, have been introduced.

1.2.2.1 Curricular reforms

Over last few decades, the curricula were progressively modified to include courses in Sustainability, Humanities and Social Sciences, Ethics, as well as soft skills such as writing, communication and team work. Such curricular reforms are vital, since, "... curricula define the first perspective by which students will approach new problems".[45]

The Indian National Knowledge Commission (NKC)'s Working Group on Engineering Education[46] recommended the inclusion of a course on current topics of social or industrial or national relevance in the first semester of engineering, to give "a flavor of engineering".

Biswas and colleagues report sustainability as a concern in the training of engineers. However, the expectation from engineers is limited to environmental impact analysis, against the backdrop of environmental degradation caused by current technologies.

> *"[The] Impression has grown that economic development and environmental preservation are often mutually exclusive and incompatible. This notion has to be removed from the minds of young graduates through training in sustainable technologies and benign manufacturing processes which will support a healthy economy and a healthy environment. Engineers in all their project formulation are legally required today to do an environmental impact analysis before the Project can be initiated. Proper training in such impact analysis must be part of all engineering curricula."*[47]

44 National Board of Accreditation, "General Manual of Accreditation," nd, p 23.
45 Sohoni, "Engineering teaching and research in IITs and its impact on India," 2012.
46 National Knowledge Commission, "Report of Working Group on Engineering Education," 2008.
47 Biswas et al., "Profile of engineering education in India: Status, concerns and recommendations," 2010, p 28.

Their curricular recommendations includes “one course in Earth and Environmental Sciences (3-1-0-4) would be the minimum requirement. The course should be a pointer towards “Green Technologies”.”[48]

Many curricular changes focused on including sustainability, either as an add on, or integrated in various degrees. With colleagues, Huntzinger[49] reviewed some selected university websites, for the course, pedagogy, and assessment details, to find out how many had 'sustainability' and 'problem-based learning (PBL)' included in the engineering curriculum. The inclusion was graded on a three-point scale, based on Sterling's response levels: bolted-on, built-in, redesigned. One university (out of about seventeen reported) was found to have a real inclusion of both.

Carew[50] and team studied the way students understand sustainability, and found that there is a broad structural variation. Segalas[51] and colleagues described the desired sustainability competencies for engineering bachelor graduates in some parts of Europe.

Chau[52] studied the integration of sustainability concepts into an undergraduate civil engineering curriculum in Hong Kong, and found that multidisciplinary skills were developed, and also that the students were rated better by prospective employers, compared to other colleges with similar programs without sustainability. Quist[53] found that it is possible to develop a 'light' version of the participatory backcasting course, which effectively

48 Biswas et al., “Profile of engineering education in India: Status, concerns and recommendations,” 2010, p 93.
49 Huntzinger et al., “Enabling Sustainable Thinking in Undergraduate Engineering Education,” 2007.
50 Carew & Mitchell, “Characterizing Undergraduate Engineering Students’ Understanding of Sustainability,” 2002.
51 Segalas et al., “What Has to Be Learnt for Sustainability? A Comparison of Bachelor Engineering Education Competences at Three European Universities,” 2009.
52 Chau, “Incorporation of Sustainability Concepts into a Civil Engineering Curriculum,” 2007.
53 Quist et al., “Backcasting for Sustainability in Engineering Education: The Case of Delft University of Technology,” 2006.

introduced engineering students to the backcasting method of defining a desirable future and then working backwards to identify policies and programs that will connect the future to the present. Costa and Scoble[54] (2006) reported about an interdisciplinary model, the Sustainability Working Group (SWG) that brought together academia, industry, government, NGO's and mining communities, in order to integrate sustainable development into mining engineering, at the University of British Columbia.

Green engineering that only employs pollution prevention and industrial ecology is found to be not sufficient to achieve sustainability. Mihelcic[55] and team thus made a case for an entirely new metadiscipline of sustainability science and engineering, which integrates industrial, social, and environmental processes in a global context.

1.2.2.2 Pedagogical reforms

Where the engineering education challenges could not be addressed by current methods of teaching and learning engineering and design, pedagogical changes were found necessary. Strategies for pedagogical reforms included cornerstone and capstone courses for project and problem-based learning, active participatory learning opportunities, instructional laboratories, learning a second language, and foreign country internships.

Chau[56] highlighted team-based design project with problem-based learning approach as an effective method, suggesting that multidisciplinary skills developed during the learning process might contribute significantly to pertinent knowledge on sustainability.

According to Mclaughlan,[57]

54 Costa & Scoble, "An Interdisciplinary Approach To Integrating Sustainability Into Mining Engineering Education And Research," 2006.
55 Mihelcic et al., "Sustainability Science and Engineering: The Emergence of a New Metadiscipline," 2003.
56 Chau, "Incorporation of Sustainability Concepts into a Civil Engineering Curriculum," 2007.
57 Mclaughlan, "Instructional Strategies to Educate for Sustainability in Technology Assessment," 2007, p 201.

> *"focus on learning strategies is necessary to create the integrated and interdisciplinary perspective required for sustainability education. Active learning strategies, which use methods that can accommodate conceptually and practically diverse data and divergent epistemologies are needed. Roleplay-simulation, online debates and scenario building are active, participatory instructional strategies".*

Feisel and Rosa[58] looked at the role of instructional laboratories in providing exposure to real-world problems, considering the lab as 'a place to have some contact with nature, whether real or virtual.'

Shuman, Besterfield-Sacre, & McGourty[59] cite a number of successful or promising interventions, such as internships in foreign countries, international collaborations among academic institutions and NGOs to expose students to social problems, and stress on learning a second language, critical study of international development, regional focus, and humanities as a part of engineering coursework.

According to Klein,[60] engineers operating in the future will require interdisciplinary approaches to their work that are characteristic of complex problems that link science, technology, and social systems. Such capacity may be developed through apprenticeship or real-world experience.

Sam Pitroda,[61] Chairman, National Knowledge Commission (India), called attention to the fundamental issues raised in the NKC Working Group's report. Among other things, he called for pedagogical reforms, including "Industry participation to discuss real life case studies".

58 Feisel & Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," 2005.
59 Shuman et al., "The ABET 'Professional Skills' – Can They Be Taught? Can They Be Assessed?," 2005.
60 Klein, "Prospects of transdisciplinarity," 2004; Klein, "Crossing boundaries: knowledge, disciplinarities, and
interdisciplinarities," 1996.
61 Pitroda, "Letter to the Prime minister," 2008.

1.2.3 Limitations of the current reforms

Nevertheless, the broadening experiences, mostly coming from elective courses in Ethics, humanities and social sciences, remain peripheral in the current curricular structure.[62] There are issues of integrating the sustainability content and skills into the current curricular structures. Even where sustainability concepts and active-learning methods were integrated into the curricula, it was found that there are barriers hindering the re-orientation of engineering curricula toward “sustainable” engineering.[63] Pedagogically, the standard instructor-led learning model is not sufficient for developing students as sustainability engineering professionals, as indicated by many studies, including a study of practitioners' responses to a sustainable-design challenge.[64] The reforms are constrained by canonical models of technology and engineering, based on formal and commercial structures.

1.2.4 The redesign gap

While there is an effort to include sustainability content in the engineering curricula, the appropriate competencies required for sustainability engineering are still not well-understood within the community of engineering educators.[65] Moreover, the interventions are fragmented or segregated, and do not integrate knowledge, skills, and attitudes across disciplines. The reforms oriented towards addressing any one aspect of either knowledge, skills, or attitudes, neglect to take into account the impact of the reform on, or its interaction with, the other two aspects for the students. A focus on developing interventions that address all these in an integral manner are missing. This also leads to student identity

62 Downey, “PDS: Engineering as Problem Definition and Solution,” 2015.
63 Huntzinger et al., “Enabling sustainable thinking in undergraduate engineering education,” 2007.
64 Mann et al., “Using phenomenography to investigate different ways of experiencing sustainable design,” 2007.
65 Segalas et al., “What has to be learnt for sustainability? A comparison of bachelor engineering education competences at three European universities,” 2009.

formation that is merely techno-scientific, which is inadequate for handling complex sustainability problems. Overall, while the need for sustainability engineering is felt and accepted broadly, it is not very clear how traditional engineering education could be redesigned towards engineering for sustainability.

1.3 The research problem

This background indicates that a new approach to sustainability engineering (and its practice) needs to be developed, along with ways to build this approach into engineering education. The nature of limitations to engineering education reforms and the gaps in these redesign efforts suggest that integrated solutions are necessary in order to prepare engineering students for the upcoming challenges. Furthermore, there is a need to identify or develop ways in which, not only the real-world challenges of twenty-first century are brought into the engineering curricula, but also the real-world operational ways to address them sustainably are demonstrated and taught to the undergraduate students in an integrated manner.

The domain of engineering design particularly calls for such an integration of knowledge, skills, and values. Considered to be the core problem-solving process of technological development, 'design' is said to be “as fundamental to technology as inquiry is to science and reading is to language arts”.[66] While engineering design is not considered as central to engineering education as the engineering sciences, it has been argued that,

> *“... if accepted on equal footing with the use of models and science, design could serve to moderate the technocratic and instrumental focus that prevails in engineering education.”*[67]

66 International Technology Education Association. “Standards for technological literacy: Content for the study of technology”, 2000, p 90.
67 Jorgensen, U. “Constructions of the Core of Engineering: Technology and Design as Modes of Social Intervention,” 2015, p 303.

As such, engineering design would be an ideal space to look for and develop such alternate integrated reforms.

Donald Schon[68] pointed out that while engineering curricula teach the well-formed instrumental problems, it is the professional practice where 'uncertainty, uniqueness, and value conflict', which he identifies as the 'indeterminate zones of practice', are seen as central. Studies of practice can provide an opportunity to introduce students to such indeterminate zones of practice in engineering design.

A preliminary search of engineering design research and design research outlines design studies conducted with formally trained engineers and designers, both experts/practitioners and students. The studies have been primarily conducted in lab situations, but some are also studies of practice in the wild.[69] An understanding of design expertise could be gained from these studies, among other aspects of design.

However, the mainstream practice does not offer any novel and alternate models leading to sustainability. Also, this inward-looking approach captures the design process that is driven only by formal methods. As different perspectives rather than these formal methods may be necessary for new and radical designs for sustainability, the studies of formal mainstream practice cannot provide a skill and practice-level understanding of this type of perspective-driven design expertise. Also, as formal practice often 'designs to specifications', these studies cannot provide a good sense of how problems are identified and framed in the

68 Schon, *Educating the Reflective Practitioner*, 1987.

69 Hutchins, *Cognition in the Wild*, 1995a, p xii-xiv. The term ‘in the wild’ is borrowed from Edwin Hutchins, in the sense he uses it to distinguish between the lab and the real/everyday world. He explains it in the context of cognition as, “The phrase “cognition in the wild” refers to human cognition in its natural habitat - that is, to naturally occurring culturally constituted human activity. .. I have in mind the distinction between the laboratory, where cognition is studied in captivity, and the everyday world, where human cognition adapts to its natural surroundings.”

social context, or illuminate how design decisions are made, and what values and principles govern them, in the wild.

These limitations suggest that such a successful pedagogy for sustainability engineering cannot be built around the canonical models of EE. Nor can it be built around models offered by contemporary mainstream practice, which mostly do not incorporate sustainability. More promising may be the successful cases in the wild that demonstrate sustainability, as such cases could offer useful contrast cases, even possibly good role models, to develop a new pedagogy for sustainability engineering. Studies of such cases, however, are not available, and there is a need for research to understand their successful practice.

This leads to a scoping of the research problem of engineering education reform, which is to understand the following: What is that nature of the engineering design practice in the wild that is engaged in designing and innovating technology to address societal problems equitably and sustainably? Further, what ways can it suggest to train undergraduate engineering students for such a design practice?

1.4 Operationalization: Study of grassroots technology design

Donald Schon recommends,

> *".. we should not start by asking how to make better use of research-based knowledge but by asking what we can learn from a careful examination of artistry, that is, the competence by which practitioners actually handle indeterminate zones of practice."*[70]

The work of grassroots innovators provides one such opportunity to study successful cases in the wild, as cases from this work demonstrate sustainable technology design. This dissertation thus operationalizes the research study of sustainable technology

70 Schon, *Educating the Reflective Practitioner*, 1987, p 13.

design in the wild as a characterization of the practice of innovators designing technology at the grassroots. The objective is to understand and make explicit the problem-solving practices, knowledge, skills, and values involved in such design. Such explicit knowledge of grassroots design practice could contribute significantly towards developing a successful pedagogy for sustainability engineering.

In the following chapters, this thesis reports the data-driven study to explore and describe grassroots design practice, consisting of the following broad steps: understanding the practices in grassroots design, developing case studies, abstracting out design principles from the cases, and combining the cases and the design principles to suggest a possible redesign of the engineering curriculum and pedagogy.

Chapter 2: Review of Literature

Limitations of the canonical approach to sustainability engineering

“Sustainability requires more than putting a social science course into an engineering curriculum, as it also requires changes in existing engineering paradigms, a broadening of mental frameworks and changes in values and basic assumptions.”[71]

In this chapter

The engineering education research (EER) literature identifies some key challenges to training students for sustainability. On the one hand is the overall challenge of broadening the knowledge/skill-base, by fitting more (sustainability content) into an overcrowded curriculum, and integrating this with the core disciplinary knowledge. Furthermore, the multi-disciplinary knowledge needs to be integrated for sustainability, while ethics, humanities, and social sciences need to be more central to EE. On the other hand, the standard instructor-led learning model is pedagogically not sufficient for developing students as sustainability engineering professionals.

The broader literature (across engineering education, sociology, philosophy and politics of technology, as well as design studies) further points out that EE trains for textbook problems rather than real-world workplace problems, where the problem framing is limited to the techno-commercial, while largely excluding the socio-technical nature of the engineering practice. The contemporary EE is based on a canonical approach to technology and engineering, which considers engineering to be value-neutral and technology-driven, while implicitly prioritizing values of instrumentality and efficiency. Moreover, design is a situated activity rather than mere technical problem-solving. The emphasis in EE on engineering sciences and mathematics as core technological knowledge, and a purely techno-economic focus in the design process, perpetuates a societal disengagement among students, and students' engineering identities develop based on techno-scientific rationality/instrumental thinking alone.

EE reforms to address these issues are segmented and isolated at the level of both curricula and pedagogies, and thus cannot achieve success in integrally addressing the messy complexity of sustainability problems, where the competencies required are still unclear. The current EE approach is thus inadequate to develop an engineering for sustainability.

Introduction

Many curricular and pedagogical reforms have been suggested to orient engineering education towards sustainability. These reforms, though effective, have

71 Quist et al., “Backcasting for sustainability in engineering education: the case of Delft University of Technology,” 2006, p 869.

nevertheless met with limited success in transforming engineering education for sustainability. This is partly because broadening of the knowledge/skill-base for sustainability puts further burden on an already overcrowded curriculum. Students, and faculty, also lack the background to integrate such multi-disciplinary knowledge. Some suggested ways to overcome these issues include making the sustainability courses central to the curricula, or using an entirely problem/project-based pedagogy. However, these changes would not be sufficient in the face of the complexity of sustainability challenges. Two major reasons for this are below:

> *"Successful integration of sustainability principles and methods into engineering curricula requires a systemic change in our approach to education and societal values."*[72]

> *"However, there is often a preference in engineering education on incorporating environmental issues on the level of engineering tools and methods, while neglecting the holistic nature of sustainable development, its social component and the equity principle."*[73]

Overall, deeper foundational issues are involved when seeking to move EE towards sustainability, as identified in the wider literature. Particularly, notions of 'what is technology? and 'what is engineering?' need to be rethought in the context of sustainability. Some of these critiques are summarized below.

2.1 Critique from Engineering Education Research (EER)

Research in engineering education (EER) identifies two critically relevant issues:

1. students' inability to address real-world, messy problems, and
2. students' lack of engagement with societal and eco-social ethics and values.

72 Huntzinger et al., "Enabling sustainable thinking in undergraduate engineering education," 2007, p 219.
73 Quist et al., "Backcasting for sustainability in engineering education: the case of Delft University of Technology," 2006, p 869.

2.1.1 Students lack the ability to address real-world, messy engineering problems

A core component of EER focuses on the differences between classroom problems and workplace problems, and points to the need to prepare students for real-world problem-solving. Current engineering training, unfortunately, exposes students only to well-defined textbook problems, rather than complex engineering workplace problems, particularly sustainability problems, which are highly complex.

In critiquing this situation, David Jonassen[74] argues, “If students are to learn to think like engineers, they must be challenged to solve authentic, complex problems”. These problems are interdisciplinary, thus requiring the integration of several content domains, and are “... not constrained by the content domains being studied in classrooms”. The authentic engineering workplace problems are ill-structured, and unlike textbook problems, their solutions are not “predictable or convergent”.[75] In his work with Shin and McGee, Jonassen[76] found that solving ill-structured problems in an astronomy simulation called on different skills than well-structured problems, including meta-cognition and argumentation.

Clive Dym, a Gordon prize-winner for engineering design education, and many other scholars suggest the same.

> *“We need to spend more time thinking about how we define what the problem is, rather than just what the solution to the problem is. We need to teach students how to cope with complex systems; too often we revert to over-simplified versions.”*[77]

74 Jonassen, “Engineers as problem solvers,” 2014.
75 Jonassen, “Engineers as problem solvers,” 2014.
76 Shin et al., “Predictors of Well-Structured and Ill-Structured Problem Solving in an Astronomy Simulation,” 2003.
77 Dym et al., “Social Dimensions of Engineering Design: Observations from Mudd Design Workshop III,” 2003, p 4.

Scholars in EER identify various issues that need to be addressed in order to train their graduates to handle complex problems. Huntzinger, Hutchins, Gierke, and Sutherland comment that,

> *"Too often, engineering curricula place more emphasis on the memorization of facts and well-established procedures than on learning the skills necessary to deal with large, complex problems. As a result, current engineering graduates are entering the market place ill-equipped to deal with the problems society is sure to face."*[78]

David Goldberg[79] supports this view in observing that, "When design is finally taught, students are unable to solve other than rote problems...". Calling out for the current 'cold war engineering curriculum' to be 'buried', he points out that "... I am continually reminded, year after year, about the mismatch between the education a cold war curriculum provides and the demands of a real-world engineering problem".[80] Among explanations for engineering students' (seven) difficulties in designing for industry, he highlights: 1) engineering is mistaken for applied science/math and 2) engineering reasoning and epistemology are not articulated.

From an extensive study of engineering students' problem solving skills, as opposed to 'exercise-solving', Woods et al.[81] summarize the following points.

> *"1) there is an identified, subject-independent skill set called problem solving, and 2) that students do not develop the skill in a four-year program by having teachers display how they solve problems, by giving out sample solutions, by using open-ended problems or by having peers show their problem solving. Workshops to explicitly develop skill seemed to hold potential for improving students' problem solving skill and confidence."*

78 Huntzinger et al., "Enabling sustainable thinking in undergraduate engineering education," 2007, p 218.
79 Goldberg, "What Engineers Don't Learn and Why They Don't Learn It," 2008.
80 Goldberg, "What Engineers Don't Learn and Why They Don't Learn It," 2008.
81 Woods et al., "Developing Problem Solving Skills: The McMaster Problem Solving Program," 1997, p77.

Jonassen[82] recommended problem-based learning as the most suitable instructional methodology for design education, but also pointed out that course-level implementation of this approach poses challenges for both students and faculty.

Dym et al.[83] stress that projects and experiential learning are central to design education, and careful project selection is critical. Unfortunately, though projects are a part of most engineering curricula, and students are expected to gain experiential learning through these, careful project selection seems lacking. Millions of students mindlessly repeat the same projects year after year, while most real-world problems in their locality remain unaddressed.

There are a few efforts towards training undergraduate engineers for real-world problem-solving. These include the Senior Design in General Engineering program at University of Illinois, Urbana-Champaign (discussed by Goldberg[84]), McBride Honors,[85] and EPICS[86] programs at the Colorado School of Mines, which provide authentic engineering problems (AEPs) such as a heat transfer course (discussed by Kathleen Cook and others[87]).

2.1.2 Students lack engagement with societal and eco-social ethics and values

A few avenues now exist for engineering students to engage with socially relevant design practice through unorganized or organized volunteering activity. However, the cornerstone and capstone projects are mostly conducted with engineering industry. Engineers Without Borders, Engineers for a Sustainable World, and International Development Innovation Network (IDIN) are examples of organizations that offer students the

82 Jonassen, “Engineers as problem solvers,” 2014.
83 Dym et al., “Engineering design thinking, teaching, and learning,” 2005.
84 Goldberg, “What Engineers Don’t Learn and Why They Don't Learn It,” 2008.
85 Olds, “Engineers of the Future: The Colorado School of Mines' McBride Honors Program,” 1988.
86 Olds, “Integrated Engineering Education at the Colorado School of Mines,” nd.
87 Cook, “Effects of Integrating Authentic Engineering Problem Centered Learning on Student Problem Solving,” 2017.

opportunities to engage with, and design technology for, problems of the underserved in developing and developed societies. These organizations have an active presence in institutions of engineering education in the USA and many other countries.

In terms of curricular opportunities, social engagement is built into some courses in select universities. ‘Engineering Projects in Community Service program (EPICS)’[88] - the first program to teach ‘service-learning in engineering’ – was started at Purdue University in 1995. It has been adopted by other US universities, and has inspired similar programs in other countries. At Louisiana State University, Marybeth Lima[89] initiated and leads a service-learning program - the LSU Community Playground Project - to build playgrounds for public schools, through student design projects. Teachers, parents, volunteers, and communities participate and collaborate to fund as well as build the designs. UC Berkeley's ‘Engineering Scholars and Engaged Scholars’ course offers freshman and transfer students exposure to ‘engineering and innovation with a commitment to social justice and underserved communities’.

Such examples are few, and non-mainstream, and are mostly limited to being elective rather than core courses. In most engineering education programs, the social and environmental aspects remain externalized, while the technical aspects continue to be emphasized. A recent study of 103 top-ranked undergraduate engineering programs showed that in the coursework for engineering, “technical requirements ranged from 62% to 86% (median 75%) of total degree; non-technical requirements ranged from 12% to 35% (median 20%)”.[90]

88 EPICS: http://www.purdue.edu/catalogs/engineering/college/epics.html.
89 Lima, “Building playgrounds Engaging communities,” 2013.
90 Forbes et al., “Divergent Requirements for Technical and Non-Technical Coursework in Undergraduate Engineering Programs,” 2017.

Current engineering curricula and pedagogy implicitly encourages a dichotomy between the technical and social context, and a 'technical rationality'-based problem-solving image of engineering. Many scholars, including those in India, argue that this exclusive techno-scientific focus is detrimental.[91] Barbara Olds notes that,

> *"… the education of science and engineering students has for too long been merely "technical", often neglecting human complexity in order to achieve quantifiable correctness. Colleges and universities focus too narrowly on specialization, and produce graduates who are neither professional nor personal successes. More and more educators argue that science and technology students must be more liberally educated; recent reports on education are cases in point."*[92]

A representative undergraduate engineering curriculum of a Canadian university was examined by Vanderburg and Khan,[93] to understand the emphasis on the influence of technology on human life, society, and ecology. The objective was to see how these impacts fed back into engineering methods, and contributed to values that lead to a more context-compatible technology design. The study found that even in the senior years, such a value emphasis was lacking, and the context scores of the courses were not satisfactory.

A related issue is student identity. Engineering education is largely focused on the technical aspects, and a professional profile that is detached from society, unlike other socio-technical professions such as medicine, law, and management. This results in a student identity that is exclusively technical in its character. Felder and colleagues comment:

> *"The failure of the engineering curricula to address attitudes and values systematically has had unfortunate consequences. Engineers often make decisions without feeling a need to take into account any of the social, ethical, and moral consequences of those decisions, believing that those considerations are in someone else's purview."*[94]

91 Sohoni, "Engineering teaching and research in IITs and its impact on India," 2012.
92 Olds, "Engineers of the Future: The Colorado School of Mines' McBride Honors Program," 1988, p 16.
93 Vanderburg & Khan, "How well is engineering education incorporating societal issues?" 1994.
94 Felder et al., "The Future of Engineering Education: I A vision for a new century," 2000a, p 10.

Based on several studies to understand the relationship between engineering profession and social responsibility (as reported by students based on their educational experience), Canney, Bielefeldt and colleagues found that

> *"... the ways in which students talk about the interaction between engineering and society remained mostly at low level, bare minimum relationships of public safety and providing infrastructure. Few students talked about collaborative or co-creative relationships between engineering and society."*[95]

> *"In order to develop engineers with a broader understanding of the societal and cultural contexts in which they work, the students must first be guided to have broader views about how engineers and communities are to interact."*[96]

In another study to explore which courses, topics, and pedagogical methods engineering students found influential to their perspectives on social responsibility, they report that for 42% students, "none of their college courses had influenced their views".[97]

However, students seem to be positively influenced by discussions of ethics, as well as sustainability and environmental issues. They also seem responsive to project-based and service learning pedagogies as tools to help their social responsibility development.[98] Based on these studies, these scholars present a framework (PSRDM) to understand the development of social responsibility in engineers, rooted in the Ethic of Care.

Herkert and Viscomi[99] suggest that "... engineering departments need to design specific courses for engineering students rather than just including a few humanities courses in their curriculum". Many researchers across domains, including Dunfee and Robertson,[100]

95 Canney et al., "In their own words: Engineering students' views on the relationship between the engineering profession and society," 2013, p 8.
96 Canney et al., "In their own words: Engineering students' views on the relationship between the engineering profession and society," 2013, p 9.
97 Canney et al., "Which Courses Influence Engineering Students' Views of Social Responsibility?" 2015, p 12.
98 Canney et al., "Which Courses Influence Engineering Students' Views of Social Responsibility?" 2015, p 13.
99 Herkert & Viscomi, "Introducing professionalism and ethics in engineering curriculum," 1991.
100 Dunfee & Robertson, "Integrating ethics into the business school curriculum," 1988.

suggest that ideally ethics must be integrated throughout the curriculum into as many courses as possible. Caroline Bailie, Donna Riley, Juan Lucena, George Catalano, and other scholars in the area of engineering education and social justice extend the argument for ethics education to the consideration of social justice questions, through critical pedagogy.[101] Towards this, Colorado School of Mines' course on Engineering for Social Justice made an effort to guide students' capstone design projects using 'Engineering for Social Justice' checklists. The effort led Jered Dean[102] to suggest that engineering educators need “to think about other lenses that might get students to think about ethics as *part* of the work of engineering, rather than a separate concept”.

Erin Cech[103] reports that “... engagement with public welfare concerns is not highly valued in students’ professional identities as engineers and this engagement declines over the course of their engineering education”. She attributes this to an engineering ‘culture of disengagement’, “a constellation of beliefs, meanings, and practices that frame the way profession members conceptualize their professional responsibility to the public”. She argues that,

> *“Disengagement entails bracketing a variety of concerns not considered directly “relevant” to the design or implementation of technological objects and systems, such as socioeconomic inequality, history, and global politics.”*[104]

She points out that the institutional culture of depolitization actively leads to a disengagement of students from the non-technical aspects of engineering.[105] To counter this,

101 Catalano & Baillie, “Engineering, Social Justice And Peace: A Revolution Of The Heart,” 2006; Lucena, “The Road Ahead: Questions and Pathways for Future Teaching and Research in ESJ,” 2013; Riley, “Engineering and Social Justice,” 2008.
102 National Academy of Engineering, “Overcoming Challenges to Infusing Ethics into the Development of Engineers: Proceedings of a Workshop,” 2017, p 10, italics original.
103 Cech, “Culture of disengagement in engineering education?” 2013.
104 Cech, “Culture of disengagement in engineering education?” 2013, p 48.
105 Cech & Sherick, “Depoliticization and the Structure of Engineering Education,” 2015.

she suggests that "... if engineering programs can dismantle the ideological pillars of disengagement in their local climates, they may foster more engaged engineers".[106]

Louis Bucciarelli strongly recommends that engineering educators take into account these issues.

> *"… if we, as engineering faculty, still claim that it is our job and responsibility to teach 'the fundamentals', it's time to explicitly recognize that what is fundamental to engineering practice goes beyond the scientific, instrumental rationality; to fail to acknowledge this is "just about unethical."*[107]

2.2 Critique from Engineering Studies and STS

Critical studies of the practice of engineering, from the research domains of Engineering Studies and Science and Technology Studies (STS), document that engineering is not merely, or mainly, a technical or techno-scientific activity. It is rather a socio-technical enterprise. Such studies indicate that educational reforms are necessary not only for learning engineering knowledge and skills, but also to develop socially engaged attitudes and values. This section reviews these studies, and highlight key social aspects of engineering practice:

1. engineering (problems and) products are socially constructed,
2. engineering process is socially distributed and culturally situated, and
3. engineering activity (and output) has social responsibility.

The following sections elaborate these points.

2.2.1 Engineering products are socially constructed

Science and Technology Studies (STS) of professional engineering work suggest that "Technological systems contain messy, complex, problem-solving components. They are

106 Cech, "Culture of disengagement in engineering education?" 2013, p 43.
107 Bucciarelli, "Ethics and engineering education," 2008, p 147.

both socially constructed and society shaping".[108] Analyzing the case of the introduction of an electric car (VEL) in France, Michel Callon points out that,

> *"... it is often believed that at the beginning of the process of innovation the problems to be solved are basically technical and that economic, social, political, or indeed cultural considerations come into play only at a later stage. However, more and more studies are showing that this distinction is never as clear-cut."*[109]

Stevens, Johri, and O'Connor[110] also emphasize that the social and the technical are almost inextricably tied up together in any engineering project. Engineers are system builders, and technological problem-solving involves integrating heterogeneous elements such as humans, the environment, and technology – a practice termed by John Law[111] as 'heterogeneous engineering'. Lucy Suchman,[112] through the analysis of a bridge building project, demonstrates that apart from the design and technical work, the organizational activities of sense-making, persuasion and accountability, considered by engineers to be somewhat peripheral, are essential, to the 'real' work of design. Vermaas, Kroes, van de Poel, Franssen, and Houkes argue that engineering is -

> *"… the result of social negotiation processes in which the various groups involved, including customers but also producers, articulate their wishes and needs. The function of the product that is to be developed is thus a social construction that is based upon what divergent groups consider to be 'desirable'."*[113]

2.2.2 Engineering process is socially distributed and culturally situated

Engineering involves teamwork and communication with other engineers as well as non-engineer stakeholders.[114] James Trevelyan argues that,

108 Hughes, "The evolution of large technological systems," 1987.
109 Callon, "Society in the making: The study of technology as a tool for sociological analysis," 1987, p. 84.
110 Stevens et al., "Professional engineering work," 2014.
111 Law, "Technology and heterogeneous engineering," 1987.
112 Suchman, "Organizing alignment: A case of bridge-building," 2000.
113 Vermaas et al., "The role of social factors in technological development," 2011, p. 95.
114 Bucciarelli, *Designing engineers*, 1994; Trevelyan, "Engineering education requires a better model of engineering practice," 2009; Vinck, *Everyday engineering*, 2003.

> *"The foundation of engineering practice is distributed expertise, enacted through social interactions between people: engineering relies on harnessing the knowledge, expertise and skills carried by many people, much of it implicit and unwritten knowledge. Therefore social interactions lie at the core of engineering practice."*[115]

This point is well illustrated by Matthias Heymann,[116] using an analysis of the development of Danish wind technology. The Danish wind turbine designs turned out superior to the US and German ones, which focused exclusively on technical specifications and big scales, leading to operational failures. Heymann argues that the superiority of the Danish design emerged not only because of differences in knowledge bases and engineering mindsets, but also because of social interaction of different groups (particularly engineers and windmill artisans), facilitated through journals, social forums, advocacy, and test stations, as well as the role played by the techno-political settings. Heymann points out that culture and context act not as external constraints, but they are a critical part of the design process, towards which engineers cannot afford to be reductionist, ignorant, or insensitive.

> *"Engineering curricula with a strong focus on science and technology rather conceal these economic, political and cultural settings, of which engineers are an influential part. If students learn to develop awareness for this condition, if they learn to perceive themselves as a part of a larger culture with influential and conflicting values and goals, then they may more easily develop the political and cultural sensitivity required in technological development and innovation."*[117]

115 Trevelyan, "Reconstructing engineering from practice," 2010, p. 175.
116 Heymann, "Engineering as a socio-technical Process: Case-based learning from the example of wind technology development," 2015.
117 Heymann, "Engineering as a socio-technical Process: Case-based learning from the example of wind technology development," 2015, p. 487.

2.2.3 Engineering activity (and output) has social responsibility

In discussing the social role and responsibility of engineering, George Bugliarello[118] comments that "engineering has performed extraordinarily well in responding to technical challenges, but has shied away from the vigorous pursuit of complex sociotechnological issues." He adds:

> *"Any attempt to rate the current performance of engineering in the satisfaction of social needs must take into account at least three factors: (1) the fundamental difficulty that engineers encounter in addressing major social problems given a lack of an adequate sociotechnological preparation, (2) the propensity of engineers to find technological fixes for existing social systems rather than to develop and use technological innovations to accomplish needed social change, and (3) the ensuing limited or simplistic views of the social role of engineering."*[119]

As a result, engineers follow the techno-commercial framing of problems. A more radical view argues that engineers is a 'domesticated breed' that "in reality served only the dominant class in society," and "Engineering education is a major channel to corporate power."[120]

2.3 Critique from Philosophy and Politics of technology

2.3.1 Engineering artifacts embody the values of the makers

Matthias Heymann[121] points out that, "Technology development takes place in and makes part of a larger context of power relations, market structures and policies as well as

118 Bugliarello, "The social function of engineering: A current assessment," 1991.
119 Bugliarello, "The social function of engineering: A current assessment," 1991, p. 80.
120 Noble, "America by Design: Science. Technology, and the Rise of Corporate Capitalism," 1977, p 322-4.
121 Heymann, "Engineering as a socio-technical Process: Case-based learning from the example of wind technology development," 2015, p. 487.

beliefs, values and ideologies". In the analysis of Danish wind technology development, he emphasizes that

> *"... engineers are not acting free of political and social values, but are part of social groups and carriers of convictions and ideologies. Second, technologies carry non-technical values, commitments and goals (which may be perceived differently by different actors and social groups)."*[122]

According to Bucciarelli,

> *"The way we structure our curriculum and teach our subjects all conspire to instill in the student the idea that engineering work is value-free. Object-world work may be, but that is but one part of engineering competence. While teaching the "fundamentals" of science and mathematics, and the engineering sciences, remains necessary, we must do so in more authentic contexts, showing the uncertainty and ambiguity inherent in problem setting as well as solution, and how social and political interests contribute in important ways to the forms of technologies we produce. We ought not as faculty claim, or imply, that solving single answer problems or finding optimum designs, alone, uncontaminated by the legitimate interests of others is what engineers do all of the time. This is irresponsible."*[123]

Langdon Winner argues at length that technology is not value-neutral, and engineered "artifacts have politics".[124]

2.3.2 Technological knowledge is more than science and mathematics

David Goldberg[125] observes that in the present 'cold war curriculum', engineering is mistaken for applied science and maths, and engineering reasoning and epistemology are not articulated.

As Ropohl argues, 'technics' i.e. 'technical knowledge' is more than just engineering sciences. Furthermore, its objective is not the optimization of the function or performance of the technological artifact/system, but rather the satisfaction of actual needs or

122 Heymann, "Engineering as a socio-technical Process: Case-based learning from the example of wind technology development," 2015, p. 487.
123 Bucciarelli, "Ethics and engineering education," 2008, p 148.
124 Winner, *The Whale and the Reactor*, 2010.
125 Goldberg, "What Engineers Don't Learn and Why They Don't Learn It," 2008.

solutions for problems. According to him, one component of technics is ‘technology’, meaning ‘technological knowledge’ i.e. engineering sciences, where “Technology is not interested in scientific truth, but in practical success”.[126] Thus,

> *“The objective of natural science is theoretical cognition for its own sake. Technology, on the other hand, is interested in cognition just as far as it is useful to optimize the function and the structure of technical systems.”*[127]

Moreover, Ropohl argues for ‘socio-technical understanding’[128] as a component of technical knowledge.

> *“Socio-technological understanding is a systemic knowledge about the interrelationship between technical objects, the natural environment, and social practice. This understanding will acknowledge that not only the single technical object has to be optimized, but also the ecological and the psycho-social context within which the artifact is located.”*[129]

The other components of technical knowledge Ropohl discusses are 1) technological laws, 2) functional rules, 3) structural rules, and 4) technical know-how.

As Donald Schon observes,

> *“In the terrain of professional practice, applied science and research-based technique occupy a critically important though limited territory, bounded on several sides by artistry. There are an art of problem framing, an art of implementation, and an art of improvisation – all necessary to mediate the use in practice of applied science and technique.”*[130]

126 Ropohl, “Knowledge Types in Technology,” 1997, p 68.
127 Ropohl, “Knowledge Types in Technology,” 1997, p 66.
128 Houkes, “The Nature of Technological Knowledge,” 2009, p 326. Houkes points out that this category is either entirely missing or very covertly included in other taxonomies by Vincenti (1990), Falkner (1994), and de Vries (2003).
129 Ropohl, “Knowledge Types in Technology,” 1997, p 70.
130 Schon, *Educating the Reflective Practitioner*, 1987, p 13.

2.3.3 Technical efficiency is the central value; technology development is 'technology-driven'

'Usefulness' is recognized to be the primary value for technology. However efficiency now appears to have become wider, to become a central value. David Channell,[131] in tracing the historical emergence of engineering sciences, identifies Galileo's geometric approach at the root of the idea of efficiency in comparing an actual machine with an ideal one. Channell further reports that in early 19th century, G.G. Coriolis in France and William Whewell and Henry Moseley in Britain brought in the idea of 'work'.

> *"By comparing the transmitted work to the wasted work, they analyzed machines in terms of efficiency which would become another fundamental concept of the engineering sciences."*[132]

Efficiency offers a measurable goal of the 'perfect correspondence between output and input'[133] and being a 'ratio' of outputs to inputs, allows for comparisons between machines or systems of widely different design and function. Efficiency is widely recognized as the core design principle driving both technological innovations as well as minor product differentiations. As Carl Mitcham[134] points out, "Engineering design is a systematic effort to save effort." and that "As a guiding principle of engineering design, engineers themselves repeatedly refer to the ideal of efficiency".

Andrew Feenberg[135] argues that technical disciplines are fundamentally oriented towards creating efficient functional devices, and this process leads to systematically

131 Channell, "The Emergence of the Engineering Sciences: An Historical Analysis," 2009, p 125. "Using Archimedes' principle of the lever, Galileo showed that in a perfect, frictionless machine, the forces that set the machine in motion were the same as the forces required to keep it in a state of equilibrium. This geometric approach allowed Galileo to calculate how an ideal machine transformed the forces and motions applied to it, and by comparing an actual machine with this ideal machine, he was able to quantitatively evaluate that actual machine in terms of something that would later be called efficiency."

132 Channell, "The Emergence of the Engineering Sciences: An Historical Analysis," 2009, p 131.

133 Cardwell (1994: 85, 88-89) cf Alexander, "Efficiencies of Balance: Technical Efficiency, Popular Efficiency, and Arbitrary Standards in the Late Progressive Era USA," 2008, p 328.

134 Mitcham, *Thinking through technology*, 1994.

135 Feenberg, *Transforming technology*, 2002.

abstracting away social dimensions of the activities, which are then considered to be addressed by the humanistic disciplines.

The primacy of functional and technical efficiency gets augmented by the notion of economic efficiency, and the focus on techno-economic efficiency has become the default engineering perspective of modern mainstream industry. While technology is as old as human race itself, one of the main differentiators of traditional and modern technology, contends Ralph J. Smith,[136] is efficiency. He argues that the desire for efficiency and economic gain brings crucial differences between activities like textile or ceramic engineering, as compared to weaving or pottery. In the process of achieving techno-economic efficiency, the abstracted socio-ecological components are neglected or sacrificed. Engineering education has followed and institutionalized this dichotomy between the social and the technical, prioritizing techno-economic efficiency in design, and neglecting the social and ecological. This raises the challenge of integrating these left out components with the technical core of engineering. This is a central requirement to address sustainability problems, which span the technical, social and ecological domains in complex and messy ways.

Vanderburg observes that,

> *"Technological development is primarily guided by values and measures such as efficiency, productivity, cost-effectiveness and profitability. These measure how much output can be derived from certain inputs, but they tell us nothing about how any technological development will fit into and be compatible with human life, society and nature."*[137]

This especially become a problem when this is an industry-wide practice, as the impacts are wide and global. Vandana Shiva argues,

136 Smith, *Engineering as a Career,* 1969.

137 Vanderburg, "Political imagination in a technical age," 1988 cf Vanderburg & Khan, "How well is engineering education incorporating societal issues?" 1994, p. 5.

"...every firm and sector measures its efficiency by the extent to which it maximizes its gains, regardless of the fact that in the process it also maximizes the social and ecological costs of the production process. The logic of this internal efficiency is provided by reductionism: only those properties of a resource system are taken into account which generate profits through exploitation and extraction; properties which stabilize ecological processes but are commercially non-exploitative are ignored and eventually destroyed."[138]

Helen Nissenbaum observes that,

"… the ideal result is a world of artifacts that embody not only such instrumental values as effectiveness, efficiency, safety, reliability, and ease of use, but promote (or at least do not undermine) substantive values to which the surrounding societies or cultures subscribe."[139]

She adds though, that,

"Even the designers who support the principle of integrating values into systems are likely to have trouble applying standard design methodologies, honed for the purpose of meeting functional requirements, to the unfamiliar turf of values."[140]

The intermediate, of 'Appropriate' Technology movement of the 1960s, was an attempt to get beyond the 'techno-economic' efficiency focus of engineering and technology. In 1965, economist E. F. Schumacher[141] critiqued the large-scale technology being pushed as aid to the developing countries, post World War II. He pointed out that the large-scale capital-rich technology failed to fit the capital-poor and labor-abundant conditions in the developing countries. As Lawrence White observes,

"The failure of industrial sector jobs in LDC's ('less developed countries') to grow as fast as the demand for them has generated high and rising apparent levels of unemployment. Policy makers and researchers have become interested in finding ways of encouraging more labor-intensive technologies. These are valued, not only for the employment that they will encourage, but also for the more favorable income distribution that is likely to result."[142]

138 Shiva, "Reductionist science as epistemological violence," 1988.
139 Nissenbaum, "Values in technical design," 2005, p lxvi.
140 Nissenbaum, "Values in technical design," 2005, p lxvi.
141 Schumacher, "Small is beautiful: Economics as if people mattered," 1973.
142 White, "Appropriate technology, X-inefficiency, and a competitive environment: Some evidence from Pakistan," 1976, p 575.

While Schumacher used the term ‘intermediate technology’, many other terms, such as ‘blended technology’, ‘alternative technology’, and ‘soft technology’ by Amory Lovins (1977), were also used to discuss similar ideas.[143]

In the 1970s, the US government supported organizations such as National Center for Appropriate Technology, when non-sustainability of the large-scale technology was experienced in developed countries as well. As reported by Peterson,

> *“The bases of critique applied to industrial countries were that large-scale technologies promoted over-exploitation of natural resources, over-centralization, concentration of political and economic power, less employment because high technology substitute machines for workers, and deskilling of workers because more of the work process is embodied in the movements of the machine rather than in the actions of the operator.”*[144]

This gave rise to an appropriate technology movement in engineering. But “In attempting to redefine technology, advocates of Appropriate Technology were directly challenging the power of those who shaped the hegemonic notion of that subject”.[145] Appropriate Technology was critiqued as being non-technology by engineers.[146] In 1980s, as cultural perceptions changed post the Vietnam defeat of America, political support was withdrawn, and the Appropriate Technology movement fell back, at least in the USA. Nevertheless, several appropriate technologies continue to be developed, and diffused across the world, supported by non-governmental and inter-governmental development organizations, one of them being ‘Practical Action’, the organization founded by Schumacher in 1966 under the name ‘Intermediate Technology Development Group’.

143 Peterson, “Appropriate technology,” 2008.
144 Peterson, “Appropriate technology,” 2008, p. 1.
145 Pursell, “The rise and fall of the appropriate technology movement in the United States, 1965-1985,” 1993.
146 Florman, 1981 cf Pursell, “The rise and fall of the appropriate technology movement in the United States, 1965-1985,” 1993.

2.4 Critique from Design Studies

Over the last twenty years, research interest has shifted to studying designers in their natural settings, to understand the social processes involved in design practice, such as team interaction, communication through objects, gestures, and the role of representations.[147] These studies reveal the reality of engineering design practice, as a situated, social process.[148] Based on such studies of design practitioners, Donald Schon[149] observes that real world design problems, though messy or unclear, are the ones whose solutions are really needed by society.

> *"In the varied topography of professional practice, there is a high, hard ground overlooking a swamp. On the high ground, manageable problems lend themselves to solution through the application of research-based theory and technique. In the swampy lowland, messy, confusing problems defy technical solution. The irony of the situation is that the problems of the high ground tend to be relatively unimportant to individuals or society at large, however great their technical interest may be, while in the swamp lie the problems of greatest human concern".*[150]

Real world or workplace engineering design is now begun to be understood as a social, complex, ill-structured problem solving process. In contrast, most design studies have been conducted with formally-trained designing practitioners and students, solving standard problems, in lab conditions. As formal practice often 'designs to specifications', these studies do not provide a good sense of socially-engaged and sustainable engineering, particularly how problems/requirements are identified and framed in the eco-social context, or illuminate how design decisions are made, and what values and principles govern them 'in the wild'.

Critiquing the dominant idea of engineering design as merely techno-scientific problem-solving, design scholars warn that such a narrow conception will lead to engineering

147 Bucciarelli, *Designing Engineers*, 1994; Minneman, "The social construction of a technical reality: empirical studies of group engineering design practice," 1991.
148 Atman et al., "Engineering Design Education: Research, Practice, and Examples that link the Two," 2014.
149 Schon, *Educating the Reflective Practitioner*, 1987.
150 Schon, *Educating the Reflective Practitioner*, 1987, p 1.

losing its jurisdiction over technology design and development, and engineers' role will be limited to that of mere technical consultants, who only support – instead of lead – the design of technology. Gary Downey warns:

> *"... continuing to place primary emphasis on solving technical problems amounts to accepting a significant reduction in the status and value of engineering work."*[151]

Particularly given the potential of new engineering design practices that allow an engineer a more autonomous role, Pieter Vermaas points out that:

> *"... if engineering continues to be seen as the discipline that provides technology, design becomes a discipline different to engineering, and engineers will again be forced back into their assistant role by becoming suppliers of technical solutions to other designers."*[152]

This issue is also related the question of engineering identity discussed below and also in section 2.1.2.

2.5 Critique of engineering identity formation from professional education studies

A US Academic Pathways Study[153] found that, students remain uncertain about what it means to be an engineer, and struggle with the shift from book problems to open-ended problems. Many newly hired engineers do not anticipate the high level of social and organizational influence on their work. Further, from an analysis of engineers across six firms, Anderson, Courter, McGlamery, Nathans-Kelly, and Nicometo[154] points out that "engineers are seen to be frustrated by non-engineering work". Wendy Faulkner observes that,

151 Downey, "PDS: Engineering as Problem Definition and Solution," 2015, p 437.
152 Vermaas, "Design Methodology and Engineering Design," 2015, p 147.
153 Atman et al., "Enabling Engineering Student Success," 2010.
154 Anderson et al., "Understanding engineering work and identity: a cross-case analysis of engineers within six firms," 2010.

> *“Their educational grounding in mathematics and science allows engineers to claim an identity in the material and (mostly) predictable phenomena governed by the ‘laws of nature’, backed up by a faith in cause-and-effect reasoning. And this same materiality and scientificity enables them to claim, as the central contribution of engineering design, that it creates technologies that ‘do the job’. This is a very empowering identity.”*[155]

Using the example of one of the engineers she shadowed in her study, Faulkner explains that,

> *“Karen juxtaposes the 'upfront' roles with the more ‘backroom’ job of detailed design, in a way that echoes the technical/social dualism. She has a sense that the upfront roles are less ‘real’ engineering, perhaps because they are further away from the materiality of ‘producing’ things.”*[156]

Quoting another engineer who says, “The world would be great if it weren’t for people!”, Faulkner contends that,

> *“I read this comment as an ironic dig at the technicist version of engineering, and a recognition that the ‘people aspects’ of engineering are far more challenging and difficult to resolve than the ‘nuts and bolts’.”*[157]

This discussion of the nature of values, and the formation of professional identity, provide insights into the way social and sustainability values could be incorporated into engineering education, and thus help refocus the current professional identity of engineers towards sustainability.

2.6 The research gap

In summary, this review of the broader scholarly literature (across Philosophy and politics of technology, Engineering studies, Science, technology, and society studies, and Design studies) indicates that contemporary EE is based on a canonical approach to technology and engineering, which purports to be value-neutral, and remains limited to ‘safety’ ethics. The sought broadening of EE, through the inclusion of courses in social

155 Faulkner, “Nuts and bolts and people,” 2008, p 337-8.
156 Faulkner, “Nuts and bolts and people,” 2008, p 342.
157 Faulkner, “Nuts and bolts and people,” 2008, p 339-40.

sciences and humanities, remain peripheral. Current EE structure thus perpetuates societal disengagement, as well as a design process focused on techno-economic factors, which leads to the formation of an exclusively techno-scientific identity and thinking among students. This leads to the competencies required for sustainability engineering still remaining unclear. EE reforms to address these issues are segmented and isolated, and thus cannot achieve success in addressing the messy complexity of sustainability problems. Current EE practice is thus inadequate to develop an engineering for sustainability.

The issues identified by EER are significant and relevant, because messy and eco-social aspects are very central to all sustainability problems. On the other hand, as seen from the multi-faceted critiques offered by studies in wider disciplines beyond EER, these issues also foreground larger questions about the broader notion of engineering practice and identity itself, in the context of the current and future sustainability.

These critiques of EE and engineering practice are insightful, but they do not provide any systematic ways or operational means to develop a different kind of EE that is oriented towards sustainability engineering. Mainstream practice, which both derives from EE and reinforces it, cannot offer any alternate models. An operational-level way to redesign EE and engineering pedagogy, to support sustainability engineering, can thus only be evolved through the study of successful cases of sustainability engineering ‘in the wild’. Since such cases are hitherto unexplored, detailed research studies, and novel research methods, are required. I discuss these issues next.

Chapter 3: Research Approach

Studying practice ‘in the wild’ - an approach to redesigning EE pedagogy for sustainability engineering

> *“The historian’s approach is fundamentally inductive rather than deductive; it begins with microscopic research done in depth and detail on the level of individual episodes, in hopes that the empirical data thus gathered will lead to generalizations on some higher level.”*[158]

In this chapter
In the Indian context, grassroots innovation is a practice that demonstrates successful cases of sustainable technology design in the wild. My proposed research approach is 1) to characterize such grassroots technology design cases, 2) extract their underlying design principles and cognitive processes, both non-formal and formal, and 3) then use these to develop a new pedagogic approach to support engineering for sustainability. In other domains, studies of practice, both traditional (medicine, agriculture) and modern (bio-medical engineering), have provided evidence-based ways to design education systems. Following these approaches, a new engineering pedagogy for sustainability could be developed based on studies of sustainable grassroots technology designs, which have not been explored from this perspective.

3.1 Grassroots Innovation

Designing technology to solve grassroots problems is a non-formal practice, seen historically in the work of traditional artisan and craftspeople. Such practice still continues to support traditional communities across the world. From the perspective of formal technology and the modern world, non-formal design is recognized as ‘bricolage’ or tinkering, and is now familiar/popular in Indian parlance as ‘*Jugaad*’. Businesses and academicians have developed an interest in these practices, for reasons such as frugality or cost-saving, leading to improved affordability of technological solutions.[159]

158 Otto Mayr, 1976. cf Vincenti, *What engineers know and how they know it*, 1990, p 10.
159 Campbell, “Lay Designers: Grassroots Innovation for Appropriate Change,” 2017; Hossain et al, “Can frugal go global? Diffusion patterns of frugal innovations,” 2016; Radjou, Prabhu, & Ahuja, *Jugaad innovation: Think frugal, be flexible, generate breakthrough growth*, 2012.

However, in India, the term 'Grassroots innovation' has been specifically used by Anil K. Gupta,[160] in his effort to recognize non-formal innovation by untrained people in the unorganized sector, not just in technology, but also in the domains of agriculture and health. It is crucial to note here that the term 'Grassroots innovation' distinguishes these innovations from those identified as 'bricolage', 'jugaad', tinkering, do-it-yourself, or hack, i.e. an innovative fix or a simple work-around. The innovations recognized as 'Grassroots innovations' are not a one-time haphazard effort to design a quick solution, nor developed just by using what is on hand at the moment. It is not regardless of appropriate safety, cost, or performance considerations. Instead, as multiple case stories[161] of grassroots innovators demonstrate, 'Grassroots innovations' are serious endeavors to arrive at stable and sustained solutions, through investment of effort, experimentation, money, as well as imagination, perseverance, and patience, over long periods of time.

Since 1998, Honey Bee Network, an NGO founded by Gupta, has organized exploratory walks in interior rural areas twice a year, to identify innovators at the grassroots who have struggled and succeeded in solving their own and others' problems. The innovations are recognized at the national level, only after a systematic scrutiny of the effort and the originality of the solution, by a team of experts from renowned R&D establishments in the specific domains, as well as previously recognized grassroots innovators. An ecosystem of NGOs and governmental organizations has now emerged around this initiative, including the National Innovation Foundation, an autonomous body supported by the Department of Science and Technology. These organizations reward and further support the grassroots

160 Gupta, *Grassroots innovation: Minds on the margin are not marginal minds*, 2016.
161 For details, see http://nif.org.in/technology-catalogue/38

innovators in their efforts. This exceptional model is also being replicated in other countries such as China, and in Africa.

Grassroots innovation has been studied from the perspective of Economics, Business and Development, Innovation, and these studies have contributed to discussions of innovation policy.[162] Smith et al.[163] describe “innovation processes that are socially inclusive towards local communities in terms of the knowledge, processes and outcomes involved” as Grassroots Innovation Movements (GIM). According Smith and colleagues,

> *“Examples historically include, the appropriate technology movement in the 1970s, the People’s Science Movement in India in the 1980s; and today include, the Honey Bee Network in India, and the technologies for social inclusion movement in Latin America.”*[164]

Based on their analysis of the challenges to GIMs, Smith and colleagues propose that GIMs can constitute sustainability ‘innovation spaces’.

> *“.. for bottom-up forms of socially just and environmentally sustainable technological futures. Within these spaces, ethnographic knowledge is being created about the diversity of development situations and grassroots ingenuity, instrumental knowledge about potentially workable solutions that can diffuse and transform contexts, and, finally, critical knowledge about limitations of grassroots innovation movements in isolation.”*[165]

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162 Abrol, “Pro-poor Innovation Making, Knowledge Production, and Technology Implementation for Rural Areas,” 2014; Ahmad, “Policy making for innovations in the informal economy: Insights from National Innovation Foundation and Barefoot College in India,” 2015; Bhaduri & Kumar, “Extrinsic and intrinsic motivations to innovate: tracing the motivation of ‘grassroot’ innovators in India,” 2010; Bhaduri & Kumar, “Tracing the motivation to innovate: A study of grassroot innovators in India,” 2009; Cozzens & Sutz, “Innovation in informal settings: Reflections and proposals for a research agenda,” 2014; Dutfield, “Promoting local innovation as a development strategy: Innovations case discussion: The honey bee network,” 2006; Links et al., “The dynamics of local innovations among formal and informal enterprises: Stories from rural South Africa,” 2014; Smith & Stirling, “Innovation, Sustainability and Democracy: An Analysis of Grassroots Contributions,” 2018; Smith et al., “Grassroots innovation movements: challenges and contributions,” 2014; Srinivas & Sutz, “Developing countries and innovation: Searching for a new analytical approach,” 2008.

163 Smith et al., *Grassroots innovation movements*, 2016; Smith et al., “Grassroots innovation movements: challenges and contributions,” 2014.

164 Smith et al., “Grassroots innovation movements: challenges and contributions,” 2014, p 114.

165 Smith et al., “Grassroots innovation movements: challenges and contributions,” 2014, p 122.

Many scholars have discussed the diverse aspects of the demonstrated, as well as potential, contributions of grassroots innovations in the context of sustainability.[166]

3.1.1 Grassroots innovation as an unexplored technology design practice

Despite this high level of interest, grassroots technologies have been largely unexplored from a process perspective, particularly to understand their design approach, procedures, and thinking.[167] The insights from such an approach may better enable engineers and designers to take on the challenges of providing sustainable, appropriate solutions, breaking out of the current conventional and commercial rut. A practice-driven study of the design thinking of grassroots innovators could offer very novel, even revolutionary ideas, for rethinking formal engineering design education. Such practice-driven studies have contributed to novel pedagogical models in other domains.

3.2 Practice case-based learning as a successful pedagogy for professional education

3.2.1 Curriculum based on practice

A good recent example of an approach to designing curricula based on studying practitioners 'in the wild', is from the new discipline of bio-medical engineering. Experts from multiple formal disciplines, such as medicine, biology and engineering, join hands to

166 Abrol & Gupta, "Understanding the diffusion modes of grassroots innovations in India: A study of Honey Bee Network supported innovators," 2014; Seyfang & Haxeltine, "Growing grassroots innovations: exploring the role of community-based initiatives in governing sustainable energy transitions," 2012; Hossain, "Grassroots innovation: A systematic review of two decades of research," 2016; Pattnaik & Dhal, "Mobilizing from appropriate technologies to sustainable technologies based on grassroots innovations," 2015; Monaghan, "Conceptual niche management of grassroots innovation for sustainability: The case of body disposal practices in the UK," 2009; Smith & Stirling, "Innovation, Sustainability and Democracy: An Analysis of Grassroots Contributions," 2018; Smith et al., *Grassroots innovation movements,* 2016.

167 Campbell, "Lay Designers: Grassroots Innovation for Appropriate Change," 2017. Here Campbell discusses some product design aspects of African grassroots innovations, though not engineering or technological design aspects.

address interdisciplinary research questions in bio-medical engineering. To recruit future researchers into this interdisciplinary domain, universities have initiated undergraduate courses, for which new curricula need to be designed. However, it is not clear what should be in this curricula. To solve this problem, Georgia Institute of Technology, USA, carried out ethnographic studies of practicing bio-medical engineers, in order to identify the necessary skills, and the processes and practices followed in this new discipline.

> *"In our translational approach, we investigate, through immersive engagement with real sites of work and learning (in vivo sites), the situated, socio-cognitive practices that engineers use to reason and problem-solve day-to-day. We then translate our findings into design principles (Brown, 1992; Brown & Campione, 1994) for classrooms (in vitro)."*[168]

In this project, a problem-driven curriculum was developed, which sought to help undergraduate students gain the skills that were identified and abstracted from the ethnographic studies.

Non-formal practices have also inspired curricular changes, for example as advocated in mathematics learning. Jean Lave, and others, have brought to the fore the non-formal learning of mathematics in communities of practice.[169] 'Out of school' or street mathematics, the mathematics learned by children while doing errands or jobs as a part of a community of practice, is thought to support learning school mathematics. Bose and Subramaniam[170] characterized the knowledge of 'everyday' mathematics of middle school children from a Mumbai slum, particularly the nature, extent, and use of non-formal techniques of solving daily-life problems by children.

168 Aurigemma et al., "Turning experiments into objects: The cognitive processes involved in the design of a lab-on-a-chip device," 2013, p 2.
169 Lave, Wenger, & Wenger, *Situated learning: Legitimate peripheral participation*, 1991.
170 Bose & Subramaniam, "Exploring school children's out of school mathematics," 2011.

The engineering design curricula may be enriched similarly by a characterization of the problem-solving and knowledge-making practices of non-formal practitioners. Engineering curricula may be augmented or redesigned based on insights from grassroots design practice. Such a practice-driven approach to curricular design has been employed while forming the initial curricula of agricultural sciences, medicine, and crafts, based on the studies of practice of farmers, practitioners of traditional medicine, and artisans respectively.

3.2.2 Pedagogy based on case studies

One pedagogical approach to including studies of practice in education may be through case studies. Case-study based teaching-learning imparts knowledge, skills, values, and identity in an integrated fashion, and allows for a practice-to-practice comparison. Outlining a practice that contrasts with existing practice is an established pedagogical method in other professions.

Medicine, Law, Business, and Management studies have made case studies an integral part of their curricula. Garvin documents how Langdell, a law professor, started using cases, because he believed that is where students would see the “principles first take a tangible form”.[171] Studying the records of patients - cases and case histories - is a vital part of medical training as well.

Case studies offer students alternative perspectives and solutions. In the words of Jonassen, “Case studies are examples of ill-structured problems that may be used to help students understand more complex and ill-structured problems”.[172] Further, “Cases would

171 Garvin, “Making the case: professional education for the world of practice,” 2003.
172 Jonassen, “Engineers as problem solvers,” 2014.

provide students with opportunities to use the domain's conceptual tools in an authentic activity and wrestle with real-world problems...”.[173]

Engineering cases documenting how an engineering job was actually done, or an engineering problem was encountered, have been used in engineering education since 1950s. Vesper and Adams[174] evaluated the use of cases in terms of student responses. Students found that cases enhanced their “skills of spotting key facts among less relevant data, identifying and defining practical problems, and foreseeing consequences of alternative actions”. Raju and Sankar[175] found that students thought cases exposed them to nontechnical issues and experience and to work with limited information. Conway[176] found that case studies and active-learning pedagogies allow students to move up the (Bloom's) pyramid and take part in analytic, synthetic, and evaluative work. Royal Academy of Engineering, UK,[177] has set an example in this domain, by developing case studies with leading-edge industrial practitioners and experienced teachers, implemented as a special scheme ‘Engineering for Sustainable Development’ in 1998.

Case studies of grassroots innovators could thus play a similar role in engineering curricula, as vehicles to bring out the messy nature of real-world problems, ethical dilemmas, value challenges, and decision points. Case studies would also broaden the 'engineer' identity, by providing authentic cases, which could guide students to solving grassroots problems. This is particularly crucial in the context of sustainable engineering design, where grassroots innovations can demonstrate alternative technological choices rather than technological

173 Brown, Collins, & Duguid, “Situated cognition and the culture of learning,” 1989.
174 Vesper and Adams, 2014 cf Davis & Yadav, “Case studies in engineering,” 2014.
175 Raju & Sankar, “Teaching real-world issues through case studies,” 1999.
176 Conway, “Using cases and activity learning with undergraduate economic classes,” 2001.
177 RAE, cf Davis & Yadav, “Case studies in engineering,” 2014.

determinism, described by Derek Hodson[178] as, “the idea that the pace and direction of technological change are inevitable and irresistible”.

3.3 Objective of this research project

The objective of this research project is to characterize the non-formal and formal practice in the wild, by exploring grassroots design, i.e. technology design that addresses grassroots problems. The aim is to explore and help illustrate the following:

1. How are problems and solutions identified through everyday activity?
2. How are technological solutions developed using a non-formal process?
3. How are technological solutions developed using a formal approach followed in engineering classrooms, by an experienced engineer working at the grassroots level?
4. What are the similarities and differences between these cases?
5. What are the advantages/limitations of the formal practice?
6. What could be a possible best practice?

The research questions based on this objective are outlined in Chapter 4.

3.3.1 Approach of this research project

To address these questions, a theme was identified, in the form of a particular grassroots problem: the provision of electrical power to areas where grid-based power is not available. The following three cases of technology design that addressed it non-formally and formally, were identified and studied.

178 Hodson, “Time for action: Science education for an alternative future,” 2003.

1. A ‘grassroots innovator’ identified by National Innovation Foundation, and his/her problem-solving process
2. A formally trained engineering practitioner working at the grassroots solving a similar problem, and his problem-solving process
3. An engineering students solving a similar problem, and their problem-solving process

This case -based process approach allows overcoming limitations of earlier studies and interventions, and gain new insights. Also, real-world problem identification and solution in the ‘wild’ allow study and showcasing of how problems were identified, and framed, to design a solution. The three different approaches enable a better understanding of the advantages/limitations of the formal approach.

Case studies of grassroots problems enable documentation of real-world experience as well as showcasing of the grassroots problems and solutions, such as highlighting ‘missing’ technology, as well as understanding how ‘sociality’ is embedded in the design process. Furthermore, case studies of successful grassroots problem-solvers, who embody a different/alternate identity from the currently prevalent one, enable foregrounding of new engineering identities, such as development consultants, sustainability engineers and social entrepreneurs.

While this thesis project suggests and assumes case studies as a pedagogical outcome, it does not aim to create and test any intervention using case studies in classrooms.

3.3.2 Research questions

Based on this research approach, the following key research questions are proposed, to understand and characterize the practice of grassroots technology design.

1. What are the key elements of practice that leads to a grassroots innovation/technology design?
    i. What are the design principles that underlie grassroots innovation/design?
    ii. What are the cognitive strategies and conceptual models employed in the practice of grassroots innovation?
2. How are these components, design principles, cognitive strategies, and conceptual models different from formal design practice?
3. What design principles could these provide for the redesign of engineering curricula and pedagogy? Particularly to develop value-driven case studies, that illustrate solving of messy real-world problems in rural areas in a sustainable fashion?

Chapter 4: Research Design

Multiple case study - qualitative cross analysis

“In qualitative studies in which you both describe individuals and identify themes, a rich, complex picture emerges. From this complex picture, you make an interpretation of the meaning of the data by reflecting on how the findings relate to existing research; by stating a personal reflection about the significance of the lessons learned during the study; or by drawing out larger, more abstract meanings.”[179]

In this chapter
Grassroots innovation is a unique practice, spread across a wide range of situations. The case study method was identified as appropriate to study this practice, and the cases were purposively selected, based on the contribution they could make to engineering education. The case of Micro Hydro Power (MHP) systems was chosen as a focus area, as the technology is part of mainstream engineering, and sufficiently complex in terms of design process and thinking. Further cases were then purposively selected and added to the study of this core practice, for comparison and validation. The empirical data for the core cases included primary sources (interviews, observation, artifacts, simulation data), as well as secondary sources (photos, videos, and reports, including brochures and news articles). To probe design thinking across both formally and non-formally trained designers in a controlled fashion, a computational simulation of MHP systems, with visual and numeric modes, was developed. Data on the designers' interactions with this simulation provided a different perspective on their design processes. The data from all these sources were integrated, and qualitatively analyzed using cognitive historical analysis and thematic analysis, to develop a comprehensive understanding of the design practices and their underlying cognitive processes. Distributed cognition was the primary theoretical framework used for studying the cognitive process of design.

4.1 Research methodology

In order to develop a research design, different research methodologies in the literature were explored, to understand the methods used to study design practice.

179 Creswell, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 2012, p 18.

4.1.1 Review of research methods used in design practice research

According to David Craig,[180] four strategies have been used by researchers to conduct studies in design behavior research, across design disciplines and expertise levels. These are: 1) *Think-aloud protocols,*[181] used to "illustrate, support, or expand cognitive models of design", 2) *Verbal or content analysis,* focused on knowledge representations used in design,[182] 3) *Process isolation studies in design,*[183] to explore cognitive processes as well as representations, through controlled study of processes isolated from design episodes using simple or miniaturized experimental design tasks, and 4) *Situated studies of design*, in work[184] or experimental[185] settings, focused on design activities in their contexts, such as the socio-cultural and material ones, rather than on idealized practices or isolated cognitive processes. In these studies, "context, rather, is taken to be constitutive of practice".[186]

Craig points out a limitation of these studies, as

> *"Few studies in design deal specifically with how concepts are constructed, reproduced, or conferred through local practices. Most seem to assume that although knowledge may*

180 Craig, "Stalking Homo Faber: A Comparison of Research Strategies for Studying Design Behavior," 2001, p 13-36.
181 Akin, "How do architects design?" 1978; Eastman, "Cognitive processes and ill-defined problems: A case study from design," 1969; Ullman et al., "A model of the mechanical design process based on empirical data" 1988.
182 Akin, "How do architects design?" 1978; Atman et al., "A comparison of freshman and senior engineering design processes," 1999; Crismond, "Investigate-and-Redesign Tasks as a Context for Learning and Doing Science and Technology: A study of naive, novice and expert high school and adult designers doing product comparisons and redesign tasks," 1997.
183 Akin & Akin, "Frames of reference in architectural design: analysing the hyperacclamation (Aha-!)," 1996; Casakin & Goldschmidt, "Expertise and the use of visual analogy: Implications for design education," 1999; Lawson, "Cognitive strategies in architectural design," 1979, Verstijnen et al., "Sketching and creative discovery," 1998.
184 Bucciarelli, *Designing Engineers*, 1994; Goel, *Sketches of thought*, 1995; Harrison & Minneman, "A Bike in Hand: A Study of 3D Objects in Design," 1996; Schon, *The Reflective practitioner: How professionals think in action*, 1983.
185 Brereton et al., "Collaboration in design teams: How social interaction shapes the product," 1996; Cross & Cross, "Observation of teamwork and social processes in design," 1996.
186 Craig, "Stalking Homo Faber: A Comparison of Research Strategies for Studying Design Behavior," 2001, p 29.

> *be objective, it is ultimately derived from experiences via general reasoning (e.g. inductive generalization or pattern recognition)".*[187]

Atman et al.[188] describe five methodologies followed in engineering design education research, while also pointing out that these differ from design research not in terms of the methods used, but rather by the research questions being asked. These are protocol analysis, interviews, surveys, ethnographic and field studies, and analysis of (learning) artifacts, for studying product and process design in both experimental and natural settings.

4.1.2 Rationale for selection of research method for the present study

The literature review indicates that technology design in the wild, such as grassroots innovation practice, has not been previously explored or characterized in design studies. This thesis project thus proposed to do this, by, first of all, describing the phenomenon in as much detail as possible. For this, it was necessary to study the practice in its natural setting, and in a holistic rather than an isolated or idealized manner. This suggested that controlled, experimental, and lab-based strategies would not be useful. Further, protocol (think-aloud, verbal, content, or process isolation) studies have the constraint of reducing the complexity of a real-world practice, in order to make it a manageable task, of limited duration. This alters the long-term design processes that take place in the wild. For these reasons, I chose the option of qualitative studies, of specific cases of grassroots technology designers, as a suitable research method for this project.

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187 Craig, "Stalking Homo Faber: A Comparison of Research Strategies for Studying Design Behavior," 2001, p 30.

188 Atman et al., "Engineering Design Education: Research, Practice, and Examples that link the Two," 2014, p 208-9.

4.2 Research method used for the present study

The ‘central phenomenon of interest’[189] in this research project was the design practice of non-formal and formal grassroots technology designers. The case study method was used to characterize the process of technology design in the wild, using qualitative research methodology. This method is appropriate and relevant for a study, as Robert Yin[190] states, when you seek to answer the how and why of a phenomenon, in an extensively in-depth and descriptive manner. It provides a distinct advantage over other methods such as survey, history, or experiment ('true experiment/causal studies' may establish the efficacy of an intervention, but not offer an explanation), when the researcher is studying a contemporary phenomenon over which s/he has no control. The method allows for retaining the holistic and meaningful characteristic of real-life events. Yin also emphasizes that case studies are not just exploratory or descriptive, but can also play an explanatory role in research, and their lessons may be generalizable, “to theoretical propositions and not to populations or universes”.[191]

> *“In this sense, the case study, like the experiment, does not represent a “sample,” and in doing a case study, your goal will be to expand and generalize theories (analytic generalization) and not to enumerate frequencies (statistical generalization)”.*[192]

> *“... the [research] design is the logical sequence that connects the empirical data to a study’s initial research questions and, ultimately, to its conclusions”.*[193]

This research began as an exploratory study, with the aim of describing and characterizing how grassroots technology design (GTD) practice engages with real-world societal problems and addresses them sustainably. At this stage, there were no additional explicit propositions made about the GTD practice.

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189 Creswell, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 2012.
190 Yin, *Case study research: Design and methods*, 2009.
191 Yin, *Case study research: Design and methods*, 2009.
192 Yin, *Case study research: Design and methods*, 2009, p 15.
193 Yin, *Case study research: Design and methods*, 2009, p 26.

This was a multiple-case design,[194] even though the case of the grassroots innovator designing a micro hydro power system was unusual, and could have been studied as a single case design in itself. The multiple case design was chosen because it allowed for contrasting the non-formal practice with formal practice ('two-tail' design, where cases from both extremes are selected[195]). This design also allowed contrasting the practice context with the learning context of students.

> *“... you may have deliberately selected your two cases because they offered contrasting situations, and you were not seeking a direct replication. In this design, if the subsequent findings support the hypothesized contrast, the results represent a strong start toward theoretical replication—again vastly strengthening your findings compared to those from a single case alone)”.*[196]

In the context of selecting the number of cases, Yin suggests that,

> *“you may want to settle for two or three literal replications when your theory is straightforward and the issue at hand does not demand an excessive degree of certainty. However, if your theory is subtle or if you want a high degree of certainty, you may press for five, six, or more replications”.*[197]

> *“Multiple-case rationales also can derive from the prior hypothesizing of different types of conditions and the desire to have subgroups of cases covering each type. These and other similar designs are more complicated because the study should still have at least two individual cases within each of the subgroups, so that the theoretical replications across subgroups are complemented by literal replications within each subgroup”.*[198]

Based on this rationale, analyzing additional cases of technology design allows for expansion of the analysis, and supports understanding and characterization of grassroots technology design through similarities and contrasts across the cases.

> *“The ability to conduct 6 or 10 case studies, arranged effectively within a multiple-case design, is analogous to the ability to conduct 6 to 10 experiments on related topics; a few*

194 Yin, *Case study research: Design and methods*, 2009, p 53.
195 Yin, *Case study research: Design and methods*, 2009, p 59.
196 Yin, *Case study research: Design and methods*, 2009, p 61.
197 Yin, *Case study research: Design and methods*, 2009, p 58.
198 Yin, *Case study research: Design and methods*, 2009, p 59.

> *cases (2 or 3) would be literal replications, whereas a few other cases (4 to 6) might be designed to pursue two different patterns of theoretical replications".*[199]

The primary unit of analysis being the individual designer of technology, each participant's design process was purposively selected as a sample. (Individual designs, prototypes, or episodes are not the 'units of analysis' or cases here.) Each case study covers the designer beginning with the design problem, up to the designer's current work.

Through informed consent, all participants' gave permissions for sharing the data (quotations) as part of this research study.

4.3 Research sample

I used a purposive sampling technique to select cases that allowed me to describe and contrast the design practice at the grassroots. I call all these problem-solvers together as 'grassroots technology designers'.

- To study the non-formal practice, I studied a grassroots innovator (GRI).
- To contrast this with formal practice, I studied a formally trained and experienced practitioner solving a grassroots problem similar to the one solved by the innovator (EP).
- To contrast practice with learning, I also briefly studied engineering students (SL) conducting workshop based projects, addressing the problem similar to the one solved by the innovator.

The specific cases were identified through a step-by-step process, as described below.

199 Yin, *Case study research: Design and methods*, 2009, p 54.

4.3.1 Grassroots innovator’s non-formal practice

In order to identify cases of innovators who designed and built innovative technological devices to solve their problems, I first contacted the National Innovation Foundation (NIF), India. NIF[200] is an autonomous body of the Department of Science and Technology, working towards identifying, recognizing, and supporting grassroots innovators with the help of Honey Bee Network (HBN), Society for Research and Initiatives for Sustainable Technologies and Institutions (SRISHTI), and Grassroots Innovation Augmentation Network (GIAN).

For the last two decades, NIF, with the help of HBN, has organized a '*Shodhyatra*' (scouting walks) every six months. For about ten days, this on-foot mission scouts interior areas of India, for an exchange of knowledge, know-how, and to look for innovations in various fields such as agriculture, health, technology, and so on. A national innovation contest is also announced every two years. NIF's criteria of eligibility for this competition includes only innovators who have not had a chance to be formally educated beyond Bachelor of Arts, if at all. In fact, most innovators are school drop outs. Grassroots innovations identified through these initiatives undergo a scrutiny of their innovativeness, in terms of prior search and intellectual property. Research literature and patent databases are searched by a trained NIF team, to make sure that the initiatives are not common, known, and used in society, both in India and across the world. NIF's process of selecting awardees also ensures that the merit of the innovative design is evaluated by experts from both the top universities and research labs in India, as well as real-life experts from the pool of known innovators. If approved as novel, the innovations are formally recognized, and the innovators are rewarded by the

200 For details, see http://nif.org.in/

President of India. Depending on their interest, the NIF team also helps the innovators with design improvement, patenting, and tie-ups with venture capitalists through GIAN. This movement attempts to recognize, respect, strengthen, and nurture the effort of indigenous and local innovation by individuals and communities. NIF maintains the world's largest database of such grassroots innovators, documented over last twenty years. This is a large population of identified and endorsed innovators.

For this study, selecting the sample case(s) from the NIF database provided the following advantages:

- A large population to choose from.
- Quality of the innovative design is evaluated by experts.
- Many innovators are not educated. This may provide insights into 'raw' untrained design skills.
- The opportunity to follow an ongoing innovation of an innovator, as some are known to be serial innovators.
- Possibility to compare innovators with formally trained engineers working on grassroots problems.

I interacted with the the NIF team extensively, to understand their process and work. From the database and their inputs, I identified a set of innovators who had designed technology, and conducted a pilot/reconnaissance field study, visiting five of them. This study provided some insight into 'raw', untrained design efforts, and also directions as to how a study of such a practice could be planned.

The case of GRI (pseudonym) was finally selected from these, for a deeper and detailed exploration in this research project. GRI had designed a modified micro hydro power system, and developed a business around it. His case promised the possibility of exploring intriguing aspects of this innovation, such as its technical domain, which included multiple engineering disciplines (hydro, mechanical, electromagnetic), its wide dissemination and business model, and continuity over a length of time, among other factors.

To better understand the grassroots innovation case, I then looked for contrast cases of formal design of micro hydro power systems.

4.3.2 Formally-trained professional solving a grassroots problem

Formally trained engineers are mostly involved in designing and building large or mega hydro power systems. The design of micro hydro power systems has not enjoyed much impetus from government-supported development policies, and as a result, it is not a mainstream engineering activity for formally trained engineers. The few such projects that are initiated are more often supported through grants from funding agencies, and technical support from formally-trained engineers working with NGOs such as *Practical Action* or *Engineers Without Borders*. I collected information on some such projects in India, and from literature available over the Internet, identified a few engineers working in this sector. I interacted with one of them over email, but she had moved out of the sector and was not available for further study. Through a colleague, I was able to connect with the other engineer EP (pseudonym) I had identified. EP continues to work in this sector, and I was able to study his design activity in my research project.

4.3.3 Engineering students conducting a lab-based project

Engineering students get an opportunity to engage with real-world problems through their final year engineering projects. To get a sense of the design approach of formally-trained but inexperienced designers such as engineering students, I studied a few engineering projects of hydro power system design. One was by a group of six (female) students of final year Electrical Engineering. They were engaged in a project to improve the wattage output of a pico turbine designed and fabricated earlier by their seniors. The other was by a team of two students from final year Agricultural Technology, who improved a micro hydro system designed and partly fabricated by a team of two students from their previous batch. These student groups were identified through contacts in the engineering college community.

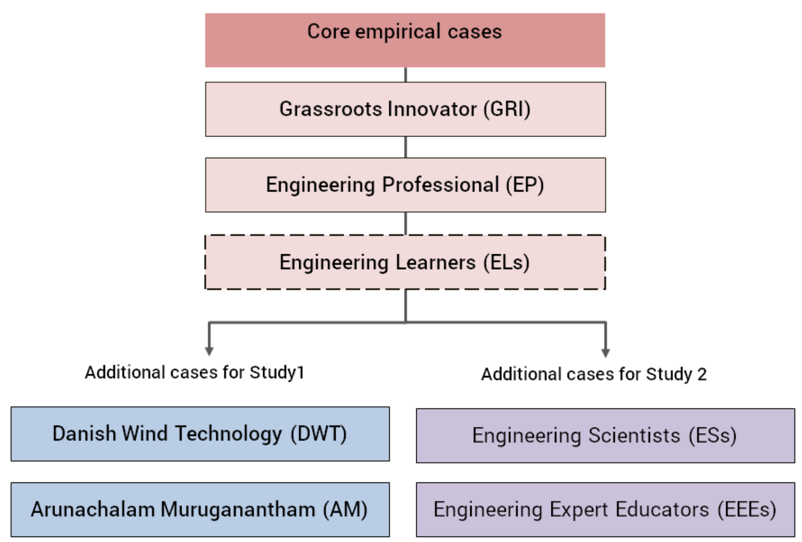

Fig. 3: Cases purposively sampled for this thesis

Along with the case of grassroots innovator, these cases allowed me to understand and document the similarities and differences in the approaches and thinking practices of trained and untrained professionals, novice students as well as experts. These cases helped highlight the design principles, values, and ethics that guide technological decision-making.

Additional cases (See Fig. 3) based on secondary data were selected and analyzed, to understand the empirical data better, to articulate the findings, and to find converging generic principles. These are described in Chapter 5.

4.4 Technology context of the study: Micro hydro power (MHP) system

In many parts of the world, villages and hamlets do not have reliable infrastructure for grid power, and the ones that do, receive insufficient and irregular power. Sustained supply of power is particularly challenging in the mountainous regions, due to difficulties in installation and maintenance of the grid, and distribution losses. Tough terrain, harsh weather conditions, dispersed and remote population, and poor load characteristics aggravate the cost.

On the other hand, many of these marginalized regions are blessed with natural resources such as near-perennial water streams, wind, and sunlight. Micro Hydro Power (MHP) systems (in the range of 1-100 kW power) is thus a good option that addresses the need for reliable power in grid-deprived remote areas, by utilizing naturally available perennial water streams and mountain gradient. Developing such decentralized mechanisms for power generation, based on these local resources, is a viable and sustainable alternative to centralized grid-based power supply.

Unlike other conventional or alternate sources of power generation, MHP is non-polluting, and does not disturb natural ecosystems. As no dams are constructed, no lasting changes are made to the environment. MHP is also socially benign as it usually does not demand displacement of villages or rehabilitation of communities. It is less capital-intensive, and faster to build and become operational. The technology is relatively simple to operate, maintain, and repair. It is highly durable, without heavy maintenance costs, and the power generation is free of inflation impact. It is thought to be less efficient in terms of investment per kW of power generation, especially due to seasonal variation in available water, and not economical for transmission over large distances. MHP is particularly well-suited for remote and isolated areas, and has the potential to invigorate economic activities in such areas.

In one of the regions where this case study was conducted, traditional water mills existed for centuries, but hydro electricity was generated only towards the end of the 19th century. The government supported the development of micro hydro power systems, along with upgrading of existing traditional water mills for power generation. But many of these stations faced problems, and some were abandoned or shut down. Power problems thus persist across the region.

The design of an MHP system is not simple, and it is a standard project given to final year engineering students. The 'wild' version of this design thus has sufficient complexity, to provide practice insights into the engineering design aspects of this problem. Formal engineering curricula of the core engineering disciplines (mechanical, civil, and electrical) usually offer the related courses (Hydro Dynamics and Hydraulic Machines) in the first two years. Most courses include basic modules on hydro power projects.

The major considerations in the design of a micro hydro power station are: sourcing water, designing a turbine and a generator, coupling the turbine with the generator, distributing the generated power, and controlling for load variation. Generically, water from the source is stored in a (forebay) tank, and taken to the turbine in pipes (penstock). A pipeline is laid along the slope, from the storage to the nozzle, which shoots a jet of water on the turbine. (See Fig. 4).

The power available from water 'P' is calculated as P=ηρQgh where, P is power in watts, η is the dimensionless efficiency of the turbine, ρ is the density of water in kilograms per cubic meter, Q is the flow in cubic meters per second, g is the acceleration due to gravity, and h is head i.e. the height difference between inlet and outlet in meters.

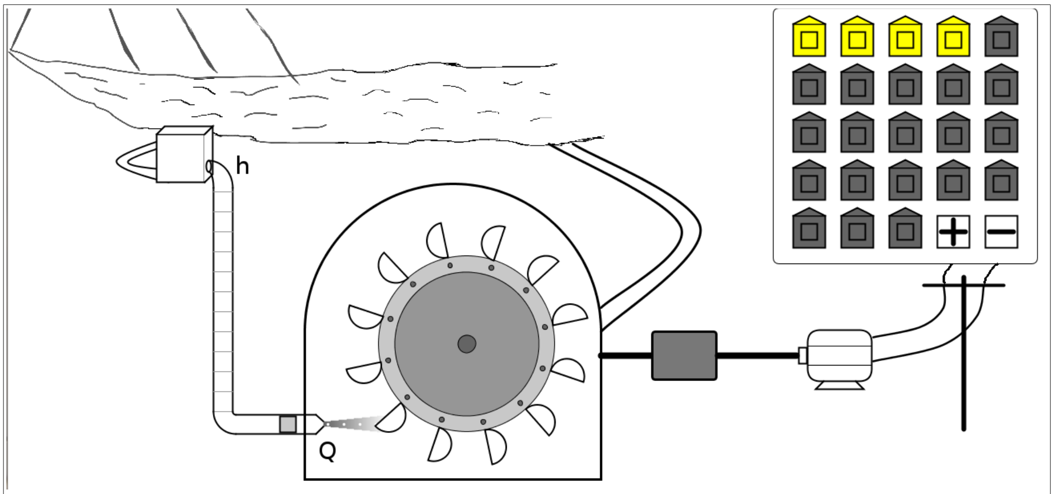

Fig. 4: A schematic of micro hydro power (MHP) generation system

Hence, the vertical distance (the 'head' h) between the storage and the nozzle, and the flow rate of water (Q), principally govern the theoretical (hydraulic) power output P from the source of water at any site. These factors also influence the choice of turbine type and the details of turbine design.

Turbines are discussed as the hydraulic machines that convert this power into mechanical rotation, for conversion to electricity by generators. Different types of standard turbines, such as Pelton, Francis, Kaplan, Cross flow etc, are recommended for different conditions of head and flow rate of water, depending on their performance characteristics.

Students are taught the theory required to arrive at technical specifications of the turbines, such as the diameter of the nozzle and turbine wheel (runner), the number of turbine blades and spacing. They are required to learn to solve problems using the theoretical equations. In these calculations, efficiency is particularly considered as an important parameter in the design of turbine as a hydraulic machine.

In this research project, I have explored two cases (GRI and EP) of real-world practice of MHP system design. These are described in detail in Chapter 5.

4.5 Data collection

4.5.1 Methodology

Following the case study method,[201] my data collection approaches included observation and semi-structured interviews and narratives, which allows the generation of ‘thick descriptions’. To guide the interview process, an interview protocol was developed, consisting of broad and open-ended set of questions. (See Appendix 3).

> *“... the protocol is directed at an entirely different party than a survey instrument. The protocol’s questions, in essence, are your reminders regarding the information that needs to be collected, and why. ... However, the main purpose of the protocol’s questions is to keep the investigator on track as data collection proceeds”.*[202]

I also studied other sources such as documents (letters, photos, videos, representations) and artifacts (prototypes,[203] models) generated by the designers. This data collection was modeled on ethnographic studies of socio-technical systems and practice in distributed cognition research, particularly by Edwin Hutchins.[204]

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201 Yin, *Case study research: Design and methods*, 2009.
202 Yin, *Case study research: Design and methods*, 2009, p 86.
203 A prototype is an early sample, model, or release of a product built to test a concept or process or to act as a thing to be replicated or learned from. (Wikipedia).
204 Hutchins, *Cognition in the Wild*, 1995a; Hutchins, “How a cockpit remembers its speeds,” 1995b.

Also, a special virtual simulation-based probing tool and tasks were developed to collect more and different data in a second round. The details of the data collection rounds are discussed below.

4.5.2 The first round of data collection

1. Interviews and narratives were used to collect data about each designer’s initial ideas, changes, the various stages/phases of design they progressed through, and their own reasoning behind their actions. This involved face-to-face semi-structured interviews conducted at the participant's site of work, office, or home. All the interviews were conducted by the researcher, and follow up questions were later asked for clarification, elaboration, or explanation. For data collection, I made four field visits (12 days), four office visits (7 days), four college visits (5 days), and two remote interviews. All these interviews were audio recorded, and later transcribed verbatim by the researcher, with the help of transcribers.

2. Artifacts (documents, representations, prototypes): Documents such as drawings, and artifacts such as design prototypes, were used to collect data about the way designs evolved.

3. Study of work spaces, activities and problem-solving: Ethnographic observation of designers’ practice, where the design activity was in progress. Also observation of several innovations/installations based on the same principle, where the innovation was already implemented. These were used to collect data on the trajectory of designers' thought processes and their design principles.

4. Secondary data (NIF data, experts, industry specs): Apart from this empirical data, I studied different and contrasting cases of formal engineers and students, and non-formal practice of other grassroots innovators. Through secondary data from NIF, the Internet, media, textbooks, historical development of technology, other experts, and industry, I derived questions that guided a deep and detailed exploration of the designers' practice.

4.5.3 Development of a new data collection probe

Since the designers had designed their systems over past several years, all the design process data were historical. Their current running systems were the final designs, and intermediate stages were rarely available. As a result, the process data and progressive design trajectory were only available through interviews. Methodologically, the interview method is limited to memory-based responses, which could be incomplete or corrupt because of erroneous recall. One way to address this limitation is triangulation, by collecting non-recall data, i.e. procedural data, through a task where the designers perform and demonstrate part of their design process in real time. This also allows the study to overcome the limitations of self-reports, as participants are not always aware of what they think and why they do things the way they do, although they may offer post-facto explanations. Literature indicates that such explanations may not necessarily be what the individuals actually thought.

Also, a common design platform was required to draw out the generic principles guiding design across multiple cases and a diversity of contexts, across designers. Further, I needed a probe to get insight into the mental models that enabled the designers to design the (socio-)technical systems for hydro power generation.

4.5.3.1 A new data collection tool

Based on previous research studies and available methods, an experimental design task environment was developed. This simulation tool captured the dynamics of a hydro power system, and allowed for the design scenario to resemble the real world site as much as possible, so that the designer's experience could be used to solve tasks in this simulation environment. This simulation system served as a common virtual problem generator.

One advantage provided by this simulation tool is that the experience of working with the virtual simulation would be similar for all the designers, as they were somewhat familiar with computers, but did not have experience with a simulated hydro power system before. In contrast to a pen-and-paper interface, where a formally-trained designer could be at an advantage, or a real-world situation, where an experienced designer may be at an advantage, the simulation was a probing interface where none of the designers had any particular advantage.

The virtual simulation tool focused on the embodiment stage of design process, which provided a concrete and common design space, while at the same time allowing exploration of its implications with respect to the conceptual and detailed design stages.

4.5.3.2 Simulation of an MHP system design

The simulation presents a virtual problem scenario, and four different design tasks based on it. The scenario shows a waterfall in a mountain, a platform next to it to build the power system, and a small settlement of houses in the valley below. The Explore screen allows exploration of the interface, to understand what it affords in terms of designing, and what feedback it provides about the system performance. The tasks involve designing a micro hydro power system, by selecting appropriate components and defining the specifications of some of the components, using water from the waterfall, and supplying power to the settlement. All the houses are assumed to use the same gadgets, which could be specified in the interface. (See Fig. 5).

Fig. 5: Simulation interface for virtual design of MHP systems.
The simulation provides two palettes: (A) to select components of the system (reservoir, pipes, nozzle, turbine wheel, flywheel, generator, belt-pulley/gear box, heating coil, houses), and (B) to select gadgets in the houses, running on electricity (bulb, fan, blender, TV, fridge, phone charger, irrigation pump, lamp post). These can be selected or removed by clicking. The simulation allows the designer to manipulate: (C) the vertical head h, by moving the reservoir up/down, and (D) the discharge Q, by moving the control to change the nozzle diameter. Once the necessary components are selected, the Play/Pause button is enabled, and the system simulates the impinging water and the turbine rotation. Resultant quantity and quality of electricity available to the houses is depicted for the selected load (number of houses and gadgets per house). Simulation task responses allow probing of how designers make design decisions for the given requirements and constraints.

4.5.3.3 Simulations tasks

In the first two tasks, only qualitative information was available for designing. For example the power generation/consumption was indicated through the number of houses lit up. The simulation depicted the system dynamics through rotation of the turbine wheel, and animation of the water jet and the lit houses. This is the visual mode.

In contrast, the next two tasks were purely quantitative/numeric, and no sense of the system dynamics was available through the animation. This is the numeric mode.

4.5.4 The second round of data collection

The two designers, from whom interview data had been collected earlier, were asked to work with the simulation probe. The designers familiarized themselves with the simulation through the Explore screen, and then completed the four tasks. A touchscreen laptop was used, and a mouse and touch pad controls were also provided. This data was logged on the server. An eye-tracker was used to track the designer's eye movements on the laptop screen. The researcher was present to clarify any queries they had. The designers were free to talk to themselves or the researcher, or to keep quiet, as it was not a verbal protocol study. There was no time constraint. After completion of the tasks, the researcher asked follow-up interview questions to the designers.

The designers talked to the researcher while working with the simulation, asking questions about the controls and functioning, and adding comments in the context of the tasks and their real-world design experience. Due to this, the eye-tracking data, recorded as red dots superimposed on a video capture of the screen, was not consistent and complete.

4.6 Data analysis

4.6.1 Methodology

Many of the designers' innovations were complete by the time they reached the NIF database. The data collected for this project may thus be understood as 'historical'. These data about the historical practice, designs, and thinking involved in technological problem-solving, were triangulated with the simulation probe interviews and historical development of technology.

According to Yin, “The analysis of case study evidence is one of the least developed and most difficult aspects of doing case studies”.[205] He recommends following an analytic strategy, which also helps “treat the evidence fairly, produce compelling conclusions, and rule out alternate explanations”.[206]

In order to analyze the historical data for the design thinking and conceptual models of the non-formal and formal grassroots designers, the method of cognitive historical analysis was used. This is similar to the cognitive historical case studies conducted in the domain of scientific and engineering innovation by Nancy Nersessian and others, where the case studies were used to reconstruct scientific and engineering thinking in the light of cognitive theories.[207] In the words of Nancy Nersessian,

> *“... every piece of recorded data needs to be treated as a reconstruction by its author. … analysis of a historical problem-solving episode requires making a case on the basis of convergent evidence from a number and variety of sources”.*[208]

Ethnography, observation, and laboratory experiments are some of the methods used to investigate and conduct a cognitive analysis of qualitative data about conceptual change in discovery and innovation. These are especially useful to understand 'psychologically' creative concepts.[209] Compared to these, cognitive historical analysis better supports the analysis of 'historically' creative conceptual insights. Since in this research project, the innovative design by the non-formal design was not a case of learning 'existing'

205 Yin, *Case study research: Design and methods*, 2009, p 127.
206 Yin, *Case study research: Design and methods*, 2009, p 130.
207 Nersessian, “How do engineering scientists think? Model-based simulation in biomedical engineering research laboratories,” 2009.
208 Nersessian, *Creating scientific concepts*, 2008, p 63.
209 Nersessian, *Creating scientific concepts*, 2008.

formal concepts, but of discovering concepts for himself, the cognitive historical method was preferred. Another reason for using this method was the historical nature of the actual design activity. It was not possible to support this analysis through other methods.

Methods from distributed cognition were also explored, to interpret the internal representations of the designers, through an analysis of their external representations (document and artifact data) including the designs themselves.

The analysis of the interview data was conducted using the method of thematic analysis. According to Boyatzis,

> *"Thematic analysis is a method for identifying, analysing, and reporting patterns (themes) within data. It minimally organises and describes your data set in (rich) detail. However, it also often goes further than this, and interprets various aspects of the research topic".*[210]

Braun and Clarke[211] argue for thematic analysis as a distinct and fundamental method in qualitative analysis, such as narrative analysis or grounded theory, applicable across a range of theoretical and epistemological approaches, rather than just being a tool. Further, they point out that researchers play an active role in identifying the themes. "If themes "reside" anywhere, they reside in our heads from our thinking about our data and creating links as we understand them".[212] Thematic analysis suits this type of research projects because it allows for highlighting similarities as well as differences, generates unanticipated insights, and informs policy development.

210 Boyatzis, 1998 cf Braun & Clarke, "Using thematic analysis in psychology," 2006, p 79.
211 Braun & Clarke, "Using thematic analysis in psychology," 2006.
212 Ely, Vinz, Downing, & Anzul, 1997, p 205-6, cf Braun and Clarke, "Using thematic analysis in psychology," 2006.

Creswell[213] discusses 'Restorying' as a central characteristic of narrative research design, for 'retelling or developing a metastory' from the field texts.

> *“Restorying is the process in which the researcher gathers stories, analyzes them for key elements of the story (e.g., time, place, plot, and scene), and then rewrites the story to place it in a chronological sequence. When individuals tell a story, this sequence is often missing or not logically developed. By restorying, the researcher provides a chronological sequence and a causal link among ideas. There are several ways to restory the narrative”.*[214]

Guided by these methods, each designer's data was restoryed, and/or segmented into themes. The themes were generated from the data, rather than from a theory-driven coding frame. Braun and Clarke[215] discuss inductive (bottom-up, data-driven) and deductive/theoretical (top-down, theory-driven) approaches in identifying and analysing themes. This research project used data-driven themes to organize rich descriptions. These themes were then mapped to the research questions, to provide detailed analysis/interpretation of those specific aspects of interest, such as formal design knowledge and principles.

One major theme was the significant episodes of design transition. Another related theme was the diversity of situations handled and design solutions provided by the designer. The design process was described through a trajectory, emerging out of these individual episodes and across episodes. Each designer's data was also segmented around the theme of design considerations, the various factors that the designer considered while making design decisions for a specific site, and across sites. Chapter 5 reports the case story for GRI and EP in brief, see Appendix 1 and 2 for details.

213 Creswell, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 2012.
214 Creswell, *Educational Research: Planning, Conducting, and Evaluating Quantitative and Qualitative Research*, 2012, p 509.
215 Braun & Clarke, “Using thematic analysis in psychology,” 2006.

Based on these empirical data, analyses were presented with respect to each designer's design process, principles, and thinking. Additional cases, based on secondary data, were described and discussed to expand the analysis. An analysis machine was developed, to capture the cross-case synthesis that was conducted in order to draw generalizable conclusions/findings related to grassroots technology design practice.

4.6.2 The analysis machine

An analysis based on a ‘practice lens' was then developed, using themes of design episodes, transitions, and design considerations (Study 1). In the next stage, a second analysis, based on a ‘cognitive’ lens, was developed, where cognitive processes and their configurations were identified (Study 2). (See Fig. 6 for the analysis machine).

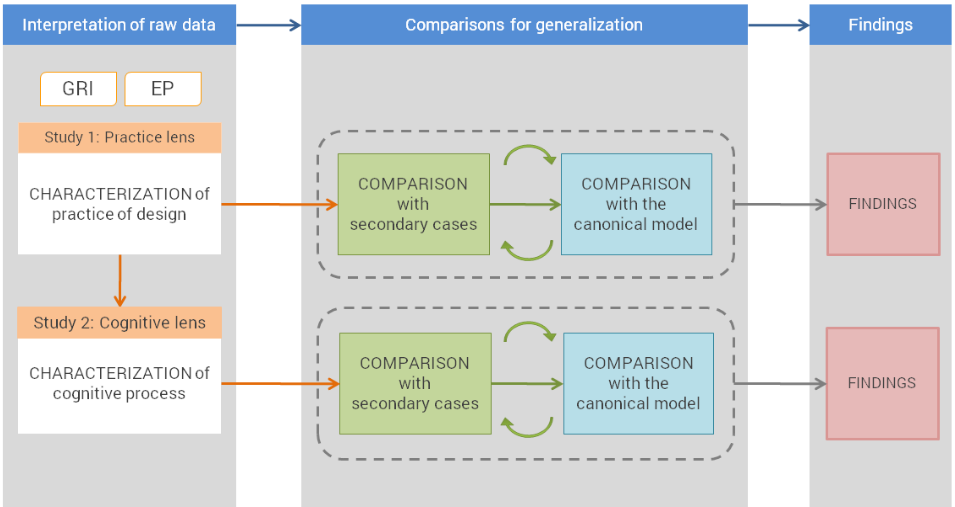

Fig. 6: Multiple case cross analysis design followed in this thesis

Based on the findings from these two analyses, implications were drawn for a possible pedagogy of sustainability engineering. Distributed cognition[216] was the primary theoretical framework used for studying the design process and thinking.

216 Hollan et al., “Distributed cognition: toward a new foundation for human-computer interaction research,” 2000; Hutchins, *Cognition in the Wild*, 1995a.

4.6.2.1 Study 1: Characterization of design practice

The two core empirical cases of GRI and EP were first described and characterized. The student (EL) case was not characterized in detail at this stage, as the data followed already reported findings in the literature about students' design processes.

In order to get more insight into the open problem of sustainability engineering, more cases were then selected, to contrast with the core cases. The first such case was the development of Danish Wind Technology, another sustainable technology developed largely by artisan and craftsmen who were untrained in formal engineering (Case 4: Danish Wind Technology - DWT). The second case was another non-formal grassroots innovator, who designs and supplies low-cost sanitary napkin-making machines to rural production houses run by self-help groups of women (Case 5: Arunachalam Muruganantham - AM). Along with the core cases (1-3), these cases (4, 5) allowed for a better characterization of sustainable design and manufacturing processes as well as business models. The cases converged, to offer a generic design principle for sustainability engineering. (See Chapter 6, also Date & Chandrasekharan, 2017 – based on cases 2, 4, 5).

4.6.2.2 Study 2: Characterization of the cognitive process of design

The findings from the first analysis provided some design principles, but no systematic way to incorporate them into existing EE curricula, which are based on formal structures. Changing the EE curricula to include sustainability thus requires understanding the cognitive roles formal structures play in engineering design, and how the design principles identified by analysis 1 relates to these cognitive roles played by formal structures. This required a second analysis based on a cognitive lens, as the first analysis did not provide an understanding of how the thinking processes involved in sustainable technology design could be integrated with thinking processes involved in mainstream engineering. This understanding would be necessary to identify how pedagogy needs to be redesigned at the operational level to support sustainability engineering. Towards this, the primary data were analyzed again, to characterize the cognitive processes involved in MHP design. A canonical model of the cognitive processes assumed by standard EE was used as a contrast case to develop this cognitive analysis.

The historic and interview data posed limitations for developing this analysis. These were addressed through interview data collected using the novel simulation tool as probe, which provided a standard view across formally and non-formally trained designers (See Chapter 7, also Date & Chandrasekharan, 2018 – based on case 1).

In order to validate the results from the analysis based on the core cases, three more cases were used in Study 2 as contrast cases, where the technology problem was open-ended, unlike MHP, which is a 'solved' problem for formal science/engineering. The first two of these were cases from a team of engineering scientists at a leading engineering research laboratory in India working on the cutting-edge problem of sustainable Fuel Cell technology (Case 6: Engineering Scientists – ESs). The third was the case of an open-ended estimation problem in technology design, solved by engineering educators who were also experienced as practicing engineers (Case 7: Expert Engineering Educator(s) – EEEs), reported as part of a study in the literature. The cognitive process characterization based on the primary cases (1-3) was cross-validated with these additional cases (6, 7). (See Date & Chandrasekharan, 2017 June – based on cases 1-3, 6, 7).

Overall, the research design was data-driven, rather than by a framework or theory. The data were collected through primary sources such as interviews, observation, artifacts, simulation data, and secondary sources such as photos, videos, and reports. The findings were arrived at using the methods of thematic analysis and cognitive historic analysis. The understanding generated was qualitative, based on the interpretation of the findings, but these findings were cross-validated using additional cases.

4.7 Addressing the method gap

As discussed in Section 4.1.2, design research studies have mostly employed think-aloud protocols, verbal or content analysis, process isolation, and on rare occasions, situated studies (more of the lab-experiments kind, but also some in the natural work settings). The limitations of these methodologies are to some extent mitigated in this study. The qualitative methodology used addresses the methods gap (at the level of research methods to conduct design research) by combining data from different probes (the multiple case study method, a new virtual simulation-based probing tool, and a thematic and cognitive historical analysis), which enabled a detailed study of real-world non-formal and formal practice in the wild.

Chapter 5: Data – Case studies

"In the varied topography of professional practice, there is a high, hard ground overlooking a swamp. On the high ground, manageable problems lend themselves to solution through the application of research-based theory and technique. In the swampy lowland, messy, confusing problems defy technical solution. The irony of the situation is that the problems of the high ground tend to be relatively unimportant to individuals or society at large, however great their technical interest may be, while in the swamp lie the problems of greatest human concern."[217]

In this chapter
This chapter provides a preliminary description of data, in terms of all the cases studied, as well as a detailed description of two core cases. The core cases include the non-formal practice of a grassroots innovator (GRI), the formal practice of an engineer (EP) designing the same technology, and the final (capstone) year engineering project of students (ELs) designing MHP system. The third core case (ELs) is not described in detail, as it primarily validates literature. The additional cases include the non-formal grassroots innovator, who designed low-cost sanitary napkin-making machines (Arunachalam Muruganantham – AM), the non-formal practice of developing Danish Wind Technology, a sustainable technology developed by artisan and craftsmen (Danish Wind Technology – DWT), the formal practice of a team of engineering scientists at a leading engineering research laboratory in India, working on the cutting-edge problem of sustainable Fuel Cell technology (Case 6: Engineering Scientists – ESs), and the case of an open-ended estimation problem in technology design, addressed by engineering educators with many years' experience as practicing engineers (Case 7: Expert Engineering Educator(s) – EEEs).

5.1 Primary cases

Interview and secondary data were collected and analyzed in detail for the following three core cases, in the technology context of Micro Hydro Power systems.

5.1.1 Case 1: Grassroots Innovator – GRI

GRI initially developed an MHP system for his own household in the Western Ghats mountains, where grid-based power was erratic, or disrupted in the rainy months, but there were many perennial water streams. He had once visited a big dam, where he saw large hydro turbines generate power, which is supplied through the grid to cities and industries. He

217 Schon, *Educating the Reflective Practitioner*, 1987, p 1.

wondered if the perennial stream near his house could be similarly used to generate power for his household. He had not heard of any such small power system. He says,

> *"Why not we will design very… umm same type… is smaller. For independently? That's a first time. I will image.. The 1st time. After then I will try."*

Fig. 7: GRI's domestic MHP system, also drives a flour mill

Educated in the vernacular medium up to grade ten, GRI had no formal knowledge of MHP science or engineering. He started his design process with a bicycle dynamo, and progressed to building his own permanent magnet generators, while also trying out a variety of fans and wheels, finally designing his own turbine wheel. (See Fig. 7). He then established his own business, and has now installed more than 300 MHP systems for coffee estates, communities in reserve forests, temples, as well as individual houses and small outfits, across many states of India. He proudly says that,

> *"per day 10000 kW power generation by my individual turbines", and "that's a contribution to the government".*

A more detailed description of GRI's design practice, restricted to design episodes and transitions is included in Section 5.3 of this chapter, and more data is reported in Appendix 1.

Fig. 8: EP's multi-purpose electromechanical MHP system

5.1.2 Case 2: Engineering Professional – EP

EP, a formally trained civil engineer from one of the leading institutes of technology in India, constructed his first power generation system for his professor, who was conducting research in the high altitude Himalayas. Lack of funds in the research budget made it necessary for him to design a low-cost MHP system, which was modeled after a traditional water mill running on perennial water streams. This design experience initiated EP on a sustainable technology journey, where he worked with NGOs and communities in remote mountains to build MHPs and provide power. (See Fig. 8). His designs are based on formal-knowledge based Pelton and Cross flow turbines, but people and the context are also central to his designs.

A more detailed description of EP's design practice, restricted to design episodes and transitions is included in Section 5.4 of this chapter, and more data is reported in Appendix 2.

5.1.3 Case 3: Engineering Learner(s) – ELs

ELs, a team of students designing technology for their final year engineering (capstone) project, at a College of Agricultural Engineering and Technology in India, started with the idea that they could provide domestic power in areas that face power scarcity, by storing rain water in roof-tops of multi-storeyed buildings, and using it to drive a pico or micro hydro power system. Based on their formal training, they decided to build a Pelton type turbine. They looked up design specifications on the Internet. Since both budget and workshop facilities were limited, they modified the given design, and manufactured a turbine with the materials available to them. (See Fig. 9).

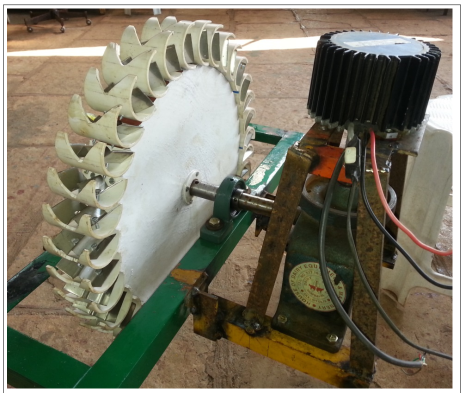

Fig. 9: ELs' pico hydro power system for engineering project

The system functioned well, but generated less power than what was projected by the technical calculations they started with. One of the students, who later went on to use a Computational Fluid Dynamics (CFD) software system, felt that if the CFD software was available during the project, their system would have performed much better.

A more detailed description and analysis of ELs' cognitive process of design is included in Chapter 7.

5.2 Additional/Secondary cases

Additional cases of technology design were purposively selected for comparison with the core cases, particularly to see if the analysis could be extended further. Data for these cases were collected from diverse primary or secondary sources. A more detailed description of these cases (briefly outlined below) is included in Chapters 6 and 7, where these cases are analyzed in the context of the primary cases.

5.2.1 Case 4: Danish Wind Technology – DWT

Denmark has a long history of using wind turbines, such as Poul la Cour's 'Klapsejler', to generate DC power, and Johannes Juul's turbine near 'Gedser' for AC power. During the energy crisis of 1970s, many countries, including Denmark, France, Germany, UK, USA, and the Netherlands, struggled to develop modern wind technology as a source of power. Of these, the Danish wind turbine systems were designed in collaboration with artisans and craftsmen (carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen, and others) and this design proved to be the

Fig. 10: Carpenter Riisager's wind turbine.

most successful, while the designs based on formal approaches failed, despite high-tech competence and high capital investments. (See Fig. 10).[218]

5.2.2 Case 5: Arunachalam Muruganantham – AM

AM, educated up to grade eight and working in a fabrication workshop, found that his wife and sisters could not afford to use sanitary napkins during their monthly menstrual periods. Thinking that a sanitary napkin was a mere cotton pad that was sold at an exorbitant price, AM tried to develop a low-cost sanitary napkin himself. After many personal struggles and design challenges, he solved the napkin design problem, and went on to develop a low cost machine to make sanitary napkins.

Fig. 11: Manufacturing of sanitary napkin in Self Help Groups

This machine is now used by women self-help groups (SHGs) (See Fig. 11)[219] all over the world, to produce napkins locally, at prices as low as Rs. 2 for a piece, compared to at least Rs. 10 charged by multinational companies. He is now recognized world over (Time 'Most Influential People' 2014, 'Padmashree' from the Government of India) for his 'white revolution', as his design has improved hygiene, health, women empowerment and communities, and has provided livelihood to many poor rural women.

5.2.3 Case 6: Engineering Scientists – ESs

A team of engineering scientists based at a research lab in India is developing a cutting-edge Fuel Cell technology for futuristic applications. Though the team is formally trained, in the case of fuel cell technology, the engineering theory, i.e. the formal structure

218 Image © 1996 Copyright The Electricity Museum, Bjerringbro, Denmark.
219 Image © Jayashree Industries.

basis, is not entirely known, and the operational principles and configurations are still in the process of development. During the design process, the group came across and solved several technical problems, related to various components and processes.

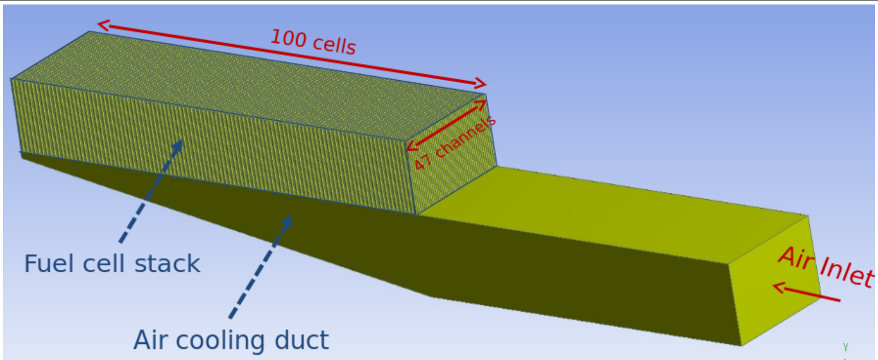

Fig. 12: A Fuel Cell cooling duct modeled in CFD

In this study, two such problems, and the process developed to address these, are discussed: i) the design of a cooling duct for the fuel cell stack (See Fig. 12), ii) the design of a rubber gasket for the fuel cell plate.

5.2.4 Case 7: Expert Engineering Educator(s) – EEEs

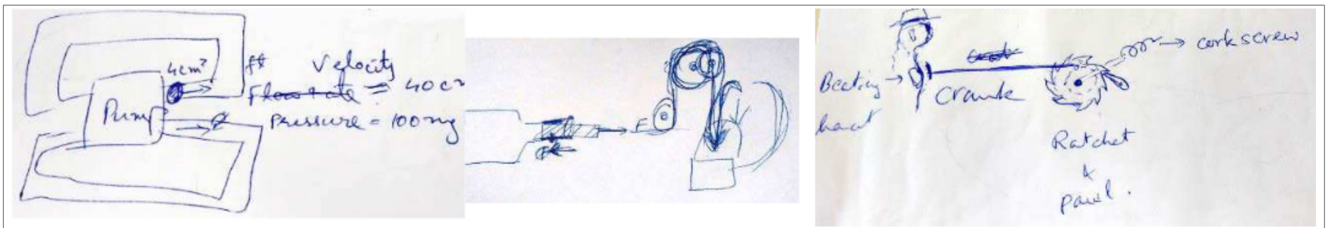

Fig. 13: Heart modeled as pumping and beating

Kothiyal et al.[220] conducted an empirical study of the engineering estimation process, in which two expert engineering educators (EEEs) were independently given the problem of estimating whether the power produced by the human heart could run a wine opener. Interestingly, both the experts started by generating different analogies and different design approaches to address this task, but both arrived at similar estimates through this

220 Kothiyal et al., ““Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning,” 2016.

process. (See Fig. 13). One of the experts (E1) modeled the heart's pumping function, and thought of the heart as a pump, while the other (E2) modeled the beating function, and thought of the heart as driving a ratchet. Both offered the conclusion that human heart would take forever to open the cork, but it would be able to open the cork. Only in the last phase of the estimation process did one of them perform formal calculations.

5.3 GRI's case study

In this section, I describe the primary case GRI's non-formal technology design practice to address power generation problem at the grassroots. I describe in detail the data related to his early design process and considerations.

5.3.1 GRI's early design trajectory

The historical trajectory of GRI's designs, developed over an initial period of at least five years, offer certain landmark stages or distinct episodes of design prototypes. I present these as key transition episodes culminating in his final working design.

1. Lighting a torch bulb
2. DC storage and more power
3. AC power
4. Grid quality power (Constant voltage)

5.3.1.1 Episode 1 - Lighting a torch bulb

Background

GRI did not have formal knowledge of hydro power systems. His first design was based on a gadget he was familiar with - a bicycle DC dynamo. He had seen people pedaling bicycles on the road with headlights powered by dynamos.

> *“I am a farmer. I have studied only SSC. But I have interest... Twenty years back I have no shop [workshop], or my house. So I started simply with DC dynamo... ”*

But he wanted to use water to generate power. He reasoned that how one rotates the dynamo should not matter. As long it was rotated, it would generate power.

> *“Why it is not.. any how you know.. when it will rotate .. it any how any torque[221] is there..” “Why not other movement except by pedal or hand? Why not water on a fiber-fan? I have plenty of water..”*

He knew of a device that used water to rotate a fan. The fan-like device was traditionally used to beat drums in paddy fields at night to keep away wild boars. Although GRI did not name this device, he drew and described it.

> *“It has a fan-like component that freely rotates on an axle. It is fitted underneath falling water stream in the paddy field. As it rotates, it drives a gong to beat a tin, making noise that frightens wild animals away, especially at night.”*

Reference to a similar device is found in the description of Sri Lankan paddy farmers, who call it the 'water ghost' or 'Diya holmana' (REF) because it makes noise without anyone being present.

221 It needs to be noted that while in the interviews GRI uses many terms, such as 'torque', from Physics or the formal theory of hydrodynamics and hydraulic machines, twenty years back when he designed his MHP system, he had no exposure or access to this formal theory. Over the years, as he became well-known for his work, he had visits from and interactions with many formally trained visitors and college students. He may have possibly learned the terms trained persons use, to capture or convey certain meanings, through this communication.

Solution

GRI combined the dynamo and a 'water ghost' like gadget, in order to use water falling on a fan to rotate the dynamo shaft. His drawing (Fig. 14) indicates this concept, in the form of the 'water ghost' directly installed under a small water stream, with its shaft connected to the shaft of the bicycle dynamo.

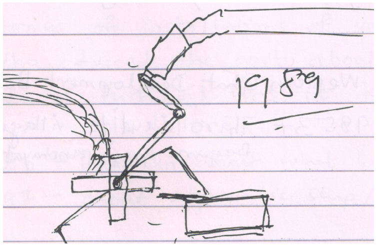

Fig. 14: Water falling on a fan to rotate the dynamo

"I will afterward give one small pipe.. it will rotate."

Later, he took out the rim of the bicycle along with a dynamo, and attached plastic cups to the rim such that the rim rotated when water crashed on the cups. The dynamo shaft attached to the rim rotated, and powered a small torch bulb. He was able to generate small DC hydro power. Eventually improving this design, he was able to power more bulbs.

"(I had) five torch bulbs burning in one year in my house."

5.3.1.2 Episode 2 - More power and DC storage

Background

Having built a preliminary system to generate power from water, he realized that he needed more power to light the household bulbs. This triggered the next design episode. He explored how he could do this, by using more water, and designing a system to run on more water.

Solution

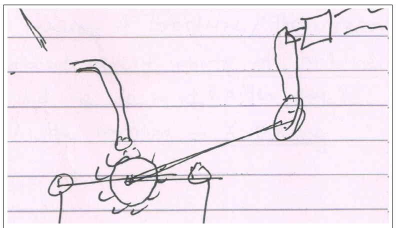
Fig. 15: A DC dynamo

GRI explored the junk markets in nearby industrial towns and replaced the bicycle dynamo with a DC dynamo used in motor vehicles. He added a DC storage battery to store the generated power. (Fig. 15).

> *"After then I do some improved version.. alternator.. motor vehicle alternator... DC dynamo. I will rotate it and store power in the battery and connect it to my house: 8 light bulbs. That is in two year."*

He also needed a stronger wheel to handle more water and run the DC dynamo. So he tried to modify the bicycle wheel, and then source different ready-made wheels from scrap yards, such as a 'wind fan' i.e. a blower machine wheel. Since water slipped from the blades in this design, GRI then designed his own wheel, a 'spokes wheel', more like the original bicycle wheel, but made of mild steel (MS) and other better materials. (Fig. 16, 17, 18).

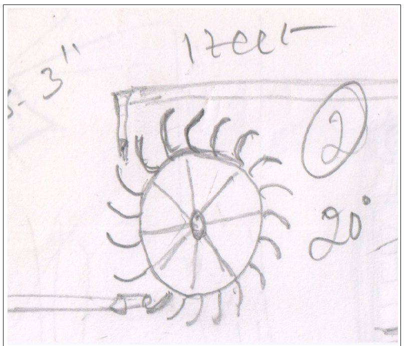

Fig. 16: Turbine 1

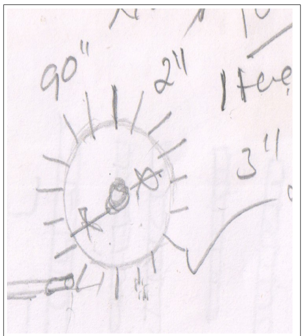

Fig. 17: Turbine 2

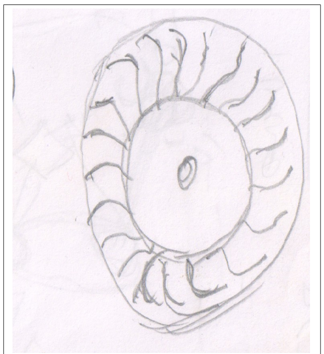
Fig. 18: Turbine 3

Trying out various positions of the pipe to hit the turbine with a water jet, he finally settled on a pipeline at the bottom, and the jet hit the turbine's bottom plates/blades. He also tried out different shapes and angles for the blades. In order to find out the best possible angle for the blade along the runner, he fabricated multiple turbine wheels, each with a different blade angle, and by installing them at a site, checked their relative performance in terms of RPM and voltage.

According to him, a standard Pelton design is good for high head, but for low head it is not. It needs a minimum 60 to 100 feet of head. But his turbine design, (though more like a Pelton turbine), performs well even in low head situations. If a cross flow turbine and GRI's turbine are compared in the same site conditions, he says his turbine will be as good, and could even be better by up to 30%.

5.3.1.3 Episode 3 - AC power

Background

There was more power, but in terms of usability, it was limited. On the one hand, DC power had its constraints in terms of charging time of the DC storage battery. On the other hand, GRI could only light bulbs. But he also wanted to run other household gadgets on the power that was available. For these, the DC power needed to be converted to AC, and that would have involved additional investment and maintenance.

Solution

In order to address this design issue, GRI came up with the idea of replacing the DC dynamo with an AC alternator. (Fig. 19).

> *"After that I continue some mechanical improvements, and direct I will... why just not try for some .. thinking.. I'll take a small AC alternator and directly rotate it."*

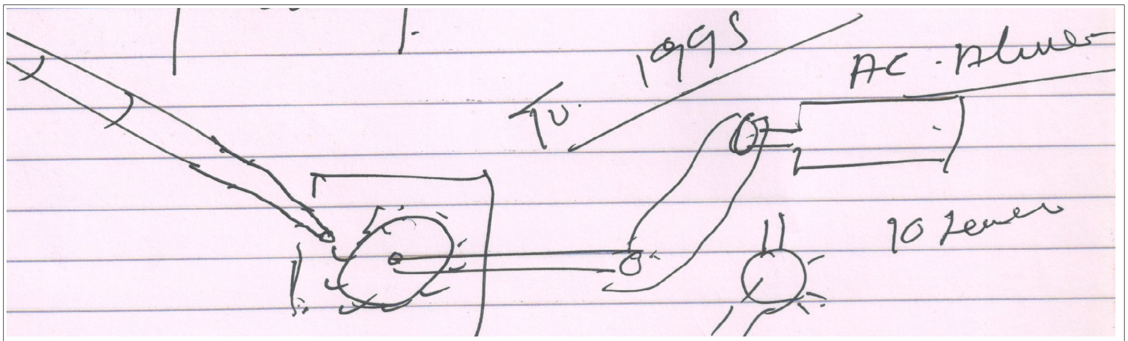

Fig. 19: AC alternator

5.3.1.4 Episode 4 - Grid quality power

Background

As long as he was lighting bulbs on AC power, the system worked fine. But when he had a TV or a blender running, switching the gadgets on or off seemed to create a problem. The voltage dropped, even though there was no change in the water source that was driving the system. GRI found that the electric load variation significantly affected his output voltage. He needed to ensure that changes in the electric load did not damage the gadgets or the hydro power system.

Solution

GRI tried three different solutions over a period of time to resolve this problem: a booster (transformer), an AVR, and a flywheel.

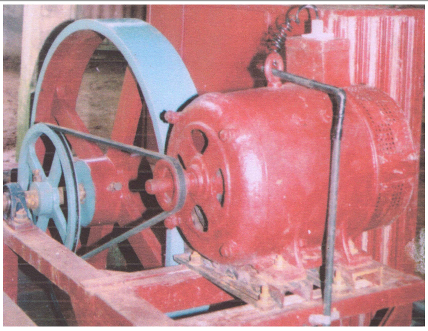

Fig. 20: Flywheel – managing rpm to control load variation

Since he did not know where to start, he asked an electrician. It was suggested that he could try the 'boosting method' i.e. he could use a transformer to boost the voltage. But he found that when the load dropped, the boosted voltage caused the bulbs to blow up. GRI then found out about automatic voltage regulators (AVRs). He invested a lot of money to get AVRs designed, and installed at some sites. But he concluded that a digital AVR led to a loss of power, and was not as effective as he wanted, in spite of the high cost. He decided to move on from transformers and AVRs, and opted for a mechanical solution – the flywheels used in various machines, to control the runaway speeds of wheels. (See Fig. 20).

> *"When you will remove the balance wheel, it will be completely … rpm is completely… unbalanced. If imbalanced.. 1000-1400 or 900. Anyhow. When you will put flywheel, it is continuous definitely completely speed maintain." "The voltage is completely regulated. It is not blinking.. "*

GRI started a business once this design settled, but continued to improve it, as he worked for diverse customers, situations, and needs, including communities in reserve forests, telecom towers, and temples. (See Appendix 1).

5.3.2 Summary of observations across GRI’s design episodes

1. The technical composition of GRI's system changes from simple to complex. The number of components increases, and in each iteration, the system becomes complete in terms of addressing all technical aspects.

    i. *Episode 1:* stream water diverted through a pipe > cups attached to a bicycle rim > bicycle dynamo (shaft) > wires > bulb

    ii. *Episode 2:* stream water diverted through a pipe > some kind of spokes-cups wheel > pipe as shaft > connector > DC dynamo > DC storage battery > domestic light bulbs run on DC power

    iii. *Episode 3:* stream water diverted through a pipe > improved cups wheel > wheel shaft > connector > AC alternator > power supply cable > domestic light bulbs, TV, fridge, mixer run on AC power

    iv. *Episode 4:* stream water diverted through a pipe > a Pelton-like turbine > wheel shaft (with bearings) > a belt pulley > a flywheel > a belt pulley (with bearings) > AC alternator > power supply cable > grid-quality AC power (to run domestic gadgets, irrigation pumps, streetlights), and also mechanical power

2. As the design goal expands and gets technically more complex, the previous solution space acts as a prototype for the new problem space. But the new solution changes this solution space completely, by eliminating certain components and the concepts they embody, from the design space. Dynamo changes into an alternator, DC changes to AC, AVR changes to a flywheel.

3. GRI directly works and thinks with the components, and then the prototypes, rarely making any drawings, measurements, or calculation-based decisions for fine-tuning the design specifications.

4. GRI's understanding of power, and various components, starts with the socio-environmental needs and moves to the technical. He primarily understands power through its functional role in running various gadgets, and thus has a qualitative understanding of the characteristics of power, apart from a quantitative one. His conceptual understanding of the components is experience-based, and conceptually at a black box/performance/behavior level. In this respect – designing without a theoretical understanding – GRI is not an exception. The historical development of batteries and induction coils also demonstrates that these were designed before Maxwell offered a theoretical understanding of electromagnetism.[222] Similarly, many flying systems (balloons, gliders, Zeppelins) were designed before a formal theory of aerodynamics was articulated.

5.4 EP’s case study

In this section, I describe the primary case of EP’s non-formal technology design practice, to address power generation problem at the grassroots. I describe in detail the data related to his early design process and considerations.

222 Wikipedia contributors. (2018, November 27). Michael Faraday discovered the principle of induction, Faraday's induction law, in 1831 and did the first experiments with induction between coils of wire. The induction coil was invented by the American physician Charles Grafton Page in 1836 and independently by Irish scientist and Catholic priest Nicholas Callan in the same year at the St. Patrick's College, Maynooth, and improved by William Sturgeon. (See Wikipedia - Induction coil). James Clerk Maxwell, who in 1861-2 used Faraday's ideas as the basis of his quantitative electromagnetic theory. (See Wikipedia - Faraday’s law of induction).

5.4.1 EP's design episodes

The historical trajectory of EP's designs, developed over an initial period of at least five years, offer certain landmark stages or distinct episodes of design prototypes. I present these as key transition episodes culminating in his final working design.

1. Modified water mill
2. Pelton turbine and digital load controller
3. Cross flow turbine
4. Electrical and mechanical power

5.4.1.1 Episode 1 - Low cost power - Modified water mill

Background

EP was asked by a professor whether he could develop a power system for a research lab in a non-electrified, high-altitude region of a protected National Park in the Himalayas. The professor's team was working on high-altitude plants, and the material they collected got spoiled due to germination by the time they got back to their labs in the city. To avoid this, they wanted to set up a lab and conduct experiments at the location where they were collecting the samples. The research project had not anticipated the need for continuous power when budgeting. Thinking that building a power system would be an 'adventure', EP took up the challenge.


Fig. 21: Wooden wheel of a typical traditional water mill

Solution

There was a small rivulet flowing near the lab tent, formed by water from seasonal rains, as well as from snow-melt during the summer. The region had traditional water mills installed on such perennial streams, mainly to grind grain into flour. (See Fig. 21).[223] EP took a crude measure of the rotations per minute (RPM) available, and rather than connecting an alternator to check if it would be sufficient to generate power, he estimated.

> *".. one day I just sat down there, and I noticed the top stone. Then after putting the mark on that, let me see in one minute how many regulations it is…making. So we assessed, not very accurately because it also runs very fast, so that moving eyes is also very [na]. So that was about 250 RPM. So I said we are getting 250 RPM, but if we reduce the turbine size, that will run faster. So reduce the turbine time umm little bit, and if you are getting the gear ratio good on top, then you'll be able to take it to 3000 RPM, very.. [na]. So this is how it was done."*

EP decided to modify and improve this wheel design and build a micro hydro power system for the research lab. He replaced the straight wooden blades of the turbine wheel with curved ones. This modification sufficiently improved the rpm. Using car spare parts such as bearings and axle, EP made some small changes to the turbine, and also made it portable. He added a big starter gear and a smaller gear to increase the shaft's RPM by ten to twelve times, from 300 to about 3000. This was coupled to a vehicle alternator that charged a DC battery. Thus water falling from the chute rotated the turbine and the alternator shaft coupled to it, generating about 700 Watt DC power. This system was successfully used to light up the lab tents, and to power electrical instruments, and a small incubator. This design eventually led to EP's involvement in more micro hydro power generation projects at the grassroots.

> *"So, after this we jumped on to another thing.. .. how do we run a small power station in a village?"*

223 Image credit Ananda K. Shrestha, 2006.

5.4.1.2 Episode 2 - Seasonal variation - Pelton turbine and a digital control system

Background

This site was twin tribal villages, in a remote area in the middle of a reserve forest that was home to wild animals. Grid-based power supply did not reach the 67 households, of about 380 people. In 2005, an NGO working with the marginalized communities in the region since 1979 envisioned a micro hydro power project to solve the power problem of the twin villages. The NGO aimed not only to provide electricity, but to ensure inclusion, social and gender equity, and sustainability, in the process. The project was to be implemented with community participation and to be handed over to the community. EP was engaged as a consultant for this project. The source water flow - a waterfall nearby - would vary throughout the year, but it offered a good head.

Solution

A Pelton-type turbine was fabricated by EP in his own city. It was a sophisticated design and the process of fabricating it was complex and meticulous. (See Fig. 22).

> *"100M fall is a very good fall actually. … And we had a very nice Pelton wheel, very nice one. And which could run with very small amounts of water."*

Fig. 22: A sophisticated Pelton turbine

In order to cope with the seasonal variation in the input flow, EP provided two alternators, generating 10 kW for low flow and 25kW for high flow. To manage the variation in electric load, EP designed a Digital Load Controller (DLC), and each house was fitted with a variable load controller with manual reset. A report of the project by the NGO states that the technology was sound, and the power station started providing electricity. But "The timeline did not allow enough emphasis on developing the community's stakes."[224]

5.4.1.3 Episode 3 - Local, easy maintenance - Cross flow turbine

Background

Even in a typical remote mountain village, high water head may not always be available. For low head situations, if the discharge is also low or seasonally variable, then the jet diameter needs to be large. As a result, the runner diameter needs to be large, and a Pelton turbine becomes too big. Alternately, there need to be multiple jets. Also, both the Pelton turbine and the digital load controller are expensive, complicated to manufacture, and difficult to maintain. Repair services are not locally available.

> *"So if you use these kind of technologies [not audible] more and more complicated. And the capability in rural area is not you know such that you are able to take care of complicated technologies. .. And similarly control systems are again all electronics based control systems. Something goes wrong in control system, you are in trouble, you have to go down [to the plains]."*

Solution

When good flow of water was available throughout the year, EP designed cross flow turbines that work well at low heads. A cross flow (Banki or Ossberger) turbine is simpler to design, fabricate, and maintain. (See Fig. 23). EP kept his design simple and low cost.

Fig. 23: A cross flow turbine for low head but good water discharge sites

> *"... we should make equipment in such a way that can be opened easily. So there had to be some change in it. Every time we used to think which part umm, you know, is difficult to remove, and simplify it actually... "*

> *"If you make it very sophisticated.. the micro one, and add many things to it,*

224 Vaghela, "Powering Dignity," 2006.

then it becomes expensive, otherwise it's not expensive." "It's a misconception that micro power stations are very expensive. This is a lobby that is afraid of the micro-hydro producers."

5.4.1.4 Episode 4 - Electrical and mechanical power

Background

The renewable energy ministry, along with international funding agencies, implemented a power supply project in remote villages around 2006-9. It aimed to demonstrate how renewable sources of energy can reduce poverty through improved quality of life and increased livelihood opportunities in remote, non-electrified villages that are not likely to get electricity from the grid.[225]

EP's NGO was an implementation partner for the project in a remote mountain district, based on their track record in micro hydel and in community based, innovative, low cost engineering solutions in difficult locations.[226]

Solution

Fig. 24: Livelihoods supported using electric and mechanical power from hydropower

EP's design had two turbines running side by side: one turbine for electricity generation and another turbine for motive power application, when no electricity was required. He involved local labor and trained some to be grassroots engineers for the fabrication, construction, and maintenance activities.

225 Mehta, Mohapatra, Ali, & Mukherjee, "Renewable Energy for Rural Livelihoods in MNRE-UNDP-FRG Project Villages in Rajasthan and Uttarakhand: A Report," 2009.
226 Mehta, Mohapatra, Ali, & Mukherjee, "Renewable Energy for Rural Livelihoods in MNRE-UNDP-FRG Project Villages in Rajasthan and Uttarakhand: A Report," 2009.

Further, EP designed scaled-down machinery for livelihood generation, drudgery reduction, and income earning, based on local natural resources, through wool washing, wool carding, spinning, oil milling, flour milling, and rice threshing. (See Fig. 24).

> *“... after doing the (village name) project it was a very big realization that unless people are making money out of that, you can never run this power station. But if they are able to make money out of it, it is the best scheme actually”.*

Based on this experience, EP's projects are now conceived on the model of energy for livelihood generation. According to EP,

> *“Now if a village comes to me for a micro power station, I insist for a livelihood component if they want me to accept the project ... if you provide technology that gives you returns, so people will also be able to give you some, you know, good returns that way. So we never used to think like that earlier. It was just electricity.”*

> *“The toughest part is community, and the livelihoods actually .. it is the toughest part in this.”*

> *“.. if you’re able to generate electricity in a god-forsaken place, it’s a great thing. If you are able to provide electricity to ten households, it’s a great thing. If you are able to provide electricity to one village, it’s a great thing. If you are able to provide livelihoods to the people with electricity, it’s the greatest thing.. that you can do. If you can make people just self-sufficient by this, it’s the best thing that you can do. <> So there have been steps like this.”*

5.4.2 Summary of observations across EP’s design episodes

This historical analysis of some of the key transitions in EP's design process indicates an increasingly explicit understanding of social factors, the connection between society and technology, and an explicit incorporation of these into the design process.

The following salient points emerge from this case study:

1. EP's design process indicates a progressive transition from purely technical design goals to the inclusion of non-technical or socio-environmental requirements. The composition of EP's solution accordingly changes, from merely technical to socio-technical.

    i. *Episode 1:* stream water diverted through a chute > modified traditional water mill > car alternator > DC storage battery > lab instruments

    ii. *Episode 2:* waterfall water diverted > Pelton turbine > gear box > two AC alternators > household gadgets

    iii. *Episode 3:* waterfall/stream water diverted > Cross flow turbine > pulley-belt > AC alternator > household gadgets

    iv. *Episode 4:* waterfall/stream water diverted > turbine > pulley-belt > AC alternator and mechanical drive > electrical gadgets and mechanical devices/machines for income generation

2. As EP's design goal expands and becomes socio-technically more complex, the previous solution space acts as a prototype for the new problem space. But the new solution changes this solution space completely, by eliminating certain components and the concepts they embody, from the design space. Pulleys and belts are preferred over gear boxes, and power generation is diversified into electrical and mechanical.

3. In the case of such grassroots needs, the problem definition or understanding the requirements is very complex, especially for a designer external to the context, as the needs are not always explicitly stated or directly technical. The material and social structures interact in complex ways with the technical. The needs and constraints gradually emerge through this process.

4. EP's conceptual understanding of the components as well as electric power is initially purely formal, theoretical, and quantitative. But this understanding expands into an experience-based appreciation of the qualitative nature/characteristics of power, in terms of its specific applications for grassroots people. This shift towards a qualitative understanding with expertise is counterintuitive, in terms of standard narratives where expertise is equated with formal knowledge.

5. EP's MHP system design evolves from being technically sophisticated and highly efficient, to being socio-technically relevant and effective for the community. EP's design incorporates, from the very beginning, all the components necessary for the technical functions to be performed. But the components are progressively replaced or modified, in terms of technical complexity, to suit the socio-technical functions. For this reason, the system now becomes really complete for him only after adding the components to provide mechanical drive along with electrical power.

Chapter 6: Characterization of grassroots design practice

The socio-technical connection is plastic; sustainable technology aims at empowering people and sustaining their local livelihoods

“There are those who choose the swampy lowlands. They deliberately involve themselves in messy but crucially important problems and, when asked to describe their methods of inquiry, they speak of experience, trial and error, intuition, and muddling through”.[227]

In this chapter
A thematic analysis of the core cases – non-formal and formal practice while designing MHP systems – provided insights into the process and principles of designing for sustainability. Additional cases were selected for a comparison with the core cases, to explore if other grassroots cases demonstrate similar characteristics, and whether the other cases could add to the understanding of alternate practice. A comparison with the canonical design process was done to identify generic findings that cut across the empirical cases.
The characterization of the practice of grassroots technology design showed that such design worked by reconfiguring the socio-technical connection, which was found to be very plastic and capable of generating multiple novel designs, but only when the designer started from problem formulation. Further, technology developed for grassroots was found to be aimed at empowering people and sustaining local livelihoods, which is a socio-technical design principle that is wider than the standard model of technology lowering drudgery/cost.

Introduction

The analysis of multiple case studies started with the primary cases of practice (GRI and EP). For each of these cases, key design episodes were identified from raw data, and the features of transitions from one episode to the next were captured. The design considerations during each episode, and between the transitions, were also identified. Based on this episode level data, a description of the design practice was constructed.

These narratives were then analyzed and interpreted, to characterize the grassroots technology design practice (using the Practice lens) (Section 6.1). For this, first the

227 Schon, *The Reflective Practitioner: How professionals think in action*, 1983, p 43.

characterizations developed (case studies) were widened using secondary/additional cases (DWT and AM) (Section 6.2). Secondly, the findings from these cases were compared to the canonical design process (the linear model) and principles learned in engineering classrooms (Section 6.3). Based on this analysis, a general model of the design process was developed. (Section 6.4). The generic findings are then discussed (Section 6.5).

6.1 Characterization of grassroots design practice

6.1.1 GRI's design process and design considerations

> *"What you need to know about the problem only becomes apparent as you're trying to solve it".*[228]

a) GRI's technology design is socio-ecologically sustainable

Being the user himself, GRI was embedded in the grassroots socio-economic and behavioral constraints for the design - in terms of ease of use, time of use, maintenance, cost, and return on investment. Implicitly, these considerations became an integral part of the problem-framing in his early design process. He did not need to add these on as an after-thought. Since he did not externalize the socio-economic, behavioral, and environmental aspects, he designed for a solution not merely focused on input-output efficiency. His focus was not to generate the maximum possible power, at the highest efficiency. His aim was to meet the needs and conveniences of the user (despite a lower efficiency of power generation if necessary), while balancing the socio-economic and environmental considerations.

By generating low cost grid-quality electrical power to run various gadgets, as well as mechanical power to run machines, and helping the poor to support their livelihoods

228 British architect Richard MacCormac, cf Cross, *Design thinking: Understanding how designers think and work*, 2011, p 14.

through micro power, GRI enabled more equitable income generation and wealth distribution in society. Further, he found a niche market in protected areas where grid-based power is needed but polluting technologies of power generation are strictly banned. He ensured that his designs were least damaging to the environment, and provided clean power in an ecologically sustainable manner. He also recommended ways of saving power and reducing consumption by using options such as LEDs. He was then able to extend his customer base to include geographically distributed telecom towers, as his green solution was approved to supply power to towers even in environmentally protected areas.

> *"Completely eco-friendly.. <> No noise. And no pollution. And you will not destroy any greenery, you will not.. any take about one single tree.. you will not cut it. Same as it is same situation, it is implemented. Same. Take the water.. natural.. and again it is going to regular stream. You will not break up.. check dam.. any nothing. Or any submerge.. nothing. Check dam.. or big, big dam.. nothing. Very simply, we will put the pipeline.. <> .. not any disturbance to nature."*

Recently he also completed the design and installation of an MHP system to run on and generate power from sewage water.

b) GRI's need identification is socio-ecological

GRI's design process started with the most urgent and primary need of household lighting. His design goals then progressively expanded to encompass other social needs such as a TV, a blender, and so on. His design process was triggered by the identification of a need, and consequently, it set his design goal in 'use' terms such as powering a TV, rather than in technical terms such as AC power. Socio-environmental needs, rather than abstract technical specifications, were thus the explicit drivers of his design process right from the beginning, and throughout. And he did not have to invest separate efforts to understand the needs in all their complexity.

Furthermore, he thought of the **design goal in terms of the 'need', not reducing it to a generic quantity and quality**. This possibly helped in making the design goal specific, relevant, and whole, rather than abstract, broad, and incomplete. Because it was not sanitized of the context, the complexity of the design goal could be addressed without making it simplistic.

Since he started with minimal/basic requirements, and expanded step-by-step, he developed a large repertoire of diverse solutions for a range of requirements (from household bulbs to multiple high amperage gadgets). This allowed him to design competently later on, for other users/customers, juggling diverse needs, sources of water, and available resources. For example, where it was not possible to generate more power, he knew that lights and TV were the primary requirements, and could at least provide power for these. If the head was sufficient, he knew that low load could be managed without load variation control, and so he did not invest in a flywheel and kept the cost of this MHP system minimum thus making the power available and affordable. This flexibility of problem-solution was available to him because he had developed his knowledge in close correspondence with the needs.

c) GRI's problem formulation indicates an expanding spiral of problem-scoping

Across GRI's design episodes, the problem space expanded from a primary need (of lighting bulbs), to encompass a wider ambit of requirements. Within every episode, a satisficing complete solution was developed for the need. This in turn initiated a process to address a broader need. In this spiraling model (Fig. 25) of expanding the problem space (where the problem is extremely ill-structured for the level of available knowledge), **identifying the primary need comprehensively and then widening the scope of need to**

be addressed, emerge as key approaches to problem-scoping, in designing an innovative solution. (It also hints that ill-structured-ness of problems is in some way also a function of/related to the level of knowledge.)

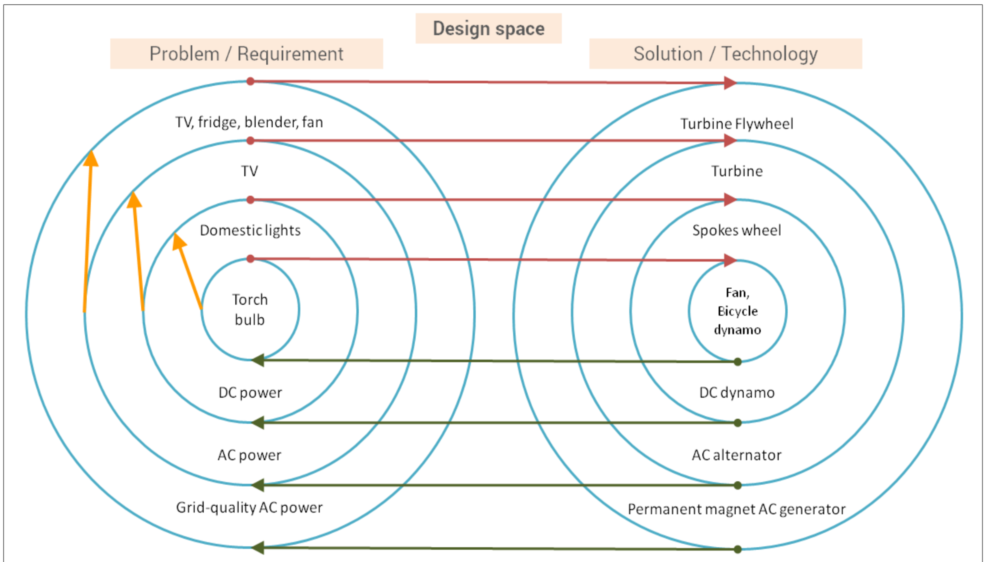

Fig. 25: Expanding spiral model of GRI's socio-technical design process

Progressively, and iteratively, the design process addressed bigger/advanced socio-cultural, economic, and technical goals - of making the power available as and when required, making AC power available for domestic gadgets, and finally, making grid-quality power (constant voltage, high amperage) available. The technical complexity of the design correspondingly increased or reduced in response to the need definition and problem formulation.

Methods of problem scoping, particularly in the context of grassroots problems, are not discussed or researched in the design process model and studies. Probably a formally-trained designer, who would have the knowledge or access to information, would directly design for grid quality power in required units of Watts. Such a designer would not go through this kind of spiral process of problem scoping. The downside is that this designer would not know what GRI knows, in terms of different levels of technology and technical complexity possible and sufficient to address diverse kinds of grassroots requirements (discussed in the previous point).

d) GRI's design is simple

GRI's system progressed from simple to complex in terms of technology. The conceptual complexity of components as well as the number increased up to a point. Beyond this point, more sophistication was possible. GR was aware of various such technical alternatives. But after exploring such options, and their pros and cons, he preferred to keep the system simple and manageable at the level appropriate for his customer base and their context.

GRI's design decisions, based on his interview and simulation data, indicate that he designed for ease of manufacturing, transport, installation, and maintenance with respect to the customer sites and context. GRI's interaction with the exploration screen in the simulation tool indicates that he preferred pulley over the gear system. His choice of pulley confirms ease of maintenance for local people as an important design principle for him, in the context of the remote sites where he installs MHP systems. With respect to load variation control, GRI's strategy was to divert power to street lights, instead of using heating coils as dummy load. He explained that heating coils were not convenient as the villagers did not know how they worked.

> *“.. when you use a heating coil, it is very sensitive. In the villages, it is .. [to] know about this what is the action or cost.. not known. Give more water is very easy.. any uneducated man also can do it.” “I will say suggestion.. street lights. That's a easy solution.”*

GRI designs with simple components, such that many spares are locally available. This enables his customers to conduct minor maintenance and repair works by themselves, thus saving time and cost.

e) GRI's innovation is for solving problems of the society and to create jobs

Having designed and built with minimal resources, GRI's knows how to keep the costs low. This allows him to design MHP systems for even the lowest strata of the society. His business model also offers tremendous flexibility in terms of pooling financial resources from the customer, the government, or various philanthropic bodies, as well as allowing the customers to pick up some costs through contributing local knowledge and labor. For example, in community MHP projects, he leaves the civil construction to the community, and they get paid for that work. Being closely aware of the plights of the poor, he also takes pride, not only in his low-cost innovative design, but also in his industry based on it, where he offers employment to more people. GRI emphasizes that rather than innovating merely for commercial gains, one should solve one's problem, and share the solution with the society. Further, one should also try to create jobs for others, as he did.

> *“And you will enjoy your life, your innovation, and you will supported another peoples to .. by job.. or you can make a small industry.. <> at least minimum five to ten people give them job to.. [na].”*

He also understood the need for power as a need to reduce drudgery, and to run machines that enabled this. Since mechanical power could address such needs, he used water to generate mechanical power to run machines directly, instead of generating electrical power to do so. For example, he built house-hold flour mills running on Pelton-like turbines. He also built water wheels that provide strong mechanical drive, say for coffee pulping, in places where he could not generate sufficient RPM to generate electricity. In a sense, this is a better approach to energy conservation, as he avoids the losses in conversion from electrical to mechanical power.

6.1.2 EP's design process and design considerations

> *"... the design brief is not a specification for a solution, but the starting point for an exploration."*[229]

Though EP came to the problem of MHP system design with formal engineering training, his very first case exposed him to various real-world constraints as well as opportunities arising from the socio-economic context. Nevertheless, his focus remained technical, until later projects exposed him to many non-technical parameters of the problem situation. This led him to explicitly incorporate these parameters in his task specification, and to design for a network of multiple factors rather than input-output efficiency. His design space widened beyond the mere techno-scientific, and his experiments with the plasticity (flexibility/versatility) of the socio-technical connection gave rise to an alternate model of designing technology for society.

a) EP's technology design is sustainable

Although the building of large dams has been justified for efficient generation of mega power through centralized water source, EP is a strong proponent of the micro hydro turbine as an ideal renewable source of energy at least for the mountain areas. As his design demonstrates, MHP is economically, socially, as well as environmentally the most sustainable solution, and there is no need to design a centralized, large-scale (mega power) system in order to achieve economic feasibility. An MHP system incurs far fewer environmental costs than a mega power dam. It induces minimum disturbance to the natural ecosystem of a water

229 Cross, *Design thinking: Understanding how designers think and work*, 2011, p 14.

source, as the required water is diverted and merged back into the source flow, without blocking the main stream with dam walls. The natural niche habitats and life cycles in the water stream are thus conserved. Social costs of displacing villages, which would be submerged in the case of mega dams, are also not incurred.

Further, the economic viability of micro hydro systems can be ensured using simplicity of design and by including income generation components. Maintenance is better managed through local interest and training.

> *“If you make it very sophisticated.. the micro one, and add many things to it, then it becomes expensive, otherwise it's not expensive.” “It's a misconception that micro power stations are very expensive. This is a lobby that is afraid of the micro-hydro producers.”*

The production and distribution of power in EP’s design remains local and decentralized. This not only avoids major distribution losses incurred by long-distance grid-based transmission, but also empowers people to locally control and maintain the system. For example, they have the option to divert water to generate a mechanical drive when electricity is not required, or to prioritize water for irrigation if necessary.

Furthermore, the technical specifications of the system can be designed to cater to specific needs of the locale, the quality and quantity of power to be generated being decided based on its intended specific applications. EP’s design approach allows designing of systems based on diverse applications such as grinding mills, lighting, car-washing compressor, wool-processing machine, or restaurant ovens. This allows for cottage-level opportunities of income generation for people where they are based, and more equitable wealth distribution than from big, centralized industries based on mega power.

b) EP's need identification and problem formulation is socio-technical and complex

In the initial projects, EP was primarily focused on the technical aspects of providing electricity, but was not involved in the community aspects.

> *"We thought that village Pradhan, or head of the village, is taking care of all this. Actually it was not getting into our thinking process.. that it is very important to have the community with us."*

Even while working with NGOs that had a mandate of ensuring inclusion, social and gender equity, and sustainability, as well as of implementing the project with community participation, the technical was prioritized.

> "The corpus was not collected because initially the project needed to be technology driven in order to meet donor timelines. The timeline did not allow enough emphasis on developing the community's stakes. … No corpus or tariff was collected, leading to the community not valuing the system and no fund for future repairs and maintenance.*"*[230]

Over several such projects, EP realized that villagers would be invested in the MHP system and its upkeep only when they had serious stakes in its running, beyond the understanding of it as a system that just lights up their households. He understood the need for power to be part of a much larger and graver need for opportunities to earn an income, to have a livelihood. EP's recent projects are thus conceived on the model of the electro-mechanical livelihood project. These multi-purpose systems are designed to create opportunities of generating income and distributing wealth more evenly into the remote corners. According to EP,

> *"Now if a village comes to me for a micro power station I insist for a livelihood component if they want me to accept the project ... So we never used to think like that earlier. It was just electricity." "The toughest part is community, and the livelihoods actually .. it is the toughest part in this."*

230 Vaghela, "Powering Dignity," 2006.

As EP's simulation interaction indicates, his idea of power consumption/utilization is now much broader that lighting bulbs in households, or running a few gadgets. He designs his systems, keeping in mind power need to support income generation.

> *"Electricity has to be.. this part is.. to give employment to people.. because homes in the villages are also factories, they do some work actually, they do some work, and they also need cheap power and all that for their work. Hum wo nahi sochte hai, hum ye sochte hai ki ek bulb jal raha hai na toh uus ski sari jarurate puri ho jayegi, ye galat hai, you are just achieved 10 percent of your objective not [na] objective."*

EP is pained to see that solutions are designed and funded without taking into consideration the real needs of marginalized people. He questions the sense in generating power only to upload it to the grid for the cities, when, as his model demonstrates, so many income generating activities can be supported with the power in the remote rural households.

> *"How can anybody come and install a micro hydro without knowing the local needs? Then, we have to ask for so much of money, you set up a micro hydro and put electricity in the grid, I said, "how does it help people?" <> Dekhiye maine aap ko bataya.. the business model, you see how much people earn out of that. Once you have seen that, would you like.. still like to put it in grid? <> .. you saw Rampur, 10 ghante nahi chalate hai wo log, 10 ghante phir grid me daal do aap usko. Baki time to aap kaam kar sakte hai na uss se."*

Starting with the need, context, and bringing the society-technology connection into the design process, expanded EP's design space. This enabled him to design the most suitable and sustainable technology solutions.

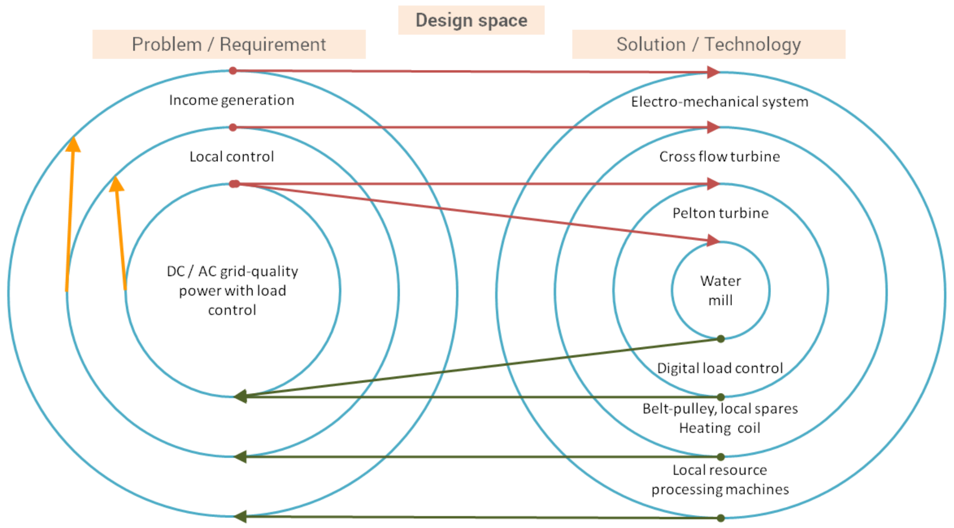

Fig. 26: EP's evolving socio-technical design process

For EP, for the power problem, a complete solution is developed in the solution space (See Fig. 26, red arrows). The technology acts as a prototype to address the requirements (green arrows) at the next level (yellow arrows). As the understanding of power requirement goes from technical to socio-technical (expanding circles in the problem space), the complex technology is simplified (expanding circles in the solution space). The design space expands spirally, and socio-technically sustainable solutions emerge.

Such a model could evolve because EP stepped outside the traditional role of an engineer, and learned methods such as Participatory Rural Appraisal (PRA), from disciplines such as Development Studies, to better understand the communities and their real needs. He learned to work with lay people, acknowledging their traditional knowledge and abilities, and training them in modern techniques and technologies. He took the steps necessary to understand someone else's problem in depth, in order to really solve the problem and not just to build a technology. In doing so, he demonstrated how a person external to a community can engage with it to identify needs and formulate the problem in all its complexity.

c) EP's design is simple

EP fabricated the Pelton turbine in his city, and the community had no experience of handling issues related to it. The project report documents[231] that although it was planned that the project would be handed over to the community for maintenance, this created several glitches. In later projects, the NGO emphasized training local people to fabricate the turbines locally. Further, EP had developed and used a Digital Load Controller (DLC). Digital technology often needs a trained and equipped person for its maintenance, troubleshooting, or repairs, and this may be expensive or not readily available locally.

Such experiences eventually led EP to reconsider his choice of components and he modified his power system design for subsequent projects, from the point of view of ease of fabrication, installation, and maintenance, in the context of the users and conditions in the remote villages.

> *".. we should make equipment in such a way that can be opened easily. So there had to be some change in it. Every time we used to think which part umm, you know, is difficult to remove, and simplify it actually."*

> *".. if you start using belts and umm gear boxes, then there's lot of wear and tear with belts and gear boxes. And remote areas the gear boxes.. something happens to the gear boxes, the replacements are very difficult. <> Umm you can avoid lot of gadgets, unnecessary gadgets in it, you can avoid umm, you can simplify the shapes, sometimes shape is also important. You make it easy for carriage for instance. Alright? Light weight. This kind of criteria we follow for simplicity."*

Another concern he highlights in this context is the spare parts. He gives the example of simple nuts and bolts. The car industry has switched to the metric measurement system in manufacturing and labeling these components. But according to EP, in the remote areas, the British system is still in use.

> *"So normally if you go and buy nut bolts, you will say half inch nut bolt.. isn't it? <> If you buy in metric, you will say 1 cm nut bolt. This is the difference and their threads are also different. They will not match. <> Toh goun me kya milega… goun ke aas pass kya*

231 Vaghela, "Powering Dignity," 2006.

> *milta hai? <> Kya milega? Something which is old system. Aap ko British thread milenge. Aap ko wo milega hi nahi metric thread. Metric thread ke liye car wale ke pas jaoge but he will have only those shapes which are used in cars, not in umm, you know..<> So, you design your system using British threads. It's easier. Isn't it? You can get a replacement."*

In stressing the simplicity, EP is aware that more complex options are available, and they have been developed because they offer certain advantages and benefits. In mainstream design, efficiency would be one such highly valued advantage. But efficiency would be of value only if the system was running in the first place. In remote locations, EP explains that a complex design may bring the system to a stand still, for months, if the repairs are not feasible for various reasons.

> *"And distances are not small. Aap ne ek choti galati kar di.. your machine is down for may be for months together. Sometimes he may not have money to even call the fellow to repair it. Samjhe na aap? Toh jitna aap complicate chije avoid kar sakte hai utna jyada accha hai. Utni simple kariye."*

Considering such circumstances, the overall or average 'efficiency' of a complex system would be very low in the long run, while that of a simple system would be better. EP works with this wider notion of efficiency that takes into consideration factors beyond the technical, that affect the performance of the system, not only when it converts the input to output, but also when it requires maintenance and repairs. For these reasons, conventional 'efficiency' is secondary to 'simple' design, as per EP's guiding principles for a good design.

> "See, according to my definition of good design, number one, simplicity, number two, good efficiency, number three, easy to assemble, number four, easy to dismantle. Opening up. Alright? Simplicity means don't use too many complicated things, you know, unnecessarily you will complicate the systems."

According to Gary Downey[232], students taught to solve problems in idealized conditions would lack the skills to do such 'wide' design. In proposing an alternate image of engineering as Problem Definition and Solution (PDS) Downey also recommends practices

232 Downey, "PDS: Engineering as Problem Definition and Solution," 2015.

of “early involvement in problem definition, collaboration with those who define problems differently, assessing alternative implications for stakeholders, and leadership through technical mediation”. According to him,

> *“The key point here is that engineers trained to integrate problem definition into mathematical problem solving would involve themselves early in processes of problem solving, prior to the point at which a clear design problem emerges or can be claimed”.*[233]

d) EP's idea of optimality has evolved for an alternate socio-technical connection

One possible perspective on this case is that EP is 'customizing' a core engineering solution, which optimizes input-output performance. However, this view is based on treating input-output optimality as normative. The key point about EP's design process is that his notion of optimality evolves to include social and environmental factors. This shift goes beyond customization, as it rejects the optimality assumed by the input-output efficiency model.

For example, in EP's third design episode, he designed a Cross flow turbine for a low head - high discharge site. With this, he ensured ease of maintenance and long term sustenance of the system in the remote location. Formal turbine performance charts could have indicated sophisticated Francis or Kaplan turbines as alternatives for such situations. A comparison with these indicates that a Cross flow turbine has relatively lower input-output efficiency. Despite knowing this, EP preferred Cross flow, because he imagined the system as embedded in a socio-technical context, where a broader or wider notion of efficiency was called for, than that dictated by the formal idea of purely techno-economic efficiency. Further,

233 Downey, “PDS: Engineering as Problem Definition and Solution,” 2015, p 446.

his experience now allows him to devise modification to the Cross flow turbine that promise to improve its technical efficiency.

6.1.3 Insights from grassroots technology design practice

Together, the analysis of empirical data of GR and EP's practice of grassroots technology design indicates that their design process is non-linear and complex.

6.1.3.1 Grassroots technology design process

The following insights are drawn specific to technology design process.

1. Each episode is a complete solution, but the design space expands spirally.
2. Requirements expand from simple/technical to include complex and social.
3. Simple and uncomplicated solutions are developed for advanced technical problems.
4. Previous solution space acts as a prototype for the new problem space, and expands to include the context.
5. Heuristics, thumb rules, trial & error play a large role, even as theory is known (EP).

6.1.3.2 Grassroots technology design principles

The following insights are drawn specific to technology design principles.

1. Minimal damage to biosphere.
2. Decentralization drives availability, access, equity, and sustainability.
3. Local self-sufficiency and income generation is valued.
4. Powering ‘a gadget’ or ‘a livelihood activity’ is the functionality.
5. ‘Simplicity’ is the rule while addressing eco-social, techno-material concerns.

6. ‘No failure/flicker’ is the performance criterion, rather than efficiency/optimization.

7. Control of consumers over the production enables conservation of resources and judicious utilization as per their own diverse needs, within the local limits on the resources.

6.1.4 Exploring the limitations of this characterization

The analysis shows that need identification and problem formulation (scoping and framing)/definition are critical aspects of the design process, leading to task clarification or design goal setting. Although power (electricity) is a known need, the approach to arrive at the problem formulation significantly impacts the solution, especially its overall sustainability. Unfortunately, need identification and problem formulation approaches, methods, or techniques remain largely neglected in design process discussions and education, despite scholars having pointed out their importance in other contexts/cases.[234] This further raises the question as to what approaches, methods, or techniques help in need identification and problem formulation, can these be taught, and can a more generic understanding of their role and contribution be developed (from the cases of GR, EP, or others), for sustainable technology design?

The analysis also indicates that detailed design based on formal structures may not be very central to design, since GR designs without any formal knowledge, while EP also uses detailed design only after important design decisions have been made. This questions the (real or expected) focus on detailed design driven approach to engineering design. In order to

234 Downey, “PDS: Engineering as Problem Definition and Solution,” 2015; Schon, *Educating the Reflective Practitioner*, 1987.

answer this question, the role of formal structures in technology design needs to be better characterized. I discuss this question in detail, in the next chapter.

The analysis indicates that GR's and EP's design process seems to be guided by design principles, such as decentralization, that inherently enable sustainability. This idea of sustainability is not limited to clean (non-polluting) or green (renewable) technology, but encompasses long term technical, operational, social, economic, and environmental/ecological equity and flourishing.

Furthermore, GR and EP's cases, like architectural design, involve a strong component of site-specificity in their design process and considerations, and as such cannot be, by default, entirely centralized in developing their systems, unlike product manufacturing. The MHP systems are necessarily decentralized in design and operation. As a result, they help bring out the advantages of decentralized design and operation. But would decentralized design be advantageous in general, say for product design and manufacturing as well? What are the guiding principles emerging out of the design process of cases such as GR and EP, and do they point to more generic guiding principles for technology design in general?

Also, a renewable-source based energy, such as MHP, is an inherently sustainable alternative, so it could be argued that any technology design that was based on MHP would by default be sustainable. (Although, according to Langdon Winner,[235] it cannot be entirely argued that just because an energy system is renewable, it automatically also is an ‘intrinsically democratic, egalitarian, communitarian’ technology. He comments, “In my best estimation, however, the social consequences of building renewable energy systems will surely depend on the specific configurations of both hardware and the social institutions

235 Winner, *The Whale and the Reactor*, 1980.

created to that to us."[236] Because 'artifacts have politics', Winner recommends that, "To understand which technologies and which contexts are important to us, and why, is an enterprise that must involve both the study of specific technical systems and their history as well as a thorough grasp of the concepts and controversies of political theory."[237])

Lastly, MHP system is a relatively simple technology, based on age-old science. Design processes and principles derived from these cases thus may not apply in situations where technological solutions are not known, or are complex, and cutting-edge science and technology needs to be developed or used to design them. Further, it may be granted that there could be some lessons there for management, or for low-cost technology design in resource-poor or frugal contexts, valuable perhaps in developing countries, but those may not be globally applicable, in the face of the wider sustainability challenges. Also, the lessons may have limited relevance in most design situations where teams, and not individuals, design technology.

In other words, is this characterization of grassroots technology design practice limited in scope, and a result of the choice of cases? Are there other grassroots cases which demonstrate similar characteristics? Can other cases add to this understanding of alternate practice?

6.2 Comparison with additional cases

In order to explore these aspects further, in the following section, I expand the design practice analysis, taking it beyond micro hydro power systems, to two more cases of technology design. The first is the case of development of Danish wind technology (DWT).

236 Winner, *The Whale and the Reactor*, 1980, p. 135.
237 Winner, *The Whale and the Reactor*, 1980, p. 135.

This case allows me to explore the design process of a cutting-edge technology to develop a renewable energy alternative, not by a single individual, but of an entire country, where different stakeholders contributed to the design in various ways. The second is the case of AM, a grassroots innovator and entrepreneur who designed a low cost sanitary napkin making machine. This case allows me to explore a 'solved problem' where the existing technological solution was not inherently clean or green (unlike the MHP system), but the alternative is a disruptive product design technology that is both sustainable and equitable.

6.2.1 Case study of Danish Wind Technology (DWT)

During the energy crisis of 1970s, many countries, such as Denmark, France, Germany, UK, USA, and the Netherlands, struggled to develop modern wind technology as a source of power. Of these, the Danish wind turbine systems proved to be the most successful, despite the high tech competence and high capital investments of other countries.[238] This success came from a socio-technical approach to engineering, and this case of development of wind power in Denmark has been a part of the philosophy of engineering course taught to undergraduate engineering students at Aarhus University, to help teach them social perspectives of engineering.[239]

In early 20th century, rural Denmark used electricity generated from wind power on a small scale. Danish scientist and wind power pioneer Poul la Cour's 'Klapsejler' (clap-sailor), a “simple, robust, and reliable windmill, producing direct-current (DC) power” was a major generator of this wind power, especially during the fossil fuel shortage during World

238 Heymann, “Signs of hubris,”1998; Kamp, “Socio-technical analysis of the introduction of wind power in the Netherlands and Denmark,” 2008; Karnoe, “Technological innovation and industrial organization in the Danish wind industry,”1990; Stoddard, “The California Experience,” 1986, cf Heymann, “Signs of hubris,”1998.

239 Heymann, “Engineering as a Socio-technical Process,” 2015.

War II.[240] When Denmark turned to AC power after the Second World War, and started exploiting oil from the North Sea (in 1960s), many windmills were phased out. Nevertheless, innovations in wind power designs continued in Denmark, as also in France, Germany, UK, USA, and the Netherlands.

In late 1940s, Johannes Juul, a Danish electrician who had trained with Poul la Cour, started developing wind turbines to produce AC power, and to supply it to the Danish electricity grid. Based on the test runs of his initial two-bladed turbines, he decided to build three-bladed turbines. Similarly, after experimentation with small prototypes and test run observations, he modified the rotor position from downwind to upwind, and the yaw control from passive to active. The 200 kW turbine he built in Gedser in 1957 ran successfully for ten years.

Based on this turbine, and Juul's designs, carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen started building simple wind turbines.

> *“Riisager assembled his first wind turbines from inexpensive off-the-shelf parts, such as standard asynchronous generators and truck gears, axles, and brakes. In spite of his limited theoretical background and experience, by 1976 Riisager had produced a surprisingly reliable 22-kilowatt turbine.”*[241]
>
> *“By January 1978 he had sold six copies; within the next two years he sold fifty more.”*[242]

As Matthias Heymann[243] comments about their craft-like method,

> *“Practical experience turned out to be a key advantage. It gave rise to a rich base of personal ‘tacit’ knowledge, a feeling for forces and loads and for the performance and limitations of technical components.”*

240 Heymann, “Signs of hubris,”1998, p. 649.
241 Karnoe, 1978, cf Heymann, “Signs of hubris,”1998.
242 Heymann, “Signs of hubris,”1998, p. 661.
243 Heymann, “Engineering as a Socio-technical Process,” 2015, p. 480.

Many small manufacturers followed Riisager and started supplying small wind turbine generators to the Danish people. Initially, those who wanted independent electricity sources, even at a higher price, purchased the wind turbines. Later the government offered credits and market subsidy, and the demand increased substantially. The Danish government established a test station to test and provide licenses for the turbines. Since government subsidy could be availed only by licensed turbines, commercial manufacturers had to work with the test station engineers to standardize their turbines. With a rise in demand that could not be met by the small manufacturers, other companies such as agricultural machine manufacturers purchased their designs and entered the business of commercial wind turbine production.

When wind-based renewable energy attracted attention during the fuel crisis of 1970s, the governments of countries like USA, Germany, and Denmark invested large amounts of capital and trained manpower into organized research and development of large wind turbines. The most successful turbines though were not the ones built by the government R & D programs, but by the Danish commercial manufacturers.

> *"The American failure looks even worse when one considers that between 1975 and 1988 the United States government spent twenty times (and Germany five times) as much for wind power research and development as did Denmark, yet Danish manufacturers made better turbines".*[244]

Danish commercial turbines were developed independent of the government R & D programs.[245] In 1980s, major wind turbine installations were put up in California. Of these, 45% were supplied by about six commercial manufacturers from Denmark.

244 Heymann, "Signs of hubris,"1998, p. 642.
245 Heymann, "Signs of hubris,"1998, p. 668.

6.2.1.1 Analysis of DWT design practice

Contrary to the technology design driven by engineering sciences and mathematics, Danish wind technology designs by technicians and craftsmen proved to be more reliable and cost-effective. This superiority of Danish designs showcases yet another model of alternate socio-technical connection. Scholars have discussed many factors leading to this, not limited to the technical design, or the process alone, but to a significant extent factors such as the socio-political context and interaction opportunities. (See Fig. 27).

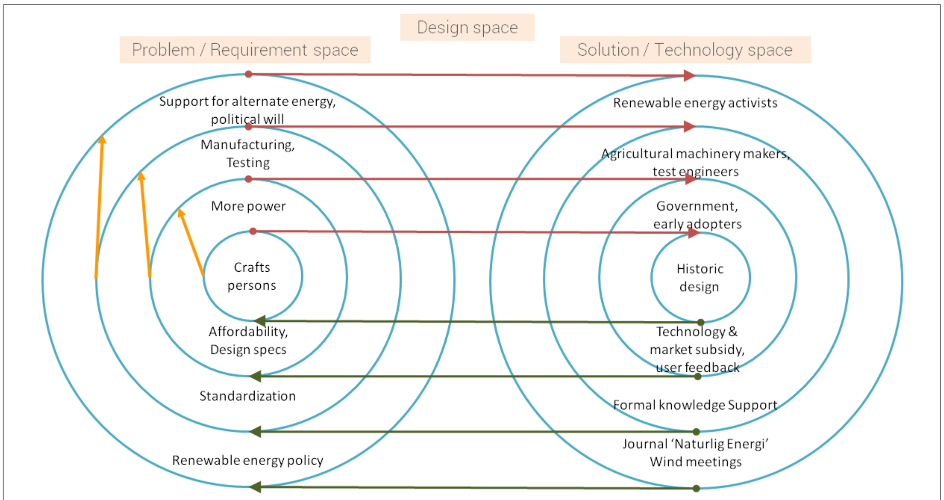

Fig. 27: The multi-stakeholder driven bottom-up process of DWT design

Many aspects of the design and design process are illustrative of these.

1. Designing wind turbines proved a challenging technical task due to static and dynamic loads, wear and tear, and the need for automaticity and constant rotor speed for AC. Design efforts driven by engineering sciences and mathematics aimed for high efficiency, and their design decisions were thus narrowly focused on optimization of input-output parameters. Forrest Stoddard[246] identified the key technical differences in the way the American, German, and Danish turbine designers

246 Stoddard, "The California Experience," 1986, cf Heymann, "Signs of hubris," 1998.

responded to these challenges, particularly as seen in the turbines installed in California in the 1980s, and attributed Danish robustness to their technical design decisions. While the Danish turbines featured three blades, upwind rotors, active yaw control, stall control, and medium or heavy weight, the American large-scale ones, oriented towards increasing the aerodynamic efficiency, preferred two blades, downwind rotors, passive yaw control, pitch or semi-pitch control, and were extremely lightweight.[247] "Although American and German turbines ran more efficiently, they proved less reliable and cost-effective than Danish turbines".[248] The foundations for these two different trajectories were laid early on, with Putnam building a 1250KW grid-feeding AC turbine in early 1940s, in the USA, while Juul starting with a small 15KW grid-feeding AC one in late 1940s in Denmark. According to Peter Karnoe[249], the Danish process was bottom-up, following a step-by-step process based on incremental learnings through practical experience. In Germany, on the other hand, Ulrich Hutter developed basic design principles based on theoretical aerodynamics of wind turbines, promoting "a small number of blades, clean aerodynamic profiles, high rotor velocity, and extremely light construction to achieve the major design priorities of high efficiency and low weight."[250] In USA, NASA and large aircraft companies were engaged in developing turbine technology projects undertaken for the government. They preferred Hutter's principles over Juul's designs. But their designs failed technically as well as economically. "A bigger-is-better ideology and a strong belief in technical efficiency characterized most government-

247 Stoddard, "The California Experience," 1986, cf Heymann, "Signs of hubris," 1998, p. 643.
248 Heymann, "Signs of hubris," 1998, p. 648.
249 Karnoe, "Technological innovation and industrial organization in the Danish wind industry," 1990.
250 Hutter, 1942, cf Heymann, "Signs of hubris," 1998, p. 653.

supported R&D efforts, especially in Germany and the United States."[251] Heymann calls this engineering approach as science based, while that of the small Danish manufacturers as practice oriented.[252] He concludes that "Reliable and successful wind turbine designs have mostly been developed by nonacademic engineers, technicians, and artisans in Denmark, while the designs proposed by academic engineers in the1970s and 1980s mostly failed."[253] He remarks, "Wind technology development in the academic and large-corporate world illustrated an excess of ambition and confidence that could more precisely be named technological hubris."[254] Different knowledge bases also create different orientations, values, mentalities and ideologies. Craftsmen were conservative, while theoretically trained engineers exhibited ambition for innovation and confidence, but under-estimated the challenge. Linda Kamp[255] points out that the design process of small-scale entrepreneurs is guided by 'learning by doing, using, and interacting', while that of the R&D institutions is by 'learning by searching'.

2. In Denmark the design process also occurred in the context of many socio-econo-political factors that came together in support of wind technology development, while this was missing or in opposition in the other countries. Early user involvement was supported through interest in renewable energy, as well as market subsidy, from the government. User feedback on early installations, and their long-term performance, thus played a role in modifying the designs to better suit the market. Forums such as 'wind meetings' and the journal Naturlig Energi resulted in designers, manufacturers,

251 Heymann, "Signs of hubris," 1998, p. 667.
252 Heymann, "Engineering as a Socio-technical Process," 2015, p. 477.
253 Heymann, "Signs of hubris," 1998, p. 666.
254 Heymann, "Signs of hubris," 1998, p. 668.
255 Kamp, "Socio-technical analysis of the introduction of wind power in the Netherlands and Denmark," 2008.

users, and government bodies keeping up-to-date on various developments as well as issues in DWT design. This allowed for an open exchange and cross-pollination of ideas and experiences, not only in terms of product design, but simultaneously also on the other fronts such as manufacturing, distribution, governance, policy, and market development for DWT. This indirectly led to a much wider design space, where the need definition or problem framing encompassed multiple technical as well as non-technical aspects of the technology. Government played an indirect but significant role in bringing about improvements through building a test station, and offering technology subsidies to the designers. This ecosystem of collaborative design was further nourished by socio-political support through renewable energy movement within Denmark. Thus in DWT design, the society-technology connection was far expanded to include various stakeholders and institutions, where all converged to provide the environment necessary for the success of DWT.

3. The socio-technical process of DWT design was thus not centralized and concentrated in one place, nor was it a captive to a singular design direction. The open, distributed, and situated nature of its design, manufacturing, and distribution further contributed to a wider design space and the better sustainability of the solution.

6.2.2 Case study of sanitary napkin machine by AM

AM, a school- dropout from Coimbatore, India, was selected as a 'Pioneer' and one of 'the hundred most influential people in the world' in 2014 by Time magazine.[256] The recognition was in honor of his grassroots innovation, a set of four semi-automatic machines to manufacture sanitary napkins. AM’s machines cost about 75,000 Indian Rupees (INR), are

256 Gupta, *Arunachalam Muruganantham*, 2014.

easy to operate,[257] and the design is provided as open source. Commercial automatic machines, on the other hand, cost twenty five to thirty million INR, are designed for industrial use, and the technology is patented. With AM's machines, a sanitary napkin costs between one and two INR a piece (about 50 napkins for a US dollar). Before AM developed his machines that manufacture low cost napkins, branded napkins available in the market (made by multinational companies) cost about 10 INR a piece, and were not affordable for most women in the low income strata. AM's design has allowed self-help groups in many countries across the globe to manufacture their own low cost napkins. He is currently experimenting with organic material and disposal options, to make the napkin a biodegradable product.

AM studied formally only up to high school, and dropped out of school to work in various trades, including as a helper in workshops, to support his mother, sisters, and wife. Apart from this hardship, he had to struggle hard against social attitudes to develop the innovative machine. In researching menstruation - a taboo subject in India - he faced ridicule and rejection, and was almost ostracized by his village community, before his innovation won national and international acclaim.

He initially developed napkins, and once this technology was perfected, he moved to developing machines that make napkins. Even though he had the option of making napkins and selling them at a high profit, he chose instead to manufacture the machines he designed, and sell the machines at a minimal profit to women's self-help groups, who could then set up their own napkin manufacturing businesses. Currently more than 600 machines made by his startup company, Jayaashree Industries, are installed across 23 provinces in India.

257 National Innovation Foundation, *Mini Sanitary Napkin Making Machine*, 2009.

Despite numerous offers, AM refuses to sell his innovation to the corporate world. “I didn't take the money route because I saw my parents struggle for survival,” he explains. “I knew that this machine could provide a sustainable livelihood for many rural women.”[258] The women are able to offer a low-priced product as well as generate wealth. These women at the grassroots (the low-income strata) of the society find gainful employment in their own neighborhood, and at the same time create awareness about sanitary hygiene. “Shops are usually run by men, which can put women off. And when customers get them from women they know, they can also acquire important information on how to use them. Purchasers may not even need any money - many women barter for onions and potatoes.”[259] AM's innovation has thus created a revolution' in public health and women empowerment at the grassroots level, and significantly disrupted the napkin business. It has forced major napkin manufacturing brands to bring out low cost products, and they now compete with women's self-help groups to grab a share of the low-income market.

AM's design is thus a solution that addresses not only the technical aspects of providing low cost sanitary napkins. It also addresses social, cultural, economic, and ecological aspects of the complex problem of women's menstrual hygiene. Productivity and empowerment of women are embedded in his design. His solution is much more innovative because it solves for long term equity and sustainability, rather than short term profit-making. Even though it does not resolve the problem of sanitary waste generation (yet), his solution is close to being a case of sustainable technology design.

258 Sandhana, *India's women given low-cost route to sanitary protection*, 2012.
259 Venema, *The Indian sanitary pad revolutionary*, 2014.

6.2.2.1 Analysis of AM's design practice

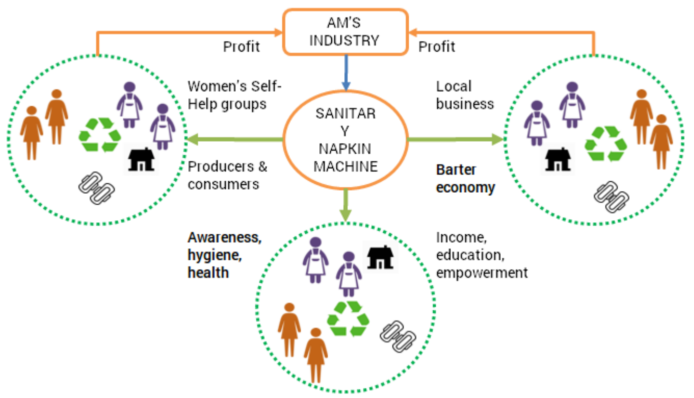

Fig. 28: AM's decentralized production business model

Current technology design is often driven by engineering sciences and mathematics,[260] which creates a problem space where the needs or requirements that could be addressed by the technology are still unknown, or are hidden. In this design approach, the need for the technology is often 'created' in the society, after a technological innovation is developed. The focus on innovations of this kind, where the socio-technical connection is established after the design of the technology, has led to many existing needs in the society remaining unaddressed. This approach to establishing the socio-technical connection has unfortunately become the default design model, and engineering education has changed to accommodate this profit-focused model, emphasizing engineering sciences and mathematics alone in their curricula.

AM's technology design provides an important contrast model, illustrating an alternate socio-technical connection. (See Fig. 28). His technology design starts from a social-economic need, and includes many socio-cultural parameters beyond efficiency in the framing/scoping of the problem. This creates a wider design space, where a novel and disruptive design solution is found. A focus on merely the techno-scientific aspects of the

260 Lucena, "Flexible Engineers: History, Challenges, and Opportunities for Engineering Education," 2003.

design would consider his problem already-solved, and would thus miss his disruptive innovation.

Many aspects of his design and design process are illustrative of these.

1. An important aspect is the identification and a deep understanding of the ‘need’ in its socio-economic and environmental context. AM did not venture into the sanitary napkin innovation as a result of some scientific breakthrough that could be applied to this segment, or because there was a good market for the product. He was drawn to the problem of women's sanitary hygiene out of empathy for his wife and sisters, who could not afford the branded sanitary napkins, and were forced to use unhygienic options. This is a case across the globe for most women in the low income strata. They need access to a low-priced product, but no company is interested in making one. AM, believing that the napkin is made of cotton, and is being sold at about 40 times its price, set about designing napkins that could be made and sold at a lower price. AM's design process also demonstrates the length to which a motivated designer would go to really understand the need, and to test the way the solution fits the need. AM initially requested his wife and sisters, and later some medical students, to try and give him feedback about the napkins he designed. But when their response waned, he became 'the man who wore a sanitary pad'. He actually wore a football bladder filled with goat blood to understand menstrual flow and its absorption in his sanitary napkin. The experience led him to wonder how women handled the inconvenience every day, when one could not work as usual even with a running nose.

2. It is worth noting how AM's design, starting from grassroots requirements (low cost, women's health, livelihood, empowerment), radically disrupts standard distinctions between requirements, specifications, product design, and manufacturing design. In most cases of innovation, the product design is the primary innovation, and the design of the manufacturing machine is treated as a scaling and optimization problem. Since the manufacturing machine almost always functions within a profit framework, the design of the machine is based solely on input-output efficiency, and thus functions also as a proxy system for generating profit. The separation of the product design and manufacturing design processes allows profit to dominate the design once the product is developed. Since AM's design started from requirements, and went all the way to manufacturing, he could combine the two design processes (product and manufacturing), and come up with a more sustainable and equitable, not to mention disruptive, design. Standard engineering practice, and curricula, rarely provide situations where designers move all the way from gathering requirements to developing specifications to product design and manufacturing design. In most situations requirements are identified by one group (the 'innovators') and they translate these requirements into technical specifications, based on the standard business and socio-technical frameworks, which are oriented towards profit. Engineers then work with this technical specification as the target for design. AM's case illustrates that the design space is not limited to these technical specifications.

3. Another aspect of AM's design is that his machines are semi-automatic.

> *"The towel-making machine transforms cellulose into sterilised towels in a four-part process. In the first stage, it chops up wood using a powerful motor. Then the operator compresses the pulp manually into a towel shape by controlling a core-forming unit with*

> *a foot pedal. They wrap each towel with a non-woven fabric and seal them with another pedal unit. Finally, they sterilise the towels by exposing them to ultraviolet light, trimming the end product and affixing strips before packing."*[261]

This design of the machine is not aimed at manufacturing the maximum possible napkins per unit time, which would be the means to maximize profit. Instead it is aimed at simplifying the building of the machines, and an ease of operation (and maintenance) by lay people, including women who may not otherwise have exposure to machines. "The technology used is simple and non-chemical. In fact, the machine uses purely mechanical processes such as grinding and defibration, pressing and sealing to convert the raw material – high-quality pine wood pulp – into a napkin."[262] His machines are also less dependent on electricity, as they use human power. The activity is not menial, as it has room for active human engagement with the process and the product. This is especially true because the consumers/users are themselves (or represented by) the producers/manufacturers here.

4. The central value guiding AM's design is not efficiency geared towards maximizing the output per unit time, and minimizing the required raw material, which is the most important technical and engineering value currently. On the other hand, this is the central value in the mostly multinational napkin industry, where the manufacturing machines are designed to maximize efficiency, not necessarily to reduce the cost to the consumer, but to maximize the profit – *efficiency works as a proxy for profit*. This design is centralized, and the automated mechanized production line excludes human labor. It is not oriented towards sanitary health, nor concerns itself with its role in livelihood generation, women empowerment, or wealth distribution. Commenting that

261 Sandhana, *India's women given low-cost route to sanitary protection*, 2012.
262 Jayaashree Industries, *About Jayaashree Industries*, 2014.

the multinationals only served the educated and the rich, AM says: “For the last 60 years they talked about comfort. But what about hygiene?” The pursuit of techno-economic efficiency led to a design that only satisfied the profit-making goals of a few, and the comfort of the upper strata of society, while AM's grassroots design demonstrates the possibility of a 'universal good' design space, where the notion of efficiency is wider, covering women’s health, livelihood and empowerment, at all levels of society. This wider socio-technical and network approach to efficiency, and the equitable and sustainable design space that such an approach opens, is lost when designs are driven exclusively by purely input-output approaches to efficiency.

5. AM's technical as well as business model enables many small groups to start their own backyard or cottage-industry. This allows for a more decentralized production and distribution chain, resulting in local access to both livelihood (work) and the product. “He believes that big business is parasitic, like a mosquito, whereas he prefers the lighter touch, like that of a butterfly. A butterfly can suck honey from the flower without damaging it, he says.”[263] His company sells the machines directly to rural women with the help of bank loans, as well as through NGOs and women's self-help groups. An operator can learn the entire towel-making process in three hours and then employ three others to help with processing and distribution.[264]

This business model does not force a large number of (most likely male) workers to a centralized manufacturing facility, away from their homes or even hometowns, or make them almost non-human parts of the automated conveyor belt and supply chain. Manufacturing workers are thus not uprooted from their locale in order to access this

263 Venema, *The Indian sanitary pad revolutionary*, 2014.
264 Sandhana, *India's women given low-cost route to sanitary protection*, 2012.

livelihood, but instead can make this an addition to their diverse basket sources of livelihood, thus making their lives more sustainable. They also have the benefit of working to their schedule, juggling various activities as needed. AM's design thus incurs fewer social costs. Further, a light-weight and voluminous product like the sanitary napkin, when made at a centralized facility, would also incur a high transportation cost. AM's business model allows local production and saves transport cost, at the same time reducing the players involved in the supply chain – the third person to handle the product (from its inception) is the consumer.[265] He thus also reduces the environmental costs of his technology. Production by consumers allows for addressing the need, while avoiding excessive unnecessary production.

6.2.3 Wider insights: Sustainable technology design practice

Insights about design process and principles for grassroots technology design, from comparison of the primary empirical practice cases with the additional cases, are summarized as follows.

6.2.3.1 Insights from sustainable grassroots technology design process

1. Situated in users' eco-socio-economic context. This illustrates, and makes explicit, the complex and socio-technical nature of design requirements.

2. Distributed across artifacts and stakeholders, as well as constant improvements and iterations based on feedback.

3. Bottom-up step-by-step process, not solely driven by formal/ theoretical knowledge, starting with a wider problem formulation.

265 Jayaashree Industries, *About Jayaashree Industries*, 2014.

4. Parameters are grounded, and conceptualized hands on.

5. Complex societal requirements/needs are addressed through generating multiple alternatives of technology solutions. These illustrate, and make explicit, the flexibility or plasticity available for connecting society and technology.

6. Design experiences – of generating many alternate ways to connect technology and society – coagulate to form a perspective of the designer, guiding the future designs.

6.2.3.2 Insights from sustainable grassroots technology design principles

1. The technology is optimized either by the consumer/user in the role of the designer (e.g. GRI), or an external designer in close consultation with/participation of the consumers in their eco-socio-technical context (EP, DWT, AM), rather than based on theory and input-output efficiency. The technology promotes sustainability. Examples include:

    i. Powering street lights, instead of using heating coils as dummy load. This saves waste of surplus power, and avoids releasing of hot water back into the stream.

    ii. Designing to allow for diversion of water for irrigation in the summer. Indicates local priorities are a part of the optimization, and communities have control over their resource use. Local control over technology enables limiting the consumption as per local resources.

    iii. Using simple components and locally available spares. Optimize for local independence, in and low-cost maintenance and repair.

2. Decentralized business models that create/support local jobs or livelihoods, avoiding migration for employment, and promoting social equity. Centralized mass production for profit is not a focus.

3. The design questions that appear to underly the design considerations have sustainability implications. Some of these could be articulated as:

   i. How can this technology help improve people's lives where they are, without adversely affecting their environment?

   ii. How can this technology help support people's livelihoods?

   iii. How can this technology be designed to be robust and locally controlled/ self-sufficient?

   iv. How can more people gain income out of this technology?

6.3 Comparison with the canonical model

6.3.1 Canonical engineering design process

Dym and colleagues[266] define engineering design as "... a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints", and emphasize that "Engineering design thinking and learning are central to the development of an engineer".

Many models[267] of design process have been described and prescribed, depicting a minimum of the following stages for engineering design:

266 Dym et al., "Engineering design thinking, teaching, and learning," 2005, p 104.
267 Haik & Shahin, *Engineering Design Process*, 2011.

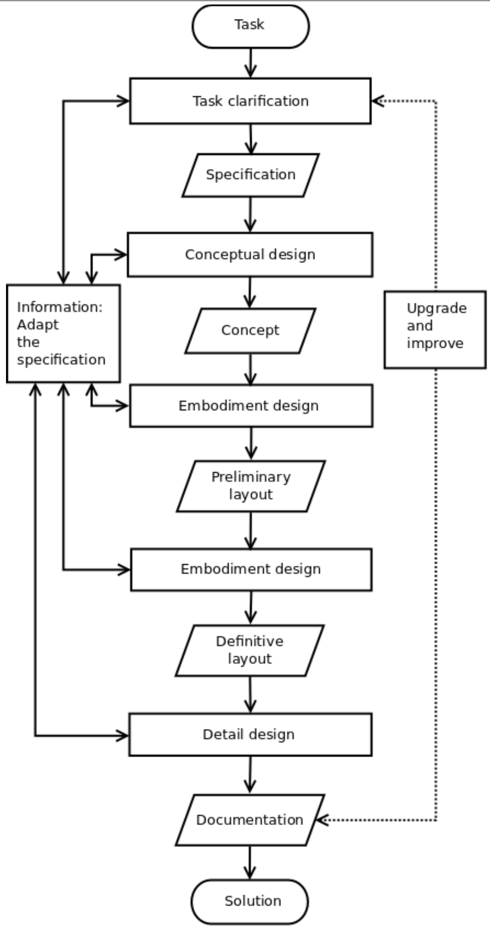

Fig. 29: Engineering design process (Based on Pahl & Beitz, 2007)

1. Problem definition/task clarification
2. Conceptual design
3. Embodiment design
4. Detailed design
5. Documentation

One of the most widely cited schematic depictions of the engineering design process model comes from Pahl and Beitz.[268] Fig. 29 shows a recreated simplified block diagram, based on Pahl & Beitz as depicted by Dubberly.[269]

According to this process model,

> *"In principle, the planning and design process proceeds from the planning and clarification of the task, through the identification of the required functions, the elaboration of principle solutions, the construction of modular structures, to the final documentation of the complete product."*[270]

According to Haik and Shahin,[271] in the Conceptual design stage "the designer is trying to assess what actions the product should perform during its lifetime and operation". They describe the Embodiment design stage as where,

> *"the product that is being designed begins to take shape. This stage does not include any details yet (no dimensions or tolerances, etc.) but will begin to illustrate a clear definition of a part, how it will look, and how it interfaces with the rest of the parts in the product assembly. This stage is separated from both the conceptual design and the*

268 Pahl & Beitz, *Engineering Design: a systematic approach*, 2007.
269 Dubberly, *How do you design? A compendium of Models*, 2004.
270 Pahl & Beitz, *Engineering Design: a systematic approach*, 2007, p 128.
271 Haik & Shahin, *Engineering Design Process*, 2011, p 17.

detailed design in that new technologies can replace old ones based on the exact same concept."[272]

Haik and Shahin comment that,

"Most engineering degree courses will be within the detailed design stage framework. During this stage, commonly referred to as analysis and simulation, the designer selects the appropriate materials for each part and calculates accurately the dimensions and tolerances of the product."[273]

In summary, the Task clarification stage involves problem definition, and its output may be a list of quantified technical task specifications. The Conceptual design stage focuses on the function while the Embodiment design stage decides the form of the machine/technology. In the Detailed design stage, the exact technical specifications are worked out for the components. Feedback from each of these stages may result in reconsideration at the previous stages, and in this sense the model captures the iterative nature of the design process, although primarily it depicts the process as linear.

The linearity of the engineering design process has been critiqued and questioned.[274] Bryan Lawson[275] emphasizes that "It is central to modern thinking about design that problems and solutions are seen as emerging together, rather than one following logically upon the other." David Jonassen[276] describes design as "... an iterative process of decision making and model building". He questions the assumptions in the design process models that design is a predictable process that will result in an optimal solution or that designers perform all the activities in the process. He points out that,

"During the problem definition stage, engineers analyze constraints in order to develop goals that represent an optimal solution. However, rather than optimizing a solution,

272 Haik & Shahin, *Engineering Design Process*, 2011, p 20.
273 Haik & Shahin, *Engineering Design Process*, 2011, p 231.
274 Bucciarelli, *Designing Engineers*, 1994; Jonassen, "Engineers as problem solvers," 2014; Vincenti, "What engineers know and how they know it," 1990.
275 Lawson, *How Designers Think*, 2006.
276 Jonassen, "Engineers as problem solvers," 2014.

> *designers most often seek to satisfice (Simon, 1955), a strategy that attempts to meet criteria for adequacy, rather than identifying an optimal solution."*[277]

6.3.1.1 Research studies of engineering design process

Mosborg, Adams, Kim, Atman, Turns, and Cardella[278] studied practicing expert professionals' conceptions of the engineering design process, in relation to 'one' design process model synthesized from several introductory engineering textbooks. Even though the block diagram model of engineering design process is critiqued by researchers of engineering practice, Mosborg and colleagues[279] found that, for various reasons, of the 19 practicing engineers, only three had major disagreement with the model, while 7 drew alternative types of diagrams. The experts as a whole emphasized problem scoping and communication. Mosborg and colleagues[280] also report that among the 27 statements describing their definition of design, the statement most strongly endorsed by the engineers was, "In design, a primary consideration ... is 'Who will be using the product?'", while the statement least endorsed was, "Good designers get it right the first time".

A further comparison of these data with that of students indicated that unlike students, the experts revisited the problem definition stage throughout the design process. For analysis, the researchers considered eight activities commonly indicated in the process models of engineering design: problem definition, information gathering, generating alternatives, modeling, feasibility checking, evaluation, decision, and communication.[281] They

277 Jonassen, "Engineers as problem solvers," 2014, p 111.
278 Mosberg et al., "Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals," 2005.
279 Mosberg et al., "Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals," 2005.
280 Mosberg et al., "Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals," 2005.
281 Moore et al., "Do Freshman Design Texts Adequately Define the Engineering Design Process," 1995, cf Atman et al., "Engineering design processes: A comparison of students and expert practitioners," 2007.

found that "... problem scoping and information gathering are major differences between advanced engineers and students, and important competencies for engineering students to develop."[282] Further support for this practice distinction is provided by a lab study comparing individual designers; the formally trained (m-designers) with the practically experienced (p-designers), on a given mechanical design task.[283] The study found that the m-designers' design process mostly followed the linear process model, and they clarified the task extensively before moving on to conceptual design, while the p-designers took the first conceptual solution as a means of clarifying the task.

In the context of task clarification, which involves understanding the requirement and how it relates to the different design phases, Chakrabarti, Morgenstern, and Knaab[284] define 'requirement' as, "a characteristic which a designer is expected to fulfill through the eventual design". They point out that ".. detailed investigation as to how requirements get identified, clarified and used in the design process and how they influence the quality of its outcome - the emergent design - has not been undertaken before". From an analysis of empirical data (protocol study) of four individual experienced (mechanical) designers, Chakrabarti et al.[285] report that "if a requirement is insufficiently identified and applied, it is insufficiently fulfilled, and vice-versa". They also shed light on some design activities and methods that help or harm the process of requirement identification and application. According to their model of requirement identification and application activities, "...

282 Atman et al., "Engineering design processes: A comparison of students and expert practitioners," 2007, p 359.
283 Gunther & Ehrlenspiel, "Comparing designers from practice and designers with systematic design education," 1999.
284 Chakrabarti et al., "Identification and application of requirements and their impact on the design process: a protocol study," 2004, p 22.
285 Chakrabarti et al., "Identification and application of requirements and their impact on the design process: a protocol study," 2004, p 34-35.

requirements are identified, clarified, detailed and used throughout the design process. However, they are identified mostly during the task clarification phase and increasingly less in the subsequent phases”.[286]

These studies together bring out the complexity inherent in the design process that is not apparent in the block diagram model, particularly in the context of continuous redefining of the problem (and the solution) throughout the process, in a non-linear and iterative manner, as done by expert designers.

According to Atman, Eris, McDonnell, Cardella, and Borgford-Parnell,[287] the term 'process' is now interpreted broadly, to mean

> *“... an interdisciplinary activity that accounts for the entire product life cycle in which designers, interacting with stakeholders, identify opportunities; frame goal; generate and test solutions; and plan for the manufacturing, marketing, and servicing of products.”*

Pieter Vermaas[288] proposes a new 'social design' emerging from new design practices ranging from designer-driven propositional design, designer-guided empathic design, to user-driven participatory design.

6.3.2 Canonical design guidelines

Pahl and Beitz[289] describe technical function, cost, and safety as the general objectives of the design process, adding clarity and simplicity as the basic rules. (See Fig. 30).

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286 Chakrabarti et al., “Identification and application of requirements and their impact on the design process: a protocol study,” 2004, p 36.
287 Atman et al., “Engineering Design Education: Research, Practice, and Examples that link the Two,” 2014, p 204.
288 Vermaas, “Design Methodology and Engineering Design,” 2015.
289 Pahl & Beitz, *Engineering Design: A Systematic Approach*, 2007.

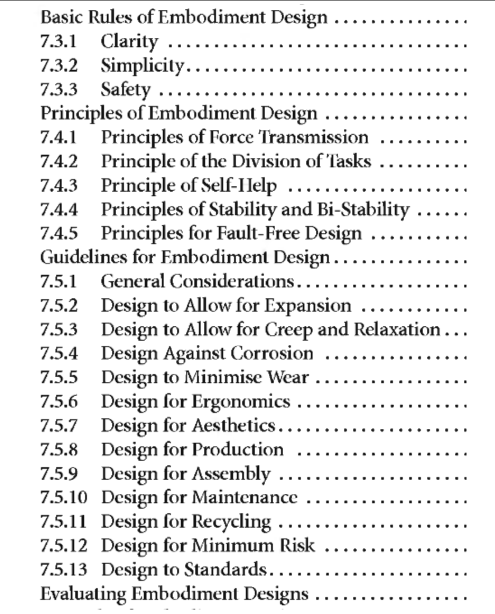
Basic Rules of Embodiment Design
7.3.1 Clarity
7.3.2 Simplicity
7.3.3 Safety
Principles of Embodiment Design
7.4.1 Principles of Force Transmission
7.4.2 Principle of the Division of Tasks
7.4.3 Principle of Self-Help
7.4.4 Principles of Stability and Bi-Stability
7.4.5 Principles for Fault-Free Design
Guidelines for Embodiment Design
7.5.1 General Considerations
7.5.2 Design to Allow for Expansion
7.5.3 Design to Allow for Creep and Relaxation
7.5.4 Design Against Corrosion
7.5.5 Design to Minimise Wear
7.5.6 Design for Ergonomics
7.5.7 Design for Aesthetics
7.5.8 Design for Production
7.5.9 Design for Assembly
7.5.10 Design for Maintenance
7.5.11 Design for Recycling
7.5.12 Design for Minimum Risk
7.5.13 Design to Standards
Evaluating Embodiment Designs

Fig. 30: Design rules and guidelines (Pahl & Beitz, 2007)

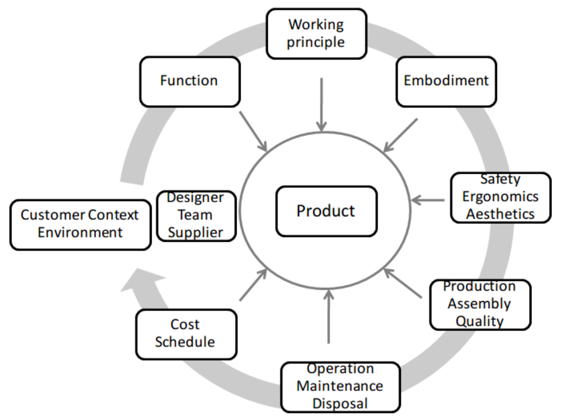

Fig. 31: Design rules and guidelines (Based on Pahl & Beitz, 2007)

Further, they suggest that the requirement guidelines generated from considerations and constraints of ergonomics, aesthetics, production, schedule, maintenance, and so on (See Fig. 31), “should be treated as *guidelines* throughout the design process”[290].

6.3.3 Comparison insights from the canonical model

6.3.3.1 GR's design process and principles as different from the canonical

GR's design stages as well as approach differs from the canonical design process, and is eco-socio-technical rather than purely technical, as explained in detail below.

a) Task clarification and detailed design

GR's design process did not begin with a distinct stage of task clarification resulting in quantified task specifications, nor did it close with a detailed design stage to arrive at numeric technical specifications of the components, based on formal calculations.

290 Pahl & Beitz, *Engineering Design: A Systematic Approach*, 2007, p 44, italics original.

The canonical design process suggests that a formally trained designer would clarify the task to arrive at a numeric/quantified requirement of power as the design goal or specification. GR, on the other hand, started with a simple goal of lighting a bulb. As he went on to address progressively larger goals of power generation, these too were always understood in terms of artifacts. (Torch bulb > household lights > TV, fan > mixer/blender, flour mill > irrigation pump, telecom tower). He did not quantify the problem, the task, or the solution, in explicit numeric terms. GR understood the power requirement in terms of an electrical device or gadget (artifact) rather than in Watts (a unit of measurement) or DC/AC/Amperage (characteristics).

He completed the design process by providing a solution that addressed the first goal, and then went on to address progressively larger goals of power generation, eventually arriving at the goal of grid-quality AC power. In this sense, GR's task clarification was iterative, and it went through iterations of not only clarifying the task but also designing intermediate but complete solutions for the so-clarified task. He did not know or start with the final goal, or directly try to design a solution for the final goal.

Not being formally trained, GR also did not use any theoretical/formal structures such as formulas, or equations to detail out specifications of components in his design. His interaction with the numeric simulation tasks indicate that he did not engage with MHP system design in any formal way.

This also underlines that his task was always comprehensive of its socio-environmental factors that constituted the 'need' in terms of both quality and quantity of power, and not exclusively technical.

b) Conceptual and embodiment design

GR started designing a power generation technology with no formal training in engineering or science beyond grade ten. He used pre-built devices and components, like a bicycle dynamo, a rice-husk blower fan, an AC alternator, a scrapped flywheel, to design his solutions. It can be seen that the conceptual and embodiment design stages of the canonical design process, of defining the function first, and then the form, are for GR combined into one. He recognized the function to be performed by the component through the form available as a ready-made technology. His design process thus built on his environmental affordances in a non-linear manner, rather than in a linear flow.

c) Socio-technical connection

In GR's technology design, the social, technical, and the environmental are never discrete and separated. They are embedded and entwined, and their interconnections constitute the problem-solution space. This necessary interaction between the social and technical is not reflected in the canonical design process, which appears to externalize or exclude the non-technical, especially beyond the task clarification stage.

d) A design perspective

GR’s design considerations demonstrate that he values the technical design principles of function and cost, while also not harming the interests of the eco-social context and needs of the users. He has developed an subtle understanding of the design principles or a keen sense of design values that enables him to balance them well in the interest of his customers and their environment.

6.3.3.2 EP's design process and principles as different from the canonical

EP's design stages as well as approach differs from the canonical design process or a formal textbook process, as explained in detail below.

a) Linearity of design stages

An analysis of some of the key transitions in EP's design process indicates that, despite formal knowledge, within a design episode EP's design process is not linear. It jumps ahead – and skips or combines stages. For example, it combines the conceptual and embodiment stages in the traditional water mill EP modified. This is similar to results from other studies of practice. As David Jonassen[291] describes, "... designers seldom perform all of the activities defined by normative design processes".

b) Task clarification, context, and detailed design

EP engages with the design process in context, and various social and environmental factors influence and interact with all stages of EP's design process. This interaction is not limited to only an initial task specification stage, which, once frozen, would as per the canonical process be expected to disconnect/disengage from the context during the rest of the design process.

The reformulated need/problem guides the design decisions at all stages of the design process, and this results in rethinking the entire solution, as well as reforming the guiding principles. It is not a process of refitting the previous solution by tweaking only the detailed design.

[I] was it just a simple process of changing the numbers in the calculations?

291 Jonassen, "Engineers as problem solvers," 2014.

> *[EP, interrupting] you need to change the whole design.. You need to change the whole design.. Pelton especially you change the blades and everything changes."*

In this design process, the kind of detailed design calculations (use of formal structures from engineering knowledge) called for depends on the design decisions of the earlier stages; and is not as direct/obvious as applying formulas to a textbook problem with given technical parameters.

c) Feedback across multiple designs

Across design episodes, the social, environmental, and material factors go from being excluded or implicit to being progressively included and explicit to EP. In this process, EP reformulates a broader need definition and problem space in the subsequent episode. The social factors are explicit in the task specifications. This necessary interaction between the social and technical, and the reflective feedback across similar design problems is not captured in the canonical design process, even though it depicts a within-episode iterative feedback loop. Task specifications may thus work as a mechanism to externalize the social factors from the engineering problem space.

d) Design for user and environment

EP's design considerations indicate that he uses the formal technical guidelines that are a part of his training while retaining a constant focus on the context of the users and the environment. For example, despite a high formal value placed on standardization to reduce costs, he does not opt for standardizing his designs or components, at the cost of designs that cater to the specific needs of a community.

6.3.3.3 Insights about the canonical design process and guidelines

In emphasizing a purely techno-scientific design process, the canonical design process model/diagram misses:

- the non-linearity, complexity
- problem formulation, as the designer is considered to start with and focus on a quantified 'task specification'
- the continuous role of context, as the canonical design process externalizes the society-technology connection
- the default S-T connection, as the canonical model considers innovation to happen mostly at the Detail design stage.

Moreover, the canonical design guidelines discuss many design principles, but do not provide an overarching perspective that compels a designer to understand these principles in the context and the environment of the end user. In the mainstream formal engineering design that takes place in the industrial and corporate organizations, more often, the industry becomes the customer for the designers, and the design is implicitly for the technical and commercial context of the industry rather than of the end user (See Fig. 32, modified from Pahl and Beitz[292]).

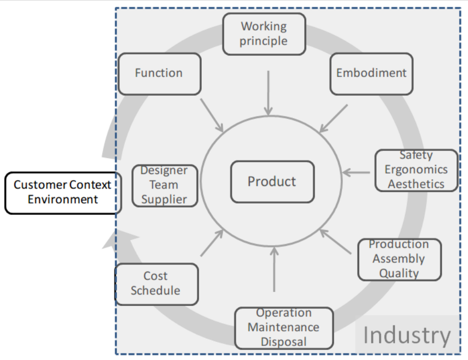

Fig. 32: Canonical design guidelines (Based on Pahl & Beitz, 2007)

As a result, the design values such as functional/performance efficiency and cost allow the design process to be transformed exclusively towards economies of scale, centralized mass

292 Pahl & Beitz, *Engineering Design: A Systematic Approach*, 2007, p 44.

production, and profit. The canonical design guidelines thus remain just that – design principles which are optionally followed. Lacking an overarching design value and perspective, such a design does not really address the constraints at the user-end, nor the broader concerns necessary for sustainability.

6.4 Generic insights from the comparisons

6.4.1 Design process

1. Design does not start with a given ‘frozen’ task specification, nor does it end with calculations to arrive at technical specifications.
2. The conceptual and embodiment stages are not always distinct, or based on formal knowledge.
3. The interaction with the ecological and social needs expands the task specifications and design space.
4. The design space is widened by changing the socio-technical connection, and this plastic understanding of the socio-technical connection enables innovation.
5. The context plays a role in narrowing down to the appropriate options and selection.

6.4.2 Design principles

- Minimally altering the biosphere to meet human needs.
- Technology for speed/power to save the cost/drudgery – but oriented more towards livelihood/income enhancement/employment, than convenience, comfort, or luxury.
- Focused on enabling local control, maintenance, repairing i.e. self-sufficiency.

- Focused on decentralization to family or group/community size.
- Focused on co-location of production and consumption.
- Not focused exclusively on technical input/output efficiency and performance optimization, through a centralized revenue model.
- Not merely ‘customized’ from a standard solution.
- A perspective that allows for considering as well as satisfactorily meeting both the technical and non-technical design values or principles, leading to eco-social sustainability.

6.5 Findings

These cases demonstrate a deep and long-term engagement of the designers with not only the problem but also with the societal and socio-political-environmental context which constitutes the problem. The design effort is not focused on implementing a particular theory-driven efficient technological solution, but on addressing the problem in all its complexity. Further, these case studies bring out this complexity of real-world messy problems, where implementing even simple or 'known' technologies becomes a challenge, and it takes persistent effort over extended periods of time (even with formal training), to arrive at novel and successful designs that really make a difference to the society. (In this sense, the problems are not just ill-structured, but tend to be 'wicked'[293]). Each of these designers demonstrate that the real job of designing technology does not start with a given ‘frozen’ task specification, nor does it end with calculations to arrive at technical

293 Rittel & Weber, “Wicked problems,” 1974.

specifications. It needs to take into account the socio-technical connection and work with the plasticity that it affords.

Collectively these cases illustrate and help emphasize the following main findings.

6.5.1 Finding 1-a: Plasticity of socio-technical connection enables design innovation

When the socio-technical connection is taken into account, there can be many possible designs and no single efficient or optimal solution. In this sense, the connection between product/technology and society is actually fluid or plastic and supports wider innovations. In practice terms, this plasticity is available only if the designer begins at the need/problem definition stage, which allows for a much wider design space. The default industrial socio-technical connection is just one possible design. As David Edgerton observes, “alternatives exist for nearly all technologies.. Too often histories are written as if no alternative could or did exist.”.[294]

Once the socio-technical connection is understood as a plastic relation, and many different designs are developed to connect the technology differently with eco-social requirements and groups of people, the design possibilities are very wide and interesting, where standard design categories (such as product, manufacturing, embodiment, concept etc.) can be recombined in novel ways, thus enabling innovation.

Engineering design practice, and engineering education, misses out on the wider design and innovation space when the society-technology connection is framed by default as the industrial one, which restricts the design space – the direction of exploration for solutions – to 'within' the detailed design phase of the design (problem-solving) process.

294 Edgerton, *The Shock of the Old*, 2006, p xiii.

6.5.2 Finding 1-b: Problem formulation is required to bring in socio-technical plasticity

Donald Schon[295] emphasizes that, “Problem-setting is a process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them.” (italics original).

> *“A conflict of ends cannot be resolved by the use of techniques derived from applied research. It is rather through the non-technical process of framing the problematic situation that we may organize and clarify both the ends to be achieved and the possible means of achieving them.”*[296]

In GR's case, his own need was instrumental in guiding his entire design approach and problem framing, and helped him succeed despite a lack of formal knowledge. Partly because of the lack of formal training, his work does not externalize the eco-social aspects, and he designs solutions that meet the need in a holistic fashion. His ability to address power requirements in diverse situations, and his flexible business model emerges from his close engagement and experience with the eco-social along with the technical. AM's case demonstrates the extent to which requirements need to be understood, and the length to which a designer goes to arrive at such an understanding, in order to design a satisfactory solution. His design then has the power to affect the society, at levels wider than the one it is embedded in, in innovative ways.

EP's case illustrates how constant interaction with socio-ecological needs is required to expand the efficiency approach to design, established by formal training. This interaction influences and broadens his task specifications, and eventually changes the

295 Schon, *The Reflective Practitioner: How professionals think in action*, 1983, p 40.
296 Schon, *The Reflective Practitioner: How professionals think in action*, 1983, p 41.

embodiment of the technological solution, in order to meet the society's needs.[297] In a design approach that allows such fluidity in practice, in the words of Louis Bucciarelli,

> *"Nothing is sacred, not even performance specifications, for those, too, are negotiated, changed, or even thrown out altogether, while those that matter are embellished and made rigid with time as design proceeds. … Specifications become artifacts of process, reconstrued in the engaging of different perspectives of different object worlds."*[298]

EP also emphasizes that the designer not only requires to understand the need, but also ensure that the users have stakes in the technology. Unlike the canonical requirement guidelines, when EP explores for an MHP site, he not only has to understand its technical aspects such as head, discharge, flood-line, and seasonal variation, but also negotiate with the motivation of the land owner, the local interests, the land disputes, and so on. He has to work with/around these to find a suitable option.

> *"Whether he [owner of the traditional mill] is interested or not. Alright? Whether he has enough water or not? If you have gradient, means you have to do something with channels.. whether he is interested or not.. in this or not? Or he wants to run on the basis of Self-Help group. As of now you don't know [Abhi pata nahi hai kya hai]."*

> *"Then there are issues like, land or water issues, there are disputes over it, you took my water, it's yours.. mine, it's my land (property). You need to verify all that at the site."*

The case of DWT exemplifies how the design space is widened, as various stakeholders negotiate their own needs and address other's needs in a distributed and situated technology design process. The society-technology connection in terms of the need and the solution is thus able to take on a new form through this process, and eventually provides better technology than from the theory-driven ventures.

These cases indicate that their design process and operation not just accommodates the local stakes, but works with them in a constructive and equitable manner, in order for

297 Date & Chandrasekharan, "The Socio-Technical Connection is Plastic, but Only When Design Starts from Need Formulation," 2016.
298 Bucciarelli, *Designing Engineers*, 1994, p. 187.

relevant and effective technology to be developed and sustained. Engagement with the users'/local community's long terms needs and aspirations, and not just providing them income through labor work during the construction phase, or unskilled jobs in its operation, allows for a solution where the user/community's stakes are addressed. The community is then empowered and exercises a control over the technology, rather than be cogs or assembly line workers in it.

6.5.3 Finding 1-c: Optimality beyond a centralized efficiency and revenue model

While the canonical design principles do not explicitly state technical performance efficiency as the key design principle, the basic guideline to minimize costs translates into input-output efficiency, where resources (including time, money, and effort) are minimized while maximizing profit. Literature from Philosophy and Politics of Technology (discussed in Ch 2) identifies the efficiency principle as the most prioritized in modern mainstream technology design.[299] Scholars point out that the emphasis on input-output efficiency leads to externalization of the factors that cannot be quantified, and also creates challenges for bringing in/emphasizing any other design values.[300]

For example, mainstream designs, in aiming for techno-economic efficiency, often distance the user/customer from any active control over the designed technology. Solutions such as specialized services and trained personnel may be offered by the manufacturer, for the maintenance, repair, or disposal of the designed technology, but these may not be accessible

299 Feenberg, *Transforming technology: A critical theory revisited*, 2002; Mitcham, *Thinking through technology: The path between engineering and philosophy*, 1994; Smith, *Engineering as a Career*, 1969.
300 Nissenbaum, “Values in technical design,” 2005, p lxvi; Shiva, “Reductionist science as epistemological violence,” 1988; Vanderburg, “Political imagination in a technical age,” 1988 cf Vanderburg & Khan, “How well is engineering education incorporating societal issues?,” 1994.

or affordable to many users. The cases of sustainable technology design practice studied here, demonstrate a changed and expanded notion of efficiency. GRI and EP demonstrate that technical efficiency is valued, but is balanced with enabling local control over the technology. This allows for successful long-term running of the technology even in remote areas, and the efficiency notion is expanded to long-term technical performance through self-sufficiency in such contexts. Moreover, in the designs by GRI, EP, and DWT, the quantitative input-output efficiency of energy is balanced with a design that goes beyond tweaking the parameters for customizing. This design, based on a qualitative understanding of inputs and outputs, leads to a better overall satisfaction of the needs, compared to efficiency alone.

Designing technology to support economies of scale is one of the central measures to achieve techno-economic efficiency in modern mainstream technology design. This is done through large scale production in a centralized facility. In mainstream practice, the designer works with a pre-defined and 'frozen' task specification that embeds the currently dominant centralization assumptions, including centralized manufacturing processes. This usually also leads to the concentration of the generated revenue into the hands of a few.

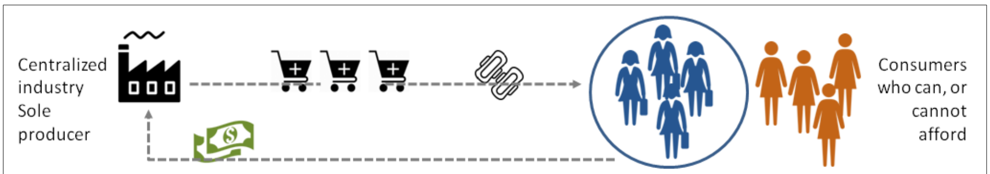

Fig. 33: An MNC-based centralized revenue model, for which AM's technology and business model (Fig 28) enabling a sustainable optimality offers a feasible contrast

Manufacturing of sanitary napkins by mainstream multi-national companies is an example of such a centralized model. (See Fig. 33).

AM designed a technology such that a for-profit business model could be based on a small, decentralized manufacturing set up, situated close to the workers. The model is amenable to their way of life, and also located in the midst of the consumers of the product, which made the distribution chain shorter. This decentralization allowed each manufacturing setup to create their own brand, and cater to a catchment of users in their vicinity as well as within their manufacturing capacity, thus achieving a deep penetration of market without any media-based advertising. They may manufacture only as much as they can sell in their 'neighborhood', rather than aiming to capture the 'global market'. The technology became socially sustainable because its design also supported livelihood (income) generation and more equitable distribution of wealth through this decentralized model.

Similarly, GR and EP’s decentralized power generation allowed for better socio-environmental sustainability than any centralized hydro power plant built on big dams. The DWT design process itself was highly decentralized compared to American or German institutionalized R&D, and contributed largely to its socio-technical problem-framing and solving. The DWT system, with its lower power output, was also more amenable to decentralized, individual use within Denmark, thus leading to Denmark’s success as a country utilizing largely a renewable and sustainable source of power.

In the practice of GRI, EP, and AM, economies of scale (through centralization and automation) are sacrificed. But the costs of transport, marketing, and distribution are saved, through co-location of production and consumption. As discussed, this also saves the respective environmental and social costs of labor migration to centralized facilities of manufacturing. The generated profits are shared more equitably, and local livelihoods are bolstered. In doing so, examples of this practice provide working demonstrations of a strong strategy for sustainable technology design, along with ways to implement it, overcoming the prevailing centralization norm.

Decentralization has been historically discussed as a strategy for democratic or participatory sharing of power in institutions of governance. In the age of computers and networks, decentralization has also been expected to automatically lead to more freedom, and creativity. As an economic implication of this kind of ‘liberating’ technology, it is anticipated, even assumed, that an equitable distribution of resources and wealth will follow. Unfortunately, as Langdon Winner points out,

> *“... to decentralize technology would mean redesigning and replacing much of our existing hardware and reforming the ways our technologies are managed. One can imagine many different forms these changes might take. But in either the technical or political sphere (or both) any significant move to decentralize would amount to retro-fitting our whole society, since centralized institutions have become the norm.”*[301]

However, the grassroots designers designed/made product/process/system(s) that could be easily handed over to the people themselves, including the operation, maintenance, minor repairs, marketing, and income generation, even manufacturing and installation in some cases. These cases show that such decentralized designing is possible, and it is socially and ecologically more sustainable.

This suggests that, starting from the default centralized model, there could be a continuum of socio-technical designs, going all the way to full decentralization, including full sharing of surpluses (as in the AM case), or partial centralization and an equitable sharing of surpluses (as in the case of Amul milk, and other cooperatives).

It is interesting to note here that while the classical, efficiency-driven production processes focus on centralization, new digital and software technologies from Silicon Valley

301 Winner, *The Whale and the Reactor*, 1986, p 96.

(such as Kiva and Kickstarter) demonstrate more social engagement and a decentralized approach embedded in their designs. More generally, the social is now a key component of software design. This trend suggests that expanding the design space, and decentralization as one way to do it, may be a requirement even within the standard model of engineering design, where sustainability is not a central design concern yet.

6.5.4 Finding 1-d: Designing for sustainable local livelihoods

Ernst F. Schumacher[302] argued for an Intermediate or Appropriate Technology (AT), where human labor was not to be replaced by automated technology, particularly in the labor-rich, capital-poor developing countries. However, the issues of technology for sustainability are not just the issues of developing countries, employment, or traditional technologies. Even the most cutting-edge technologies need to be designed such that the technology consciously/purposefully supports and upholds the larger patterns of ecosystems, self-sustenance of owned livelihoods, and equitable distribution of wealth. Such social and ecological equity is an important aspect of achieving sustainability.

Traditionally, technologies have been designed to provide greater power for the implementation of tasks, in order to reduce drudgery, save cost or time, and for comfort or luxury. On the other hand, the problems and the needs at the grassroots indicate that their demand for technology most urgently and importantly stems from the need to protect/support their existing, sustainable, and owned sources of income generation. In this sense, grassroots technology design for sustainability goes beyond the idea of Appropriate Technology. It brings to center the need to preserve, support, and extend human livelihoods based on owned

302 Schumacher, *Small is Beautiful*, 1973.

(or common) resources, and not just the opportunities for human labor, as emphasized by appropriate technology.

A deep understanding of this leads EP to categorically insist,

> *". . . after doing the [village name] project it was a very big realization that unless people are making money out of that, you can never run this power station. But if they are able to make money out of it, it is the best scheme actually."*
>
> *"Now if a village comes to me for a micro power station, I insist for a livelihood component if they want me to accept the project ... if you provide technology that gives you returns, so people will also be able to give you some, you know, good returns that way. So we never used to think like that earlier. It was just electricity."*

As a formally-trained engineer designing sustainable technology for the grassroots, EP underlines this as a complex but key aspect of such a technology.

> *"The toughest part is community, and the livelihoods actually .. it is the toughest part in this."*

Unfortunately, these basic goals have not been addressed, met, or even recognized in the case of the underprivileged, as no technologies have been developed specifically to support their livelihoods. The factory model, where industrial wage-earning jobs are provided to people who have been driven away from their owned resources, is an unsustainable model of employment. Technology designed with this model at its core cannot be understood as sustainable in the long run.

In contrast to this standard observed trend, the cases of grassroots design seek to develop technology that empowers the underprivileged people, providing them self-sufficiency in their livelihoods. EP and GR both develop technological systems that support local resource-based activities, and generate mechanical drive from hydro power, along with electricity. GR, while building MHP systems to support livelihoods and communities, also emphasizes the creation of local jobs for himself and others within his own enterprise.

> *"Innovation is to serve to society, and you enjoy yourself in your life and your job.. means make it job.. [na] commercial.. make it job. And you will enjoy your life, your innovation, and you will supported another peoples to .. by job.. or you can make a small industry.. <> at least minimum five to ten people.. give them job .. [na]."*

Traditionally, technology design was not consciously and pro-actively aimed at creating and supporting self-sufficient livelihoods. Grassroots technology design practice, on the other hand, designs technology that sustains people's livelihoods, and in turn, provides people a control over their lives.

Ivan Illich[303] describes and critiques modern technology for 'escalating what it is meant to eliminate', i.e. in making 'machines that can replace slaves', we end up 'enslaving men'.

> *"The individual's autonomy is intolerably reduced by a society that defines the maximum satisfaction of the maximum number as the largest consumption of industrial goods", and "As the power of machines increases, the role of persons more and more decreases to that of mere consumers".*[304]

The grassroots technology concurs with Illich's[305] ideal of 'conviviality', as against 'industrial productivity', where he argues for a liberating role for technology, enabling an "autonomous and creative intercourse among persons, and the intercourse of persons with their environment". The grassroots technology design practice demonstrates one way towards addressing and operationalizing these goals into design process and considerations, leading to a more socio-economically interdependent, as well as empowering and equitable, model of technology, leading to sustainability.

If understood in terms of the guiding principles for technology design discussed as 'Design for X', in addition to the minimal considerations of performance and safety, this

303 Illich, *Tools of Conviviality*, 1973.
304 Illich, *Tools of Conviviality*, 1973, p 19.
305 Illich, *Tools of Conviviality*, 1973.

could be called ‘design for supporting sustainable livelihoods’. It supports sustainable life specifically, through supporting sustainable livelihoods.

These four cases of grassroots technology design thus demonstrate in practice (process and approach) what Langdon Winner pointed out as the idea-level contribution of the appropriate technologists a few decades earlier.

> *“They [appropriate technologists] helped broaden the meaning of such categories as "efficiency," "rationality," "productivity," "cost," and "benefit" and added fresh (if not altogether novel) criteria of judgment-"human scale," "the interconnectedness of things," "second law efficiencies," "sustainability," and the like – to the range of considerations that engineers, technicians, agriculturalists, planners, and consumers ought to take seriously in making choices”.*[306]

6.6 Discussion and conclusion

6.6.1 The limited notion of sustainability in current technology design

A commonly referred definition of engineering design states it to be the process of

> *“devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs”.*[307]

Such a definition provides a theory-driven and top-down approach to design, which externalizes sustainability considerations (of ecological and social equity), and thus fails to address the society's long term needs. It is focused on meeting society’s short term needs, and even on creating such needs, and leads to a nearly reckless optimization for input-output efficiency alone. This design approach has damaged the planet's ecosystem over the last several decades, bringing into sharp focus a need to design for sustainability.

306 Winner, *The Whale and the Reactor*, 2010, p 29.
307 ABET, “Criteria for accrediting engineering programs,” 2017, p 5.

Technical performance and optimization for economic profit have been upheld as the prime goals of design. But many scholars have pointed out that technical and economic efficiency is not the only or the best norm to aim for, if sustainability problems are to be addressed. Nor are there any singular most-efficient designs. Throwing out the hard autonomy of technology argument, Bucciarelli posits that, “Only after the artifact is fixed does it appear otherwise, as rational … In process there are many objects, many potential artifacts, many object worlds. … Science push and market pull, optimization and satisficing are not determinate.” [308] An elaboration of this can be seen in Heymann's comment, “Technology development takes place in and makes part of a larger context of power relations, market structures and policies as well as beliefs, values and ideologies.”[309]

In fact, using historical examples of Moses' low bridges and McCormick's molding machines, Langdon Winner even points out how efficiency itself has been sacrificed for (vested rather than fair) political and social interests.

> *“If we suppose that new technologies are introduced to achieve increased efficiency, the history of technology shows that we will sometimes be disappointed. Technological change expresses a panoply of human motives, not the least of which is the desire of some to have dominion over others even though it may require an occasional sacrifice of cost savings and some violation of the normal standard of trying to get more from less.”*[310]

GR's design on the other hand is not tied to the principle of efficiency as its core value. For him, the core value is to address the need of the user in a sustainable manner. By arriving at a balance between the need, the affordability, and the resources, he strives to make sure that at least some power is offered to the needy, to sustain their lives as well as livelihoods better.

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308 Bucciarelli, *Designing Engineers*, 1994, p 196.
309 Heymann, “Engineering as a Socio-technical Process,” 2015, p. 487.
310 Winner, *The Whale and the Reactor*, 2010, p. 24.

EP also prioritizes the capacity of the MHP design to support and sustain livelihoods of the people. For this, he maximizes the ways in which he can support the running of diverse business enterprises powered by water, rather than focusing on maximizing the efficiency of electricity generation. In this process, a perspective rooted in the centralized revenue model would consider EP as merely 'customizing' a core engineering solution, which optimizes performance. However, this view considers the centralized revenue model, and optimality based on profit, as normative. The key point about EP's design process is that his notion of optimality evolves to include social and environmental factors. This shift goes beyond customization, as it rejects the optimality assumed by the centralized revenue model. One central insight from the analysis of these cases is that, in mainstream design, optimality, based exclusively on performance, acts as a gateway and stand-in for a value system, where profit is the central design norm and virtue, and other notions of optimality are aberrations. This was also the case, in the context of various energy studies during the energy crisis of 1970s, where Langdon Winner observes, “Regardless of how a particular energy solution would affect the distribution of wealth and social power, the case for or against it had to be stated as a practical necessity deriving from demonstrable conditions of technical or economic efficiency.”[311]

Such externalization of socio-ecological costs fails to serve the society in the long run, even though technical efficiency is geared towards the performance goal of meeting society’s needs at a minimum economic cost. While sustainability is not opposed to profit, and while it does not imply that all profit-making engineering design, be it capitalist, cooperative, or socialist, is necessarily unsustainable, the exclusive focus on profit-making

311 Winner, *The Whale and the Reactor*, 2010, p. 53.

and techno-economic efficiency, ignoring the interconnected nature of technology and socio-ecological aspects, invariably leads to unsustainable solutions.

Also, in some profit-making engineering design practice, socio-ecological considerations may remain add-on features that are subject to trade-offs (such as the use of plastic versus aluminum in laptop covers). Such trade-offs essentialize an estimation of the value of the socio-ecological consideration, a quantification that can be compared with other considerations. For example, the combination of ecological and economic efficiency into 'eco-efficiency' has been proposed in the WBCSD report,[312] implying 'creating more goods and services with ever less use of resources, waste and pollution'.[313] It stands to be a guideline for this kind of 'sustainable' technology design.

> *"... sustainable development, in the long term resulting in considerable environmental improvement, requires an increase of eco-efficiency by a factor of 10-50. To achieve such improvements radical changes on a system level affecting present ways of production, consumption and innovation practices must be made."*[314]

Although such trade-offs are a step towards sustainability, the practice in such cases is limited to only those socio-ecological considerations that can be quantified and traded off. These continue to operate in the paradigm of the technical, and fall short of breaking out of it. However, as Bucciarelli suggests, "Designing is not simply a matter of trade-offs, of instrumental, rational weighing of interests against each other, a process of measuring alternatives and options against some given performance conditions,"[315] even in the case of mainstream technology, and especially not in the case of sustainability.

312 Schmidheiny, *Changing course: A global business perspective on development and the environment*, 1992.
313 WBCSD, *Eco-efficiency: Creating more value with less impact*, 2000.
314 Quist et al., "Backcasting for sustainability in engineering education: the case of Delft University of Technology," 2006, p 869.
315 Bucciarelli, *Designing Engineers*, 1994, p 187.

Environmental impact assessment, product life-cycle analysis, technology assessment, triple bottom line (people, planet, and profit), industrial ecology, and systems engineering are some recent frameworks under development to mitigate the damage done by the narrow efficiency approach to technology design. Though these recommend a holistic approach to technology development, their analytical foundation is in the engineering domain, where the primary goals are control and economic profit. As a result, these approaches develop quantification frameworks, where trade-offs are the dominant theoretical construct. The notion of sustainable technology here is focused on products (or processes) with features or characteristics addressing goals or constraints such as non-pollution, bio-degradability, resource frugality, or renewable energy. The central design principles do not change, and continue to focus on optimization and better input-output efficiencies. This technocratic conception of sustainability then limts the discourse of sustainable development, which is presented as being “maximum sustainable consumption of optimally efficient technologies.”[316]

6.6.2 A broader notion of sustainability as thriving or flourishing for all

In contrast to these, ‘Design for X’,[317] inclusive design,[318] and affective design[319] are discussed as some of the approaches that could help broaden engineering design. Moreover,

316 Davison, *Technology and the Contested Meanings of Sustainability*, 2001 cf Lau, “Sustainable design: A new paradigm for engineering education,” 2010, p 254.
317 Holt & Barnes, “Towards an integrated approach to “Design for X”: an agenda for decision-based DFX research,” 2010.
318 Erlandson, *Universal and accessible design for products, services, and processes*, 2007.
319 Holt & Barnes, “Towards an integrated approach to “Design for X”: an agenda for decision-based DFX research,” 2010.

an approach known as Value-Sensitive Design (VSD) has been developed in computer ethics.[320]

Wade Robison[321] suggests making 'Benign by design' a fundamental principle for engineering design practice, so as to ensure, as best we can, that harm will not result through designing.

> *"Ethics enters into the design of engineering artifacts because such artifacts can cause harm. Whether they wish it or not, what engineers design will as a matter of necessity be benign or less than benign, and they have some control at least over how benign it can be."*[322]

Robison argues that engineers are thus already driven by ethical considerations, and once they realize and accept this, they will widen their concerns from individual safety to the social and the environmental. However, in the case of ethics of risk, where it is not possible to know the consequences beforehand, a broader guiding principle is required as a way to assess the risks based on already known phenomena and the webs of interrelationships on the planet.

Towards this, capturing the limitations of the sustainable development approach as ".. sustainability is not *a thing* in the sense that it can be achieved once and for all, nor can it be readily measured,"[323] Andrew Lau proposes a wider positive ethic that 'Engineers shall hold paramount the improvement of both human life and the larger community of life, for present and future generations'.[324]

The grassroots design cases characterized in this study demonstrate one way to transcend the technocratic view of sustainability, towards an even wider perspective of technology for sustainability. This perspective emphasizes the 'flourishing of all those

320 Friedman et al., "Value sensitive design: Theory and methods," 2002.
321 Robison, "Design Problems and Ethics," 2010.
322 Robison, "Design Problems and Ethics," 2010, p 212.
323 Lau, "Sustainable design: a new paradigm for engineering education," 2010, p 253, emphasis mine.
324 Lau, "Sustainable design: a new paradigm for engineering education," 2010, p 255.

interconnected' as the goal of any technological intervention or solution, where the 'progress' or 'development' of one is not achieved by sacrificing the living and well-being of the other, be it other human beings, other species, or the environment. The ethics of such technology go beyond safety and inclusivity, towards long-term sustainability. They extend the ethical or moral principles such as 'Benign by design' and Value Sensitive Design, by putting a more positive spin on 'benign' to 'Enabling the flourishing of all' - by design.

This perspective of sustainability concurs with what Stephen Stirling describes as "an emergent quality arising from sets of relationships in a system, whether viewed at the macro or micro scale".[325] John Ehrenfeld too, while focusing on technology from the perspective of the use and the user, discusses sustainability as "the possibility that human and other life will flourish on the planet forever".[326] Stirling or Ehrenfeld, however, do not discuss specific ways to alter or reform engineering design practice and education, which continue to be technocratic, and thus limited in designing technology for sustainability.

The findings from grassroots design cases characterized in this study enable us, as appears imperative, to transcend a technocratic view towards sustainability, not only to suggest in a bottom-up manner this overarching perspective of 'sustainability as flourishing for all' as a design guideline, but also to offer operational ways to journey towards this perspective, in the design process and design thinking in both practice and education. In chapter 8, I develop this operationalized approach and perspective as 'Solving for Pattern'.

325 Stirling, 2004, cf Lau, "Sustainable design: a new paradigm for engineering education," 2010, p 255.
326 Ehrenfeld, *Sustainability by Design*, 2008, p 6.

Chapter 7: Cognitive processes in grassroots technology design

Imagination and synthesis are the core cognitive processes in engineering design; formal structures play only subsidiary roles

"The whole problem becomes more unstable as you widen it. As you take more and more of life to be part of the problem you don't get a more stable problem you get a less stable problem. And this I think is not what the rationalists like."[327]

In this chapter
As current engineering education (EE) focuses on formal structures, and the formal structures mainly support only the Detailed design stage in the design process, it is unclear how the design principles and processes, identified in the previous study (Ch 6), could be integrated into EE. To understand how engineering students can start thinking like the designers of sustainable technology, in order to implement sustainable design process and principles, a cognitive historical analysis of the core cases (non-formal and formal design process for the MHP system), was done, to understand the cognitive processes involved in designing such systems, particularly the role played by formal structures. Additional cases were then selected for comparison and a wider characterization. A comparison with the canonical training process allowed for some generalization of the findings, across the results from the empirical cases and the additional cases.
This analysis demonstrated that imagination (mental simulation of material structure and dynamics) and synthesis are the core cognitive processes in engineering design, and the role of formal structures is supportive/supplementary to these core processes. As imagination and synthesis are general cognitive processes, they can include the sustainability engineering principles identified by the earlier analysis, and these can thus be part of EE.

Introduction

The wider notion of sustainability as 'thriving or flourishing for all', discussed in the previous chapter, could be better supported if this design principle and perspective is incorporated as a central component of engineering practice. Engineering education (EE) needs to act as one of the drivers of this critical change. Current engineering education,

327 Jones, "How My Thoughts About Design Methodology Have Changed During the Years," 1984, p 332.

however, is focused entirely on theoretical knowledge and formal structures,[328] and the application of engineering sciences[329] and mathematics. Engineering design is not the core engineering discipline, and engineering education continues to face challenges for the incorporation of sustainability aspects as central design principles. Scholars from STS, Engineering Studies, as well as Design Studies have critiqued the excessive emphasis on formal structures as undue, and sometimes detrimental (Section 1).

In order to develop engineering education (EE) curricula and learning processes that systematically incorporate sustainability principles, the assumptions underlying current curricula and pedagogy need to be reexamined. One way to do this is to examine the cognitive justification for EE's current focus on formal structures. This requires a clear characterization of the *cognitive* role formal structures play in the *process* of engineering design. Section 2 argues for this case. Towards developing such a characterization, I first develop a cognitive process model (descriptive) from empirical cases of sustainable grassroots technology design, based on the analysis of their design practice (Section 3). For a wider characterization, I compare this model with additional cases of technology design (Section 4). I then compare this model with the canonical understanding of the cognitive process assumed in EE (Section 5), and finally discuss the findings and implications (Section 6).

328 Theory, equations, formulas, calculations, graphs, charts, models and other representations based on engineering sciences or mathematics.

329 The engineering sciences have their roots in mathematics and basic sciences but carry knowledge further toward creative application. Cf ABET, “Criteria for accrediting engineering programs,” 2017, p 5.

7.1 Scholars' view of EE emphasis on formal structures

Formal structures and theoretical knowledge occupy the center-stage in engineering education, to the near-exclusion of other forms and areas of knowledge. Though this focus poses a challenge for the inclusion of ideas such as sustainability, such an emphasis on theory and formal structures may seem justified, as engineering sciences and mathematics appear to be the distinguishing feature of engineering design. However, a wide range of scholars have challenged this view, and critiqued the excessive emphasis on formal knowledge in engineering (design) education. This section reports some of the salient arguments, from engineering studies and design studies, that identify and highlight the critiques.

Louis Bucciarelli points out that engineering design is not just about formal knowledge and its application. While the context of learning depicts engineering design as a mere "straight forward, rational application of science, of instrumental reasoning", Bucciarelli argues in favor of adopting the ideology of the context of practice, where engineering design is understood to be "… about creative exchange and negotiating meaning within a social milieu, about uncertainty and ambiguity and multiple framings, approaches and conclusions…".[330]

Arguing that design is not primarily a problem in mathematics, Eugene Ferguson contends that an excessive emphasis on formal structures will have adverse consequences for designers.

> *"… engineers in charge of projects will lose their flexibility of approach to solving problems as they adhere to the doctrine that every problem must be treated as an exercise in numerical systems analysis... the systems engineer in charge will be unaware*

330 Bucciarelli, "Designing and learning: a disjunction in contexts," 2003a, p 304.

> *that his nonverbal imagination and sense of fitness have been atrophied by the rules of a systematic but intellectually impoverished engineering approach."*[331]

Extending the point that it takes more than formal knowledge to do design, Scott Minneman[332] critiques the understanding of 'expertise in design', in the context of research in computational methods in design, which emphasizes solely "performing operations on abstract engineering representations". He reasons that this limited understanding is upheld only because other aspects of design may not be as easy to model.

> *"Perception, intuition, experience, and manual skills, for instance, are discredited since they are not amenable to current computational techniques; other aspects of skilled design practice are crudely brought into the realm of computation as heuristics."*[333]

These other aspects of design, though vital, may also be similarly 'not amenable' to current pedagogy for design thinking, and this may be leading to a focus on computational techniques. This view underlines the challenge of developing an engineering education for sustainable technology design.

The role of intuition in design is highlighted by diverse studies of design. In a pioneering study, Charles Eastman[334] studied practitioners' intuitive processes in design, in the context of 'processing of wide range of information in design'. Proposing a model of cognitive design processes, Eastman developed a computer program to simulate the general cognitive processes of design, and also those of particular designers. Despite this effort in the direction of developing a 'science of design' itself, Eastman categorically comments that going to the bottom of engineering sciences is not how designers arrive at wider choices or better design options.

331 Ferguson, "The Mind's Eye: Non-verbal Thought in Technology," 1977, p 835.
332 Minneman, "The social construction of a technical reality: empirical studies of group engineering design practice," 1991.
333 Minneman, "The social construction of a technical reality: empirical studies of group engineering design practice," 1991, p 49.
334 Eastman, "Explorations of the cognitive processes in design," 1968.

> *"It is recognized by designers that a huge recursion of DUs [Design Units] is thus possible, eventually regressing into metallurgy and chemistry for considerations. Rigorous design naively is assumed to require the maximum recursion possible so that the largest search realm will be explored. A few attempts at such recursions have convinced more than one designer that unselfconscious, intuitive design is the only one possible."*[335]

Eugene Ferguson[336] discusses a famous case of intuitive design. Richard Whitcomb, an aeronautical engineer, is reported to have developed the Area Rule - a design principle to minimize shock waves in supersonic flight - based on his intuition rather than formal knowledge. Whitcomb first suggested a design change in the wings, as 'a pinch' at a point to reduce drag where the wings are attached to the fuselage. This change is difficult to arrive at using just calculations, and is best understood as based on his extensive experience with air flow in wind tunnels. Whitcomb has been described by his colleague as "a guy who just had a sense of intuition about these kind of aerodynamics problems. He sort of feels what the air wants to do." Based on this case of a very challenging design problem, Ferguson points out that "Much of the creative thought of the designers of our technological world is non-verbal, not easily reducible to words". Declarative, formal knowledge is not the central character of design. Ferguson makes the point that synthesizing is necessary in design, and is independent of formal knowledge. He cites the historian Hansen, who reports on the formal approach taken to solve the same cutting-edge design problem.

> *"… perhaps, because they reduced everything mathematically – which involves thinking with symbols – Ward, Lord, and Hayes had failed to* see*, as Whitcomb would, how to bring the physical elements together in a new aerodynamic combination."*[337]

Together, these and related studies identify many design cases where the design was arrived at using cognitive processes not based on formal structures and processes, and

335 Eastman, "Explorations of the cognitive processes in design," 1968, p 13.
336 Ferguson, "Engineering and the Mind's Eye," 1992.
337 Hansen, cf Ferguson, "Engineering and the Mind's Eye," 1992, p54, italics original.

highlight their role, especially in bringing about flexibility and diversity in design and design thinking. However, while these studies argue against the emphasis on formal knowledge in engineering design education, the literature does not sufficiently elaborate the role that formal structures do play in technology design. This question is critical while developing possible ways to bring a sustainability focus to engineering education.

7.2 Design cognition view of cognitive processes in engineering design

In order to develop engineering learning processes that systematically incorporate sustainability principles in the design process, it is necessary to clearly characterize the role of formal structures in engineering design thinking. Towards this, in this section I attempt to arrive at an understanding of the overall cognitive processes in (engineering) design, by exploring a broader literature.

Formal knowledge is a distinctive feature of engineering design, compared to other kinds of design such as architecture or fashion design. Formal structures may thus be assumed to play a central role in engineering design. Design thinking research has not engaged directly with the question of what role formal structures play in engineering design, and the assumption is thus not confirmed. Philosophy of technology and philosophy of engineering have debated the related question of whether technology is applied science, which is an indirect way to ask whether technology development derives from formal scientific knowledge. It has been argued that scientific and technological knowledge differ, and technology is not merely applied science, although it may sometimes apply science (Vincenti, 1990). Such studies do not focus on the cognitive processes underlying design thinking. In this section, I provide a brief review of the design thinking literature against this background.

Reviewing research in design cognition over last several decades, Charles Eastman[338] comments that protocol analysis studies have contributed to developing an understanding of design cognition as distinct from other problem solving. He finds the ill-defined problem-solving terminology inadequate, and uses the term 'design context' to identify the rich structure of the outer environment, involving the system, physical, social, cultural, and environmental contexts.

Protocol analysis studies also identify some constituent activities such as context definition, multiple alternative generation, and so on, as well as external representations in use.[339] Particularly in the context of using and teaching-learning various external representations, Eastman points out that "How these representations are used, and especially how they are related to other mental constructs, seem central in understanding effective design".[340] Students were not found to be competent at using external representations or their analytical knowledge while solving unstructured design tasks. In this context, Tang's[341] study identified storing information, expressing ideas, and mediating interaction as some of the design thinking functions off-loaded to shared drawing surfaces such as large paper pads or white boards.

338 Eastman, "New directions in design cognition: Studies of representation and recall," 2001.
339 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 151.
340 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 151.
341 Tang, 1989, cf Minneman, "The social construction of a technical reality: empirical studies of group engineering design practice," 1991.

According to Goldschmidt,[342] visual analogy, a type of similarity-based reasoning, is most valuable for designing. Eastman also points out the use of mental imagery in the development of a design, and its relation to external representations.

> *"I have assumed that both effective use of external representations and learning them to the point that they can be effectively used internally as mental representations are basic skills that support more advanced work in all design fields. By understanding how this learning takes place and how different representations interact, we may come to understand the process by which these representation-dependent capabilities are built up, both within school and during professional experience."*[343]

According to Eastman,[344] Schon's analyses (Schon 1983, 1992) of design activities captures well a designer's 'dialogue' between internal and external representations, with 'seeing' as a way of internally representing spaces and forms, and 'moves' as a way of acting on/changing the internal and external representations, leading to either changing the form or to just reframing or reinterpretation.

Eastman also comments that some designers train themselves to experience the designs they come across in a specialized way. According to him, "design recall is a complex interaction between structuring experience, reflection about design knowledge and later recall in new design situations".[345]

Nevertheless, he points out that "While research in design cognition has been successful in identifying *what* designers do, it has been less so in identifying *how* they do it".[346]

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342 Goldschmidt, "Visual analogy – a strategy for design reasoning and learning," 2001.
343 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 187.
344 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 169.
345 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 176.
346 Eastman, "New directions in design cognition: Studies of representation and recall," 2001, p 150, italics original.

In summary, this wide and varied literature indicates that design thinking and the cognitive processes of design have been studied with keen research interest, especially for improving design practice and education. However, most of the studies assume an 'information-processing' model of cognition as the base of design cognition research. Recently, there is a turn towards more contemporary cognition approaches (distributed, situated and embodied cognition), but there are still large gaps in terms of understanding the cognitive processes and mechanisms underlying design. What was clear from the literature review is that these wide and disparate studies have not shed much light on the role formal structures play in design.

7.3 Cognitive processes in sustainable technology design practice: two empirical cases

Against this background, this study proposed a data-driven approach to characterize the cognitive processes in engineering design. First I analyze the empirical cases of GRI and EP, using a cognitive lens.

7.3.1 GRI's cognitive processes in the design of MHP systems

An analysis of GRI's historical design episodes and transitions, as well as empirical data from his interactions with a virtual MHP design system, offers the following insights into his cognitive processes, and the role of formal structures in his design thinking.

1. GRI's design process started with his felt need for electrical power, and this need is situated in his local eco-social context. He built his first prototype system by combining existing devices (such as a simple bicycle dynamo) available in his context. Though he lacked

formal training, he knew from experience that electricity could be generated (lamp would be lit) by rotating the shaft of a dynamo. His first idea for rotating the shaft using hydro power was derived from a simple traditional contraption (sometimes called the 'water ghost') used in the local paddy fields. GRI combined the two gadgets to light a simple torch bulb using water power.

He says of his thinking:

> *"Why not other movement except by pedal or hand? Why not water on a fiber-fan? I have plenty of water.."*

GRI's cognitive process of design (See Fig. 34) thus started from artifacts in the world, and the direction was from society through the artifact (prototype) to the designer (here GRI). GRI then built his first prototype by imagining a combination of the two real-world artifacts, and the cognitive process was from the designer to the prototype.

GRI's prototype was an implemented external representation of the structures and functions he mentally imagined.[347] He built in the real world what he imagined in his mind. As he built it and ran them in the real world, the prototypes interacted with his internal image and mental simulation, and further modified his understanding of the problem and the components.

This changed his mental image, allowing him to imagine further design elements. As David Kirsh[348] describes,

> *"… Because there is an external structure present, subjects can try out different internal and external representational forms, the two forms can play off each other in an interactive manner, leading to new insights."*

347 In this study, imagination is primarily taken to be the mental simulation of physical structures, and the internal /mental generation of activity or dynamics based on these structures.

348 Kirsh, "Thinking with external representations," 2010, p 444.

According to Kirsh,

"… external representations enhance cognitive power: they change the cost structure of the inferential landscape; they provide a structure that can serve as a shareable object of thought; they create persistent referents."[349]

2. As GRI engaged with the need to power more lights, TV etc., the socio-technical context became a part of the imagination[350] process from the prototype to designer. He continued to modify the prototypes, and the previous prototypes worked as models for his subsequent designs. (See pink arrows in Fig. 35). His design did not progress with the help of

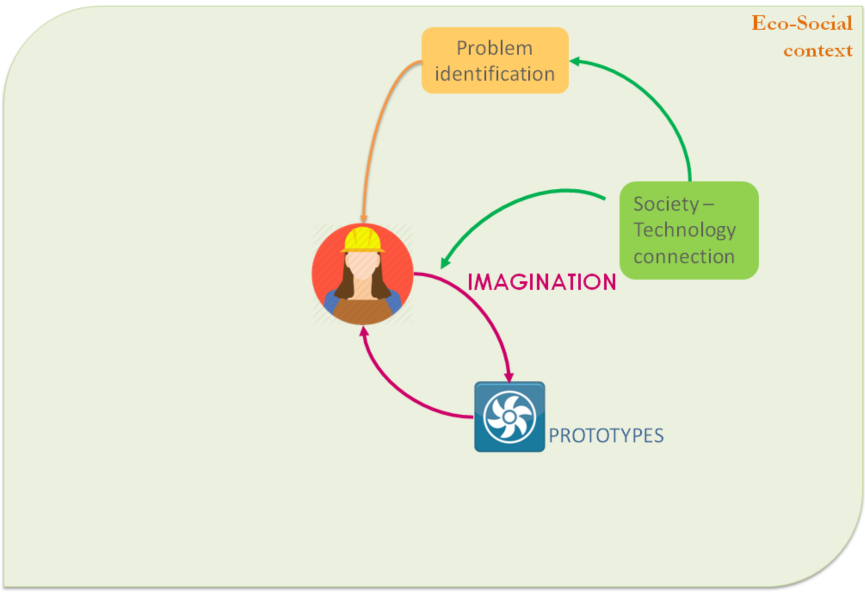

Fig. 34: GRI's cognitive process is mainly based on imagination.

formal structures, theories and equations, nor did he make drawings or theory-driven calculations. Instead, he created the systems themselves, and experimented with them to understand what he needed to modify. In terms of the cognitive process, he used each prototype as a model to think with, to understand the problem space and to think of the solutions.

349 Kirsh, "Thinking with external representations," 2010, p 441.
350 In this study, imagination is understood as the mental simulation of physical structures, and the mental generation of activity or dynamics based on these structures.

"It's [blower fan] ready available. First I will use. But is not umm it is not good. When it is water is crushed to the plate… water is fall down here… slipping.. it is not movement. But efficiency is .. very very less efficient.. Only 10 to 15%." "And after then I will change the … this type. 20 degrees. Light angle… light angle… so cups bend. Bend cup. .. Bend light twisted… light twisted." "I had no any industry in myself. But other wise I am going to other industry… other workshop. I will a … different designs.."

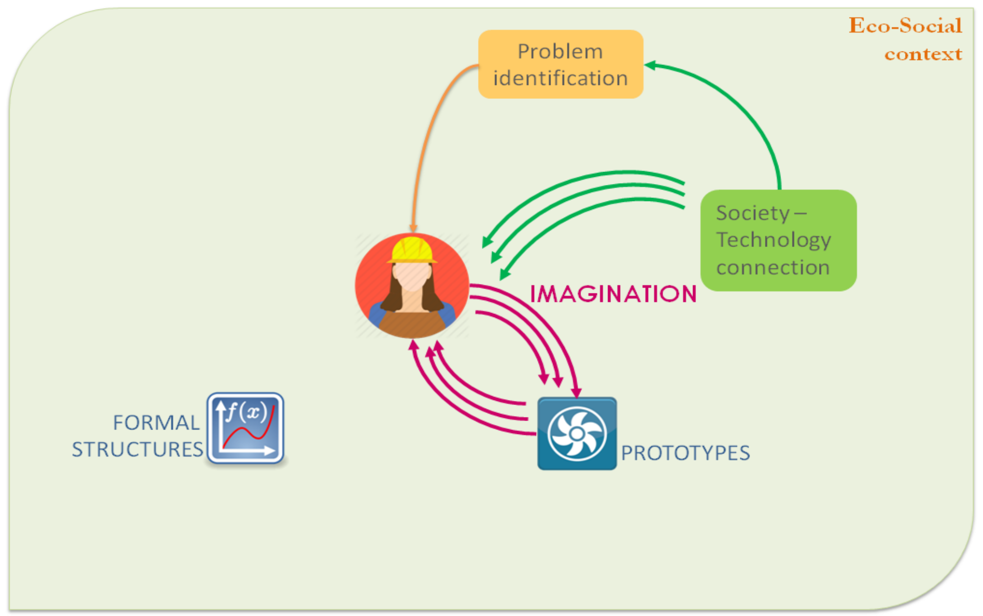

Fig. 35: GRI's cognitive process - prototypes worked as models for GRI's subsequent designs (pink arrows to and from prototype to designer), no formal structures or representations were used.

3. GRI then experimented with different materials, forms, and structural details, such as the blade angle, to modify and improve his first prototype of the turbine wheel. For this, he sourced discarded gadgets and parts from junk yards and scrap markets. His cognitive process of design, distributed across the prototypes and technological artifacts, and situated in the eco-social context, was driven by imagination (see the pink iterative arrows in Fig. 36).

"Cycle wheel completely paste cement.. cement wheel. <> One is.. it is not completely through.. <> through means alignment.. it is not alignment.. wobbling.. And another one is completely weight. Heavy. So it's .. it is not umm.."

"After then I will use.. same.. wooden.. <> [Like a] Bullock cart wheel.. hmm same.. same. Like spokes. Yes. <> That's [Bullock cart wheel] very heavy.. very big. I will start with Pelton wheel.. mostly it is 20 inches or 24 inches. [170109_006 – 03:00] I will completely make.. get one umm carpenter.. <> after then.. yeah, metal."

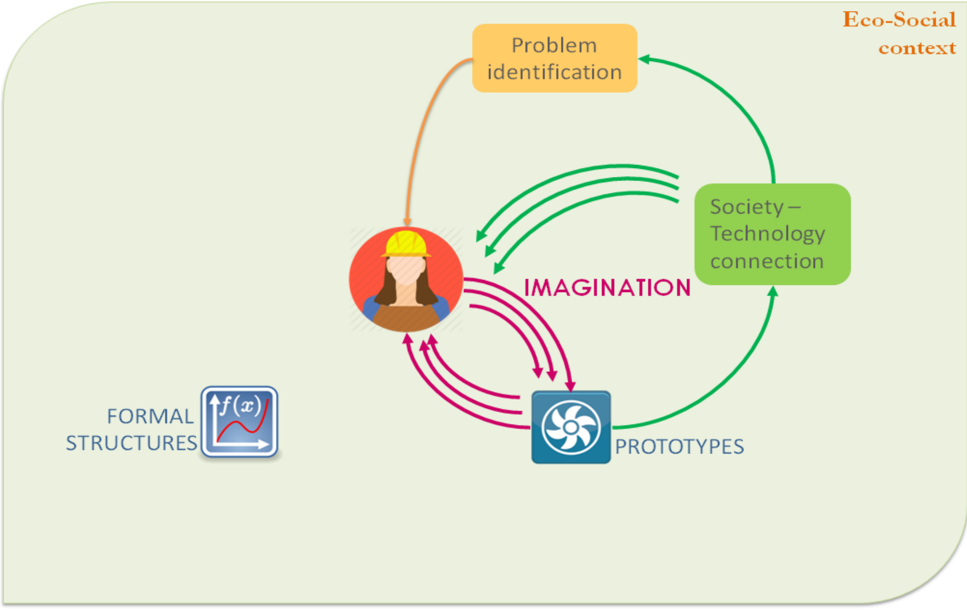

Fig. 36: GRI's cognitive process - Socio-technical connections (green arrows) were integrated with the cognitive process throughout the design cycle.

Similarly he improved the electromagnetic technology (replacing the dynamo with an alternator), and perfected the design for other necessary components of the system.

For example, to decide the required gradient of the penstock (pipeline that brings water to the turbine), GRI aligned the pipes and dropped a marble through the pipe at the top. Observing the speed as the marble emerged from the pipe at the bottom, he imagined (mentally simulated) the flow rate of water, and in turn the turbine rotation he would achieve with the gradient.

> *"Completely you will put the pipeline. .. After then.. using small umm inside the pipeline, a ball or a.. [hmm a marble] marble.. marble. Put inside .. in a marble.. top side. Then it will come to this side.. down.. umm.. [na.. flow?] very gradual. After then you will put the support .. That's a one technique.. that's a pipeline technique."*

> *"That's a calculation. How many time it will take to .. umm.. pull the .. in between the umm pipeline.. and in umm for the down side .. how many times it will take. .. that will relation to .. rpm. .. Slowly it will come in .. it's a gradual turbine. Suddenly it'll come.. definitely it is fast. Torque. Calculation of torque.. rpm and torque.. 2 pound, 1 pound. 3 pound. This type."*

> *"What's the timing.. the put in.. he will he will call.. I will put the ball inside in the pipe. Just I will.. just I will stopwatch. Then.. "*

> *"After 50-60, after then, some design .. it is.. tough.. after calculations.. the efficiency calculations. Turbine efficiency is 50%.. Almost.. the marble is coming the low speed.. decrease the efficiency.. 30-40-50. But average 50. 40 is maximum. Below in 40, it is not efficient.. it's not worth."*

He continued to address more complex needs and technical challenges in this manner, till he arrived at his final generic design to generate grid-quality power.

4. Lack of formal knowledge constrained GRI in terms of speed. He could not hasten the design process through ready comparisons and calibration using formal structures.

Instead, he improved by trial and error. For example, he did not know about the various types of turbine designs and their best performance charts for given head and discharge values. Through his own making and revising activity, he figured out where (high head) he should design a Pelton-like turbine, and where (canal/river) a modified waterwheel would work better.

Also, at the level of detailed design, even if he resolved the design into smaller sub-problems, he could not design or modify his components by using abstract criteria offered by formal parameters. He needed to build the components and run the entire system, to test the effect of any changes in design.

> *"One turbine I will completely install on the spot.. after then.. four types the Pelton wheel I will put ready to.. for testing purpose.. in the site. Same water.. same umm nozzle.. same head. It's not any changes. Only I'll changes only.. angle and direction of the wheel [means blades on the turbine wheel].. for different wheels. I will complete check the RPM. .. RPM.. the maximum RPM is finally.. One is complete check the RPM. And another is check the completely output volt. Difference eh.. lot of difference. 30 % - 20 % - 20% - 30%. .. Sometimes it is completely 40% difference. .. when the.. when change the angles."*

He thus designed by making, building, and testing, without any explicit formal structures.

This approach allowed him to frame and scope the problem differently from a formally trained engineer. In particular, he did not externalize the eco-social components from the problem formulation. This allowed him to define, test, and select the functions to be performed by his system in socio-technical terms, rather than componentized or idealized technical terms. His form definition followed these goals, and so his solutions turned out to be socially and ecologically more sustainable. (See the Prototype-Problem link through Society-Technology connection in Fig. 36).

Also, though he did not know the formal structures embedded in the design of such components, over the years, he developed an implicit function-level understanding of the underlying formal system, through the behavior of the ready components he used. He sometimes developed new ideas, and benefited from formal knowledge indirectly, through its embodiment in the various existing gadgets he used. For example, he realized that he could use permanent magnet alternators to generate power when RPM was low, when he came across wind mill technology.

> *"Then five years back, I will.. going to one umm one of the industrial towns [name of place], I will see the one alternator.. the magnet alternator.. for wind mill.. for small wind mill. Then I will think "Oh! This is a very perfect for me .. it is very.. low RPM.. yes!" Then I will suggestion.. then purchase the body.. the motor body.. then get.. that's how. Then we will completely challenge.. how you give the head or water, definitely we will give the power."*

7.3.1.1 Role of formal structures in GRI's cognitive process

1. GRI understood and selected components on the basis of their situated performance rather than idealized concepts. He learned about the functioning of the

components not in terms of abstract science and modularized behavior, but in terms of the component as a part of a system, coupled to other components, including the eco-social.

He thus understood the components not theoretically, but practically, along with their inter-relations and constraints. Due to this, he did not need to invest extra effort to integrate various bits of knowledge about the components gained. His knowledge was already integrated. For example, he searched scrap markets to see whether the modifications he wanted to make to his design were available in the form of discarded gadgets or their parts. He thus looked for the functions - that he needed to be performed - in the forms of existing machines.

With this, he also developed his own conceptual understanding of the components, such as turbines. His process indicates that prototypes are not mere instantiations of formal structures, but are thinking systems as well. It is interesting to note here that, in an influential study of the performance of waterwheels and windmills, John Smeaton used similar experiments and working scale models as the methods of study.[351] It is not clear how systematically GRI followed a method similar to 'parameter variation'. His data collection was possibly only indirect or implicit. Also, his later installations may have continued to add more data. GRI used his prototypes as real scale models, but he may have faced 'scale effect' issues, when scaling up or down a prototype for another situation. It is possible that he developed the tacit knowledge necessary to deal with this, something similar to a law of similitude described by Vincenti,[352] and an embodied sense of a dimensionless number (group of parameters), to arrive at a correspondence between parameters at different scales. GRI's

351 Smeaton, 1759, cf Vincenti, *What engineers know and how they know it*, 1990, p138.
352 Vincenti, *What engineers know and how they know it*, p 140.

reference to ‘percentage’ change in generated power or efficiency hints that this may be the case.

2. GRI designed by balancing the inputs and outputs of the various components within the overall constraints, rather than by making calculations to arrive at exact individual component specifications.

> *“By experience. It is not measurement. .. for e.g. you will calculate by 6 inch pipe, water is available in throughout year.. calculate approximately for e.g. it is available 30 feet head.. 5 kW. Thumb rule.. thumb.. means roughly that's it.”*

> *“.. increase the RPM very simply.. for e.g. this pulley.. mostly .. I'll just rough calculate.. diameter is 12 inches. Decrease.. 10 inches will do. Definitely 10% RPM is rise.”*

Even after having installed many MHP systems, he continues to finalize the pulley ratio on site, and not in advance. He installs the turbine and the alternator first, and then tries out different pulleys, to arrive at the best possible ratio for transferring and matching the RPM. His conceptual/mental model of power generation is not componentized into parts of the MHP system, or modules such as hydraulic, mechanical, and electromagnetic. He achieves the overall efficiency heuristically, rather than by improving the modular efficiency of individual components.

3. Initially GRI's focus was on designing a satisfactory domestic turbine that would generate sufficient rotation in the alternator that powered his target electrical gadgets. As he reached the limits of turbine rotation, he used coupling devices, especially belt-pulleys, as a means to magnify the turbine RPM two to three times. When this heuristic did not suffice for low discharge sites, he explored alternators that could generate electricity at lower rotations, and started adapting the permanent magnet alternator to resolve the problem. In this search for alternatives and components, GRI was exposed to formal engineering terminology used to

describe the phenomena and concepts. This exposure slowly aided him in communicating with and about formal structures. For example, he probably started talking about (and measuring exact) RPM, as he started interacting with formally trained engineers and engineering students.

7.3.2 EP’s cognitive processes in the design of MHP systems

An analysis of EP’s historical design episodes and transitions, as well as empirical data from his interactions with a virtual MHP design system, offers the following insights into his cognitive processes, and the role of formal structures in his design thinking.

1. Though EP is trained in the formal knowledge of engineering sciences and mathematics, EP's design episodes indicate that his cognitive process of design did not begin with or remain restricted to formal structures. For example, when EP designed his very first MHP system, he had very little funds. So he could not take the formal route to design and build a standard system as per the textbook. What he found around the location were traditional water mills running on perennial water streams. He adapted his conceptual model of hydro power generation (which is based on his formal training), to make use of these water mills to design a power system. To generate power, he thus had to imagine a different form to perform the function he conceptualized (See Fig. 37). See Table 1 for clarification of terms.

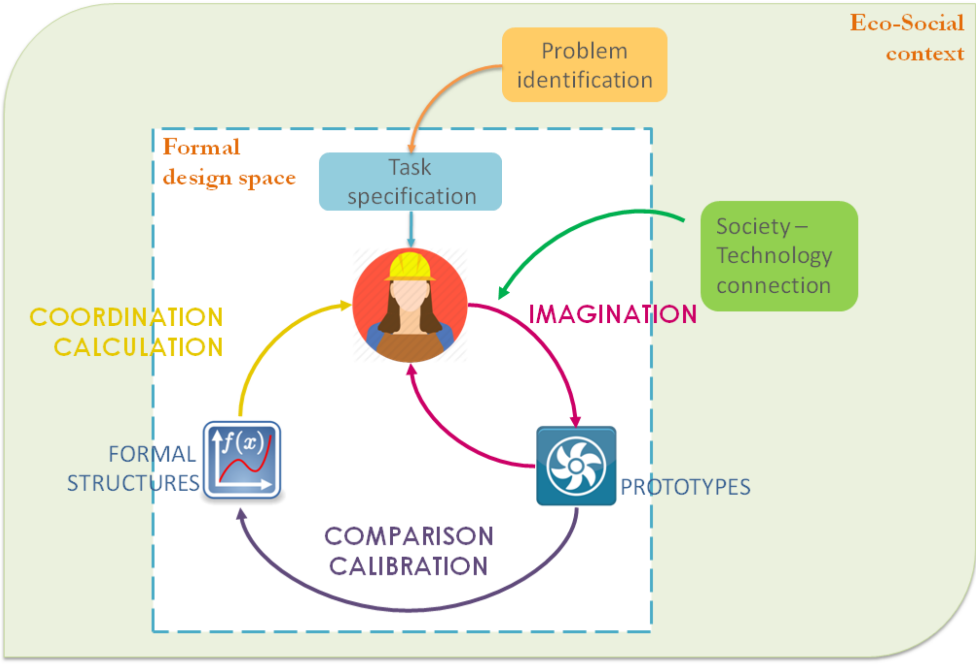

Fig. 37: EP's cognitive process - The rotation of a traditional mill by stream water allowed EP to imagine an alternate embodiment of his (formal) conceptual turbine. See Table 1 for clarification of terms.

The rotation of a traditional mill by stream water allowed him to imagine this alternate embodiment of the conceptual turbine. It acted as a prototype he could work with, and allowed him to arrive at a design through modification of the blades of the traditional mill. His formal knowledge enabled him to compare the traditional mill with a formal system, and calibrate its RPM for the required power generation using an alternator.

2. EP came up with a novel design at a site with a large seasonal variation in the source water discharge. Making the most of the high discharge potential, EP designed a system using two different alternators: one for the low and the other for the high discharge period. Following a standard textbook solution would have led to a system designed for average discharge. EP's novel design indicates that he did not think with such formal structures alone (See Fig. 38), and the design was driven by eco-social considerations.

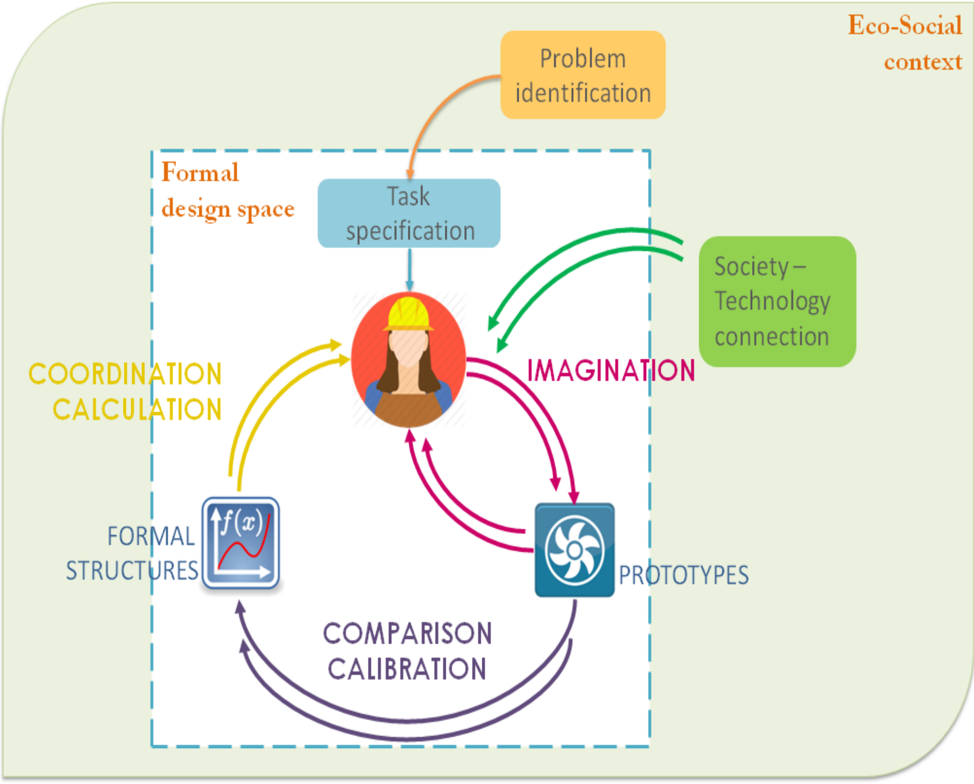

Fig. 38: EP's cognitive process - EP went beyond formal structures to innovate for the eco-social context, but was also limited to formal structures in non-technical aspects. In each of EP's design episodes, socio-technical connections (green arrows) were progressively integrated with the cognitive process. Prototypes worked as models for his subsequent designs (pink arrows to and from prototype to designer), and were also compared and calibrated with the formal structures (or representations where formal structures were not available) (purple arrows from prototypes to formal structures). Formal structures were also used for calculations and coordination (yellow arrows from formal structures to designer).

On the other hand, in opting for a Pelton turbine, EP remained guided by formal knowledge alone, and this led to his MHP system technology not being accessible to the villagers, and thus hard to maintain. EP had a head start because the problem triggered formal knowledge (that was generic), and it offered him a way to structure the problem very quickly. But it did not help him consider the aspects not included in formal structures (such as maintenance), and he had to discover those for himself after the design, to move to better solutions.

3. EP's design episodes, leading to his multi-purpose business model, indicate that he thought well beyond the disciplinary purview of hydrodynamics and hydraulic machines.

He extended his design to functions beyond lighting bulbs, to the running of income generating machines (See Fig. 39). For this he modified his MHP system and designed a combination that generated two different outputs from the same hydro turbine: electric power and mechanical drive. He then went ahead and modified processing machines to run on this mechanical drive, thus supporting livelihoods based on them.

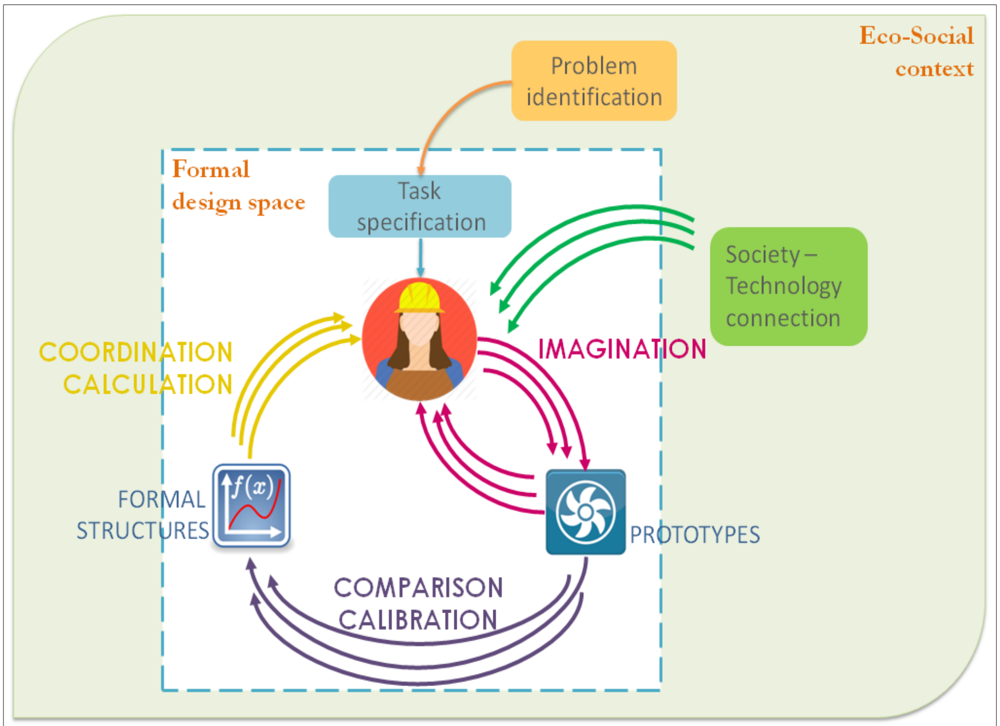

Fig. 39: EP's cognitive process - Engagement with local context and conditions broadened EP's problem definition to income-generating multi-purpose business model. EP did not start the design process with formal structures. Imagination allowed for a widening of the design space, beyond technical input-output parameters, to include the eco-social context.

EP had formal training, but engagement with local context and conditions broadened his problem definition (See Chapter 7, also Date & Chandrasekharan, 2016). In each of his design episodes, imagination allowed for a widening of the design space, beyond technical input-output parameters, to include the eco-social context.

7.3.2.1 Role of formal structures in EP's cognitive process

1. EP being formally trained, was fluent with external representations used in engineering design, especially ones based on formal mathematics and engineering sciences. For example, he referred to survey maps, graphs, and hydrological charts to estimate the discharge of water available at a site, and its seasonal variations. The formal structures allowed EP to have more information about the site conditions and variations. He was able to cross-check and design faster. He was also aware of turbine performance charts, friction loss studies, and research literature. Comparison with formal structures allowed him to validate and calibrate his prototypes, as in the case of Pelton and Cross flow turbines. Formal structures also allowed him to clearly communicate the design specifications to the fabricators, or to purchase various off-the-shelf components, including generators.

2. Despite the formal knowledge, EP's design process did not follow a calculation route. Hydrodynamics equations/algorithms are used to calculate the theoretical hydraulic power generated from a given head and discharge. Despite his formal training, EP's first response was not this calculation in the simulation Task 4 (numeric), where given a head (4 m) and discharge (16.25 lps), he was required to estimate the power generated in the virtual MHP system.

As soon as he read the task, EP asked for the use of pen and paper. He first asked himself what the velocity would be, and used the given data to approximately estimate the velocity of water, and then the area of the nozzle.

> *"What should be the velocity of this? See v square is equal to under root 2gh. Okay? Now 2 into 9.81 into h, is 4 meters. Under root this. So this will be 8 into 9.81. So this is 72 say nearly 80. Approximately, if this is .. this should be nearly 9 m/s."*

He used the discharge value to estimate the area of the nozzle. This would allow him to estimate the diameter of the nozzle.

> *"Area will be.. [na] divide by [na]. Now this.. this is saying .. 16.. 16 meters. So this will be .016 over 9, into area. (silence) so this is your.. roughly this is what it would be, right? So this is meter square. Meter square. So this will be zero point .. how much? [na] (silence) [na] (silence). This will come 0.14 into 0.14 meter. .. what will be the area of this .. if it is 16.25 l/s, 4 meter is the head so.. so this is the area."*

In real-world design activity, these parameter values would further help him design the turbine runner diameter, and progressively the number of blades. This is what he would use the given data for.

But then he read the task again, and commented that there was no need for these calculations. He realized that in the virtual scenario, he was required to just use the theoretical equation to arrive at the potential power generated at the site with the given head and discharge values. He then used the idealized equation (Hydraulic power P = ηghQ, where Q is the discharge in lps or m3/s, and η is the efficiency) to calculate power.

> *"So we don't need to do all this, we don't have to calculate this area.. I was actually checking how much it is.. Very simple this is 4 into 16.25. Divided by 1000, into 10. Actually. It is this. So that'll give you (silence) 4 into 16.25 into ten over [na.. other sounds] (calculates). It just generates .. 650? kW."*

This interaction indicates that for him, the power generated at this site would depend on the turbine and alternator configuration he would design in this way, and he did not use the values of head and discharge to calculate the potential (theoretical) hydraulic power.

It also indicates how he possibly uses the values of head and discharge in his design of various components. Despite the formal knowledge of theory and idealized equations, EP automatically followed an imagination process, where he mentally simulated the head and discharge in terms of their real-world implications for the design of various parts of his system, rather than as numeric inputs to churn out a numeric output of the amount of power generated. His mental model of power generation consisted of the complex interactions of various design considerations, of which the head and discharge values were only one part. This mental model is not made up of idealized parameters and formal structures. This indicates that even in the virtual scenario, his process of estimation - of power that could be generated -- followed not the theoretical equation, but the mental simulation path of designing the entire system, based on his experiential knowledge, thumb rules, and repertoire of previous designs.

He then used the data and equations for 'back of the envelope' level calculations for detailed design of components. For example, in the design of the settling chamber, theory as well as experiment-based exact data are available. But EP only used it to arrive at the approximate design values.

> *"I have approximated, I have not at all done this on a very scientific basis <> I have done this for large particle size, they have done it for very fine particles [also].<> Actually these are all old experiments I have done. So we have seen there that particle size smaller than 1-1 will settle down. But exactly how smaller than 1-1 will settle, I have no idea."*

3. EP did not design by formal knowledge alone. Instead, his design process was situated in the context. He interacted with the local people and the location constantly, throughout his design process, and this added to his understanding of the problem, as well as the solution that would work the best.

> *".. he [local person] does not understand velocity part. He understands only that this is the level of water flowing. So two inch water can be moving like this, or two inch water can be moving like this. There's a big difference between the two."*

> *"After looking at the site condition, only then we'll feel you know, that we can do something here."*
>
> *"So whenever we talk.. so we keep visiting.. looking at the site. You have that site in mind, and you know how much water is flowing.."*
>
> *"How much water is flowing.. what is running on that [power]? Does even a water mill run [on it]? Ya.. so that gives lot of ideas, that on this water [power] this can be run.. more than that cannot be run [powered]. So this is one thing that happens.. you understand what is the potential here [of the site]."*

EP also referred to many thumb rules, such as 'the jet should hit three blades', 'the pipe size should be over-designed to reduce friction losses', 'it is better to lose head than have the system in the line of floods', or 'the belt-pulley ratio should not be more than 1:3'. He follows these for detailed design of components as well as for testing, and verification. These indicate how his procedural, heuristic, experiential, and locally situated knowledge comes together, and have crystallized over the years into declarative, but largely qualitative, knowledge. This fused qualitative knowledge plays the largest role in his design process, the formal knowledge only plays a subsidiary role.

7.3.3 Cognitive processes in sustainable grassroots technology design

As MHP systems are a traditional technology that has been around for a while, it is possible that the design of such systems just require customization, or tweaking of the given formal parameters, to suit the requirements, as the formal structure of such systems are known. But the two cases (formally-trained engineer, non-formal innovator), both demonstrate that imagination (mental simulation) is the key mental process driving the generation of the material form, and not parameter-based thinking.

1. The cognitive process of design started with external artifacts, and not formal theoretical structures, including calculations.

2. Both GRI and EP used structures in the design context, to build with and to think with. Their prototypes were themselves external representations of the structures and functions they mentally imagined. Previous prototypes worked as models for their subsequent designs. Imagination is their central cognitive process.

3. They also used their judgment of the water flow and its variations, as well as local knowledge. Their design process was cognitively situated in the location, and the society that they worked for and with.

4. Lack of formal knowledge made it necessary for GRI to conduct many trials, and carry a range of spare parts such as flywheels of diverse specifications, whereas EP could save experimentation time, effort, and cost using formal knowledge.

5. In the particular design episode where EP's cognitive process was driven by formal structures alone, it quickly brought structure to the ill-structured problem. But in this case, his design considerations remained technical, and sustainability was attempted as an afterthought or an add-on.

6. In the design episodes where EP's cognitive process of imagination was supplemented by formal structures, he could calibrate, calculate, and optimize his design.

7. Both GRI and EP developed and used thumb rules and heuristics. Their procedural, heuristic, experiential, and locally situated knowledge came together in the design process. Even for EP, his formal knowledge was one part of the design process, and not its main driver.

The Designer – Prototype – Formal structure relationship is thus best understood as a distributed cognitive system, situated in the larger and local eco-social context. Based on this analysis, I propose the following schematic model of the cognitive processes of sustainable technology design at the grassroots (See Fig. 40).[353]

The model depicts imagination as the core cognitive process. This allows both the formal and the non-formal (eco-social) to play key parts in the design space, thus widening it beyond the formal design space. This enables the society-technology connection to be an active and constant component of the iterative cognitive process. This is seen in terms of participation of various stakeholders (including the users) in the testing of the prototypes, as well as the re-framing of the problem with the help of the prototype. These aspects provide the *potential* to develop a design process where any given sustainability design principles could have the opportunity/space to play a central role, and thus lead to technologies that promote sustainability.

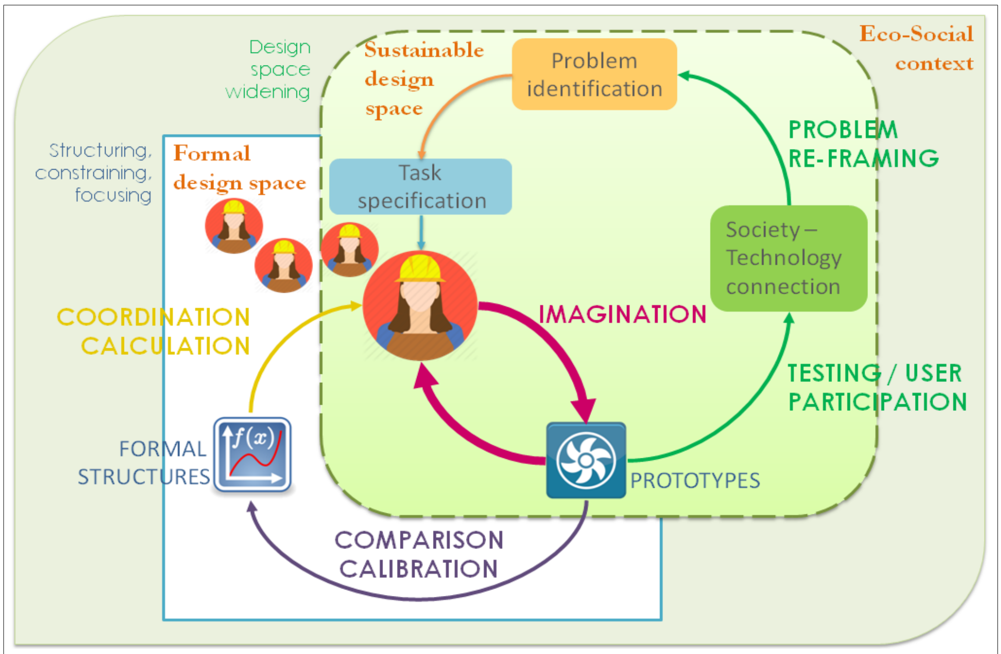

Fig. 40: Imagination widens the design space, to include the eco-social.

353 See Table 1 for clarification of terms.

The imagination process is supported by the interaction between formal structures, the prototype and the designer, and this provides structure to the problem space, through comparison, and calibration, of different designs. This process helps constrain and focus the search for solutions within the wider design space. Once the initial framework is set up using imagination, detailed design is speeded up through calculations based on formal structures, for cases where such modeling is possible. Coordination with stakeholders, or team members if any (see other designers in Fig. 40), becomes easier as well, because formal structures provide a standard framework for reaching consensus on the design specifications.

The two cases of grassroots technology design practices demonstrate that the cognitive processes of the two designers create a sustainable design space, which is open to both the eco-social context (the porous boundary in Fig. 40) as well as the use of formal structures.

7.4 Comparison with additional cases

It could be argued that this cognitive process model works only for a known and traditional ‘normal’[354] technology like the MHP system, but not for advanced or radical[355] technology design. A role for imagination may not be contested, but it could be argued that the mainstay of innovation would be formal structures, especially when expert engineering scientists design a cutting-edge or revolutionary[356] technology.

In other words, is this characterization of grassroots technology design practice limited in scope, and a result of the choice of cases? Are there other design cases which

354 Vincenti, *What engineers know and how they know it*, 1990, p. 210.
355 Vincenti, *What engineers know and how they know it*, 1990, p. 210.
356 Vincenti, *What engineers know and how they know it*, 1990, p. 210.

demonstrate similar characteristics? Can other cases add to this understanding of technology design thinking?

In order to explore if the findings are only an effect of the empirical cases selected and to widen the base for the above findings, I expanded the analysis to two comparison cases, where the design problems were very different from MHP.

As a contrast to the traditional MHP technology, I first discuss the case of designing a futuristic fuel cell technology. In this case, the engineering theory, i.e. the formal structures, are not entirely known, and the operational principles and configurations are still in the process of development. I discuss two examples from this case; the cooling duct and the gasket.

Secondly, I discuss a real-time case of design, where the task was to estimate whether the human heart can provide enough power to uncork a wine bottle.[357] As this case is an empirical study, it also provides a contrast to the other three cases, which are historical.

7.4.1 Case study of Fuel cell cooling duct design

At an Indian R & D lab researching advanced fuel cell technology, a cooling duct needed to be designed, to pass cooling air uniformly through a large number of hot fuel cell plates. This problem involved calculating the dimensions of the duct, and deciding the specifications of the blower fan at one end of the duct. The engineering scientists anticipated (i.e. imagined) lesser air flow through the plates at the end of the duct, and to compensate for this, they designed a tapering duct using Computational Fluid Dynamics (CFD) (Fig. 41).

357 Kothiyal et al., ""Hearts Pump and Hearts Beat": Engineering Estimation as a form of model-based reasoning," 2016.

The design problem 1

The computational simulation indicated that their design parameters created uneven air flow at both ends of the duct, and contrary to their anticipation, more cooling occurred at the end farthest from the air inlet. (Fig. 41 Base case plot).

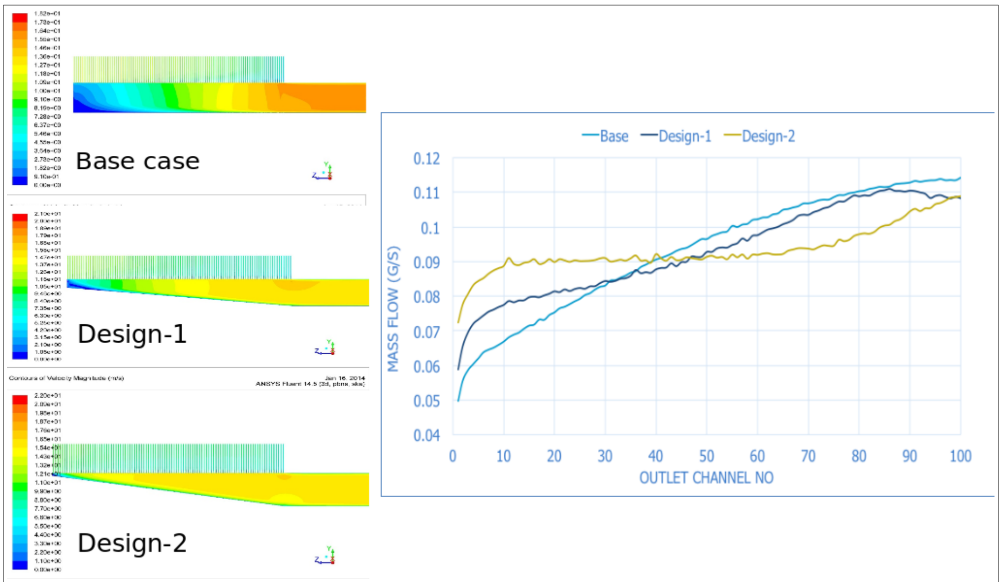

Fig. 41: CFD plots for performance of virtual cooling duct prototypes for fuel cell stack

The cognitive process of design

Imagining the air flow enabled the scientists to interpret the CFD results. The scientists reasoned that more air flowing towards the end of the duct implied a higher pressure head at the end of the duct. The tapering shape of the duct needed to be modified to reduce the pressure head at the end. (Fig. 42 Design (a)).

The solution part 1

The scientists modified the design parameters such that the diameter of the duct became less linearly (to create tapering), but towards the end, for the last few plates, the duct diameter was narrower than at the inlet, but even, not tapered. Using CFD they fine-tuned the length of the even-diameter end region to achieve near-even air flow at the end. (Fig. 41 Design-1, Design-2 plots).

The design problem 2

However, this did not resolve the uneven air flow at the beginning of the duct. (Fig. 41 Design-2 plot).

The cognitive process of design

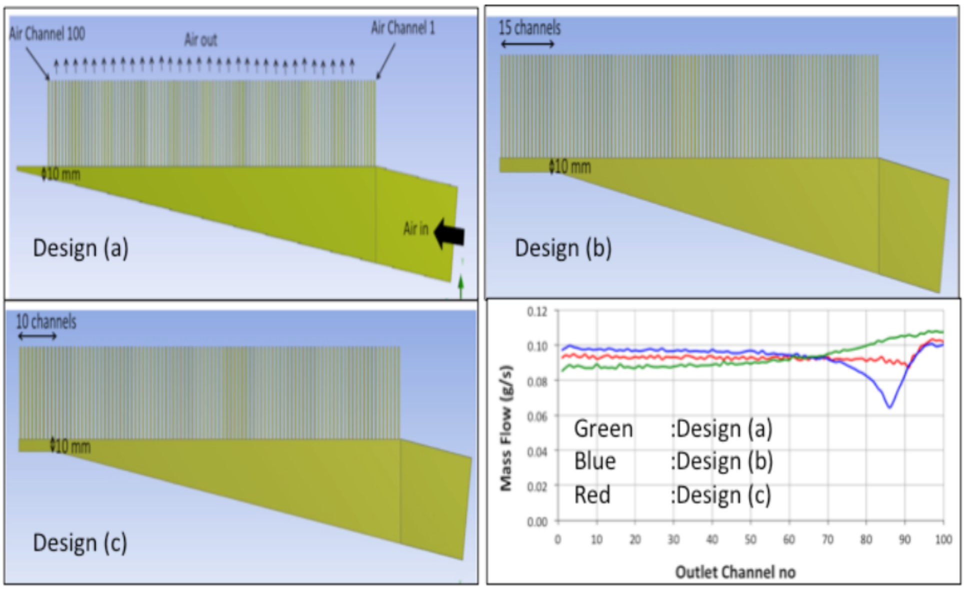

Fig. 42: ESs' prototypes of cooling ducts

Imagining the air flowing in the duct, the scientists reasoned that the air was flowing in horizontal direction as it entered, and hence bypassed the first few plates of the fuel cell stack. For the air to enter the vertical plates above the duct, the air flow needed to be directed vertically. (Fig. 42 Design (a)).

The solution part 2

The scientists modified the design parameters such that the duct opening at the blower end was not entirely horizontal. Again using CFD, they fine-tuned the angle of the duct, such that the air flow had a sufficient vertical component to enter all the stack plates evenly. (Fig. 42 Design (c)).

7.4.1.1 Engineering scientists' (ESs-1) cognitive process model for fuel cell cooling duct design

The engineering scientists imagined a tapering duct, and designed a prototype in CFD. The CFD simulation allowed them to 'run' the performance of the prototype exactly, and the simulation indicated the problems. Here the simulation works as an external imagination, as without the CFD system, this 'run' of the simulation would have been done using the mind. The external CFD model also works as a 'manifested' model,[358] which helps in arriving at a consensus.

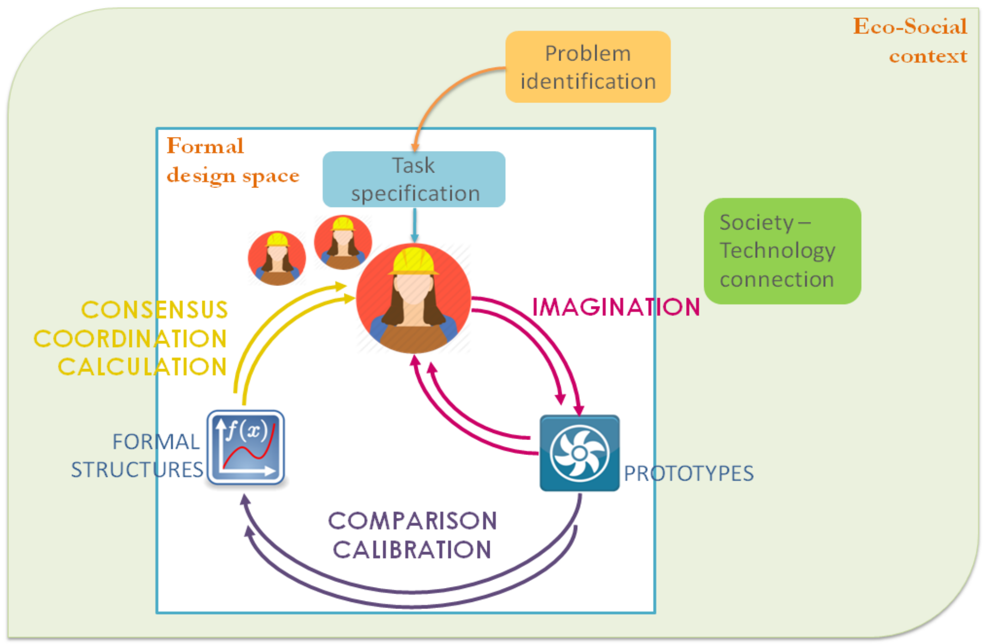

Fig. 43: ESs' cognitive process in design of cooling duct

This understanding of the cognitive process of design of the cooling system (Fig. 43) highlights the role of imagination in the diagnosis of the problems, which is achieved through an understanding of the imagined behavior of air, and not through formal training.

358 Chandrasekharan & Nersessian, "Rethinking correspondence: how the process of constructing models leads to discoveries and transfer in the bioengineering sciences," 2018.

This imagination process allowed an interpretation of the CFD results, and indicated the necessary modifications of the design parameters in CFD. Formal structures built into CFD supported the simulation of air flow through the cooling duct designed by the scientists, thus providing a rough understanding of the system's behavior. It displayed results in the form of performance graphs, enabling the scientists to compare the performances of the various virtual prototypes with both the previous results and the theoretical standards. This allowed calibrating their design at-a-glance. The 'manifested' behavior, captured by the representations, also facilitated the team’s discussions around the design problems, findings, and decisions, and helped them communicate the final specifications to the fabricator.

7.4.2 Case study of Fuel cell gasket design

At the same R & D lab, the engineering scientists were developing the technology to stack multiple fuel cell plates together, to supply more power.

The design problem

The scientists found that the hard fuel cell plates cracked under compression pressure, despite having a soft rubber gasket between every two plates. The team did not have any formal expertise on this problem. They also could not find any obvious explanation or remedy for the problem in the formal literature.

The cognitive process of design

The scientists then took measurements of several cracked plates, and plotted graphs. They found a pattern in the cracking – all the cracks appeared near the gaskets. (Fig. 44, Fig. 45). Bringing their own experience of rubber, they imagined that the gasket may be buckling under compression pressure and slipping from its groove, where the groove had only three walls. To resolve this, they added a wall support on the fourth side of the groove (Fig. 46).

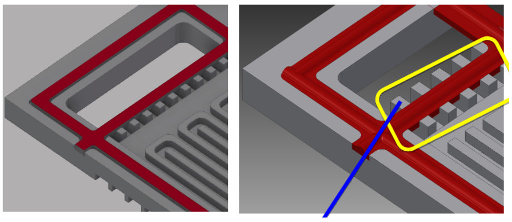

Fig. 46: Support on the fourth side of the groove

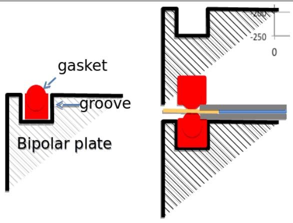

Fig. 44: Cracks near the gasket

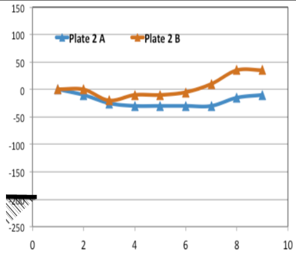

Fig. 45: Cracking patterns

While this controlled the slippage of the gasket, it did not resolve the cracking of the plates. They had a hunch that the gasket was not able to expand and absorb the pressure (Fig. 44). They discussed the issue with a gasket manufacturer and an expert who worked with gaskets. Their hunch was confirmed by both.

The solution

With several trials of the groove size using three different dies of the gasket, and 20 more cracked plates, the problem was finally solved, in three months. The gasket groove was widened, allowing just enough space for the gasket to expand when under compression pressure, but not enough to allow any leakage. (Fig. 44).

7.4.2.1 Engineering scientists' (ESs-2) cognitive process model for fuel cell gasket design

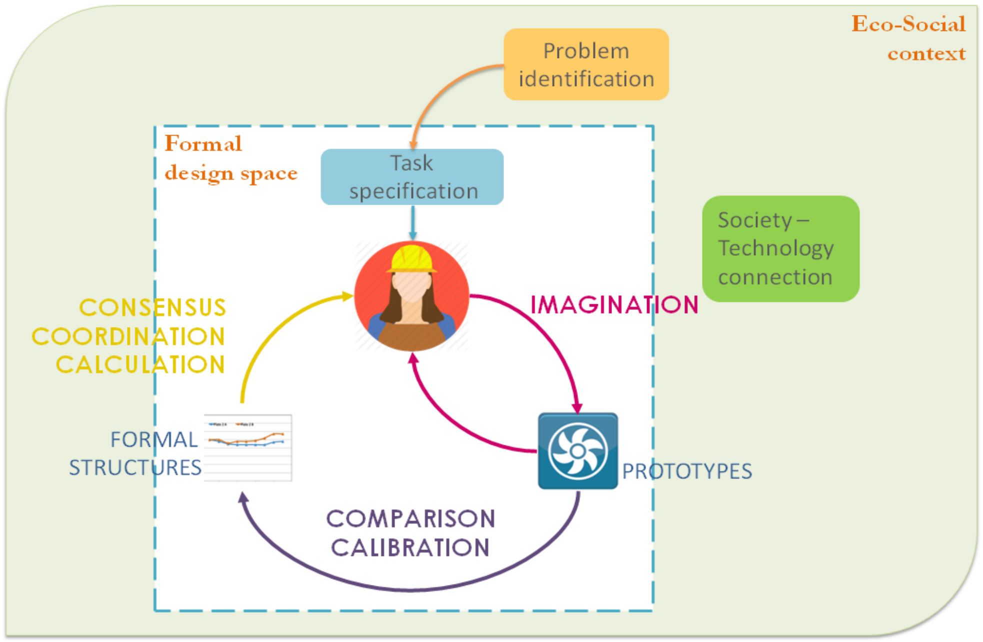

Fig. 47: ESs' cognitive process of design of the gasket groove

The engineering scientists' team could not apply any formal structures to diagnose or resolve the plate-cracking problem in the fuel cell stack design. They started by collecting observation data from the prototypes, and created graphical representations (their own part-formal structures) to identify performance patterns. This allowed them to imagine a possible scenario, where even though it was the plates that cracked, the problem was with the gasket. (Fig. 47).

The scientists used formal representations to identify patterns, and this allowed them to image a possible solution. Despite being an advanced R&D lab, and the engineering scientists being formally trained, since formal structures were not available for this open-ended problem, the group needed to engage with others in the society, who were non-formally trained, and knowledgeable about the behavior of rubber gaskets. They then used trial and error methods to resolve the problem. Their imagination process for this problem thus seems similar to the non-trained innovator building an MHP system (Fig. 48).

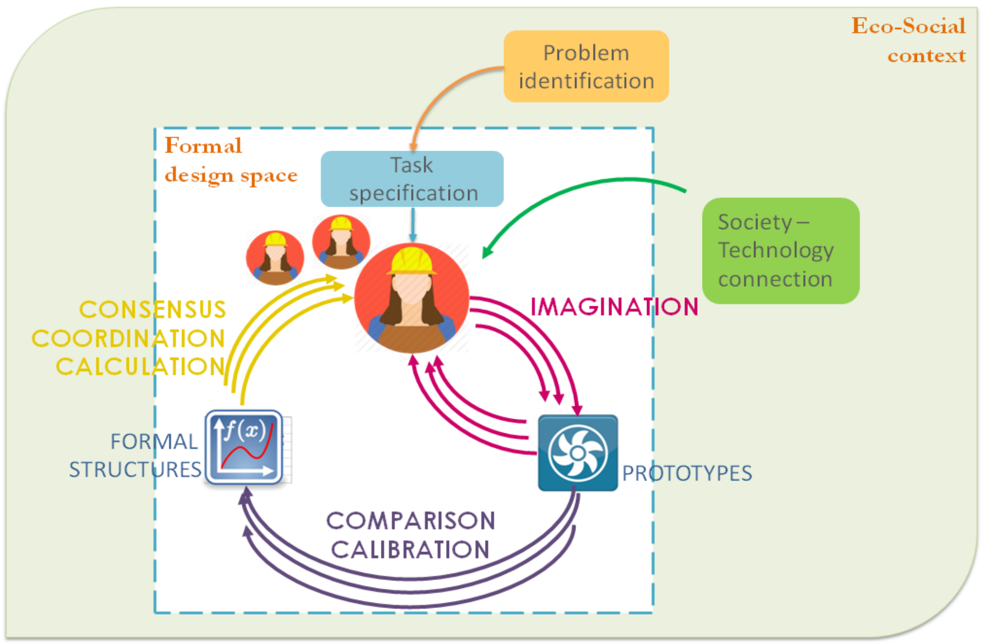

Fig. 48: ESs' cognitive process of design of the gasket groove

However, formal structures allowed the scientists to coordinate the prototype modifications through trial and error.

7.4.3 Case study of estimation: 'opening a wine bottle by the power of a human heart'

Kothiyal et al.[359] conducted a study in which two expert engineering educators (EEE) were independently given the problem of estimating whether the human heart could run a wine opener. Interestingly, both the experts followed different artifact approaches (heart-as-pump, heart-as-driving a ratchet) to design a technology to address this task, but arrived at a similar estimate through this process of design.

The design problem

In the estimation process, one of the experts (E1) modeled the heart's pumping function, while the other (E2) the beating function. Both arrived at the same qualitative

359 Kothiyal et al., ""Hearts Pump and Hearts Beat": Engineering Estimation as a form of model-based reasoning," 2016.

estimate. Only in the last phase of the estimation process, did one of them perform engineering calculations (Fig. 49).

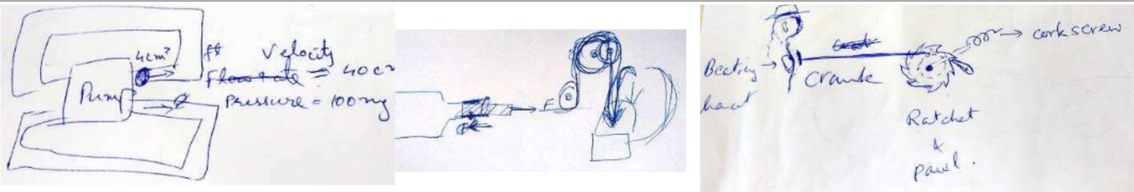

Fig. 49: a) Heart pumps b) Heart beats

The cognitive process of design

According to the researchers, the experts' design process demonstrates model-based reasoning in three phases:

1. Create a functional model by mentally modeling the dynamics of the system based on a known system (pump, ratchet)
2. Create a qualitative model by detailing out the structure and components, based on the working of the functional model
3. Create a quantitative model by applying engineering principles to reason, develop equations, calculate and evaluate

The solution

While E1 thought that hearts pump and modeled/designed a technical system based on it, and E2 thought that hearts beat and modeled/designed a technical system based on it, both of them estimated that it would take forever to open the bottle "using" the heart, but that it can be done.[360]

360 Kothiyal et al., ""Hearts Pump and Hearts Beat": Engineering Estimation as a form of model-based reasoning," 2016.

7.4.3.1 Expert engineering educators' (EEEs) cognitive process model for 'opening a wine bottle by the power of the human heart'

The experts started by mentally simulating the dynamics of the problem system (heart and unscrewing a wine bottle cork), entirely or in part. (Fig. 50).

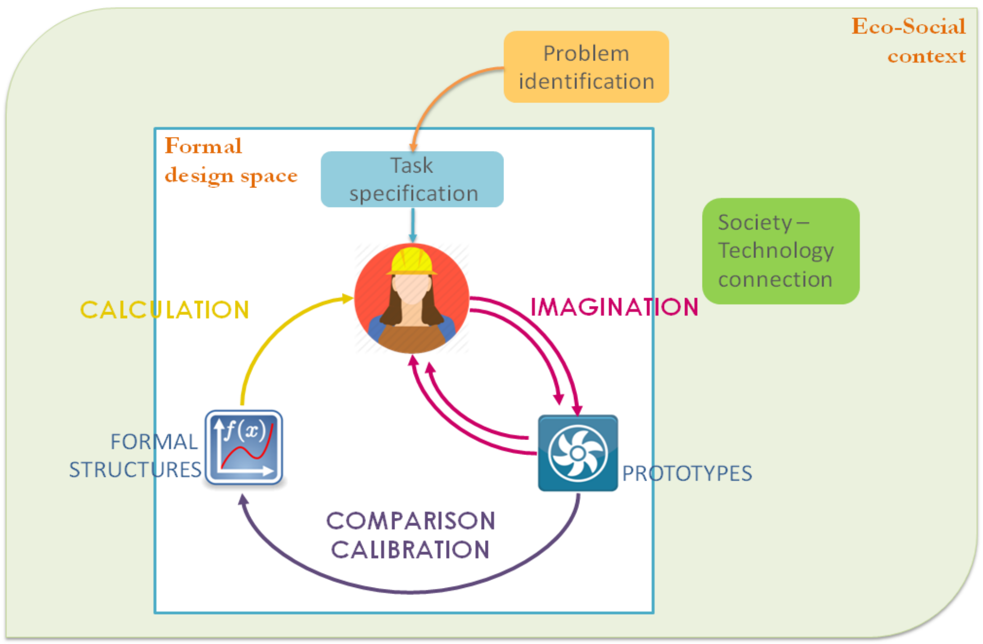

Fig. 50: EEEs' cognitive process in estimating the power of heart

A real-world system or artifact, known to the expert, was used to 'instantiate' the simulated dynamics (e.g. heart is a pump). This mental simulation helped them to develop an initial functional model of the situation. The engineering principles helped in detailing and converging the mental simulation and model-based reasoning, but were not themselves generators of solutions.[361]

This case further illustrates that imagination is at the core of engineering thinking, and formal structures only play a subsidiary role.

361 Kothiyal et al., ""Hearts Pump and Hearts Beat": Engineering Estimation as a form of model-based reasoning," 2016.

7.5 Comparison with the canonical training process for engineering design (thinking)

Jorgensen[362] has argued that ‘engineering design’ needs to be the core course in engineering training. Most engineering education, however, emphasizes engineering sciences and mathematics as the core courses. (Possibly as an effect of the launch of the Russian satellite Sputnik, after which “What came to be known as engineering design became a downstream application of science-based problem solving..”[363]). This suggests that canonical engineering education is based on the assumption that the central cognitive processes in engineering activity (i.e. engineering design) entail applying the formal knowledge from these core courses.

7.5.1 The canonical model of cognitive processes in design training

Given this, the cognitive process schematic for the canonical training in engineering design may be depicted as follows (Fig. 51). As per the schematic,

362 Jorgensen, “Constructions of the Core of Engineering: Technology and Design as Modes of Social Intervention,” 2015

363 Downey, “Are Engineers Losing Control Of Technology?” 2005, p 585.

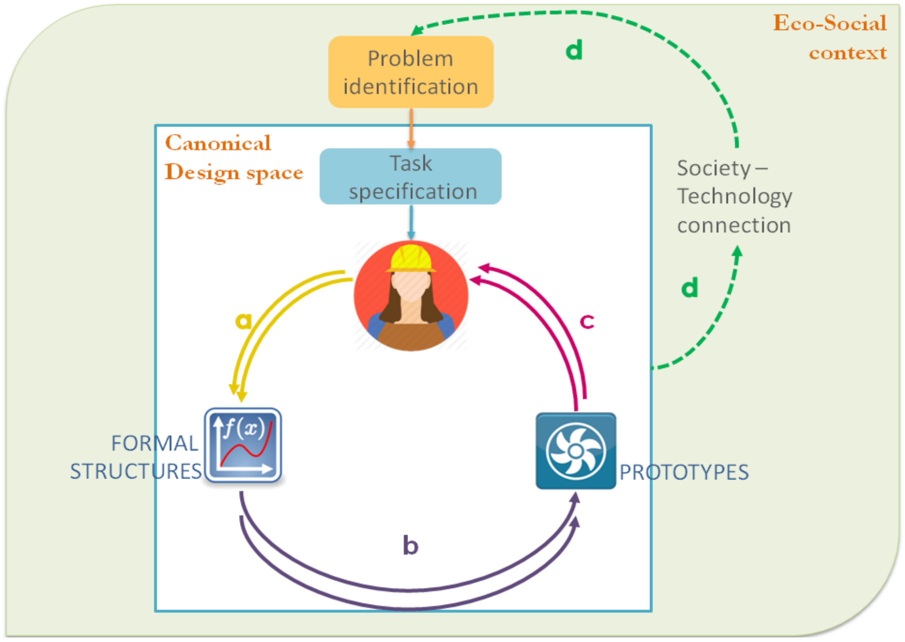

Fig. 51: Canonical model of cognitive processes in design training

a) The designer-formal structure (theory, model, formula, equation) interaction is expected to be based on the engineer's training in formal knowledge, and is assumed to be known (analysis, idealization, calculation). The interaction direction is designer to formal structure.

b) The formal structures lead to the generation of the prototype. The interaction direction is formal structure to prototype.

c) The design process is understood to be iterative. While it is acknowledged that designer-prototype interaction occurs, the role/direction of this interaction, and the cognitive processes underlying it, are not well characterized, and are more-or-less ignored in canonical training.

d) It is also not well-understood how this closed design-cognition space interacts with the eco-social, if at all. Assuming that engineering education trains students for mainstream engineering practice, this is particularly a concern in the context of designing for sustainability. In the mainstream industrial scenario, the design activity is located and embedded in a closed industrial context that forms a design space isolated from the (real-world) context of the problem. There is rarely any interaction between the eco-social context (where the problem and its solution are embedded) on the one hand and the engineer, the prototype, and the formal structures on the other. The connection between the design and context is mediated by specifications and requirements, which are usually developed by non-engineers, such as marketing professionals or 'innovators'.

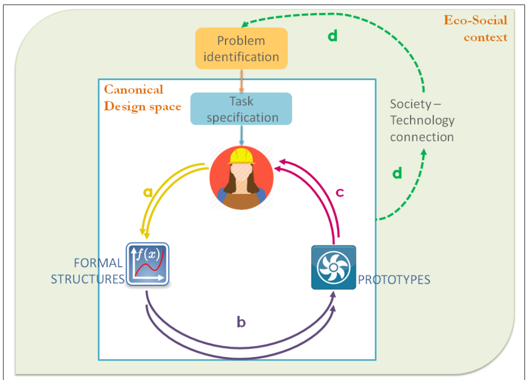

Fig. 53: Cognitive process in canonical design training (same as Fig. 51)

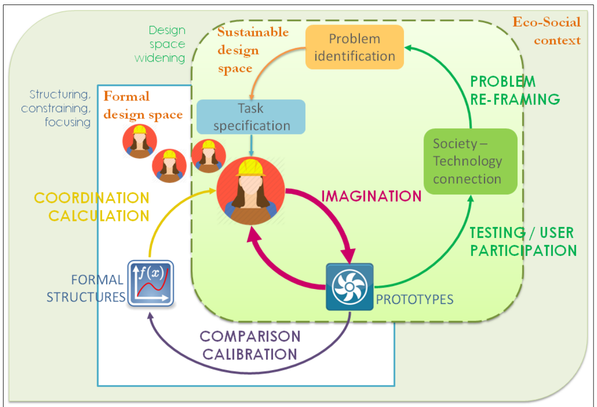

Fig. 52: Cognitive processes of engineering practitioners

Comparing the characterization of cognitive processes in design (Fig. 52) I have developed (based on empirical data, as well as the additional cases), with the above schematic (Fig. 53) of canonical engineering education (which is not based on empirical data), it is difficult to avoid the conclusion that that the canonical approach to engineering education, and the (implicit) assumptions underlying it, needs to be strongly questioned and challenged.

7.5.2 Engineering students' (ELs) cognitive process in design of MHP system in a learning context

Two pairs of engineering students in consecutive batches designed a pico hydro power system in a final-year engineering project. Assuming a problem situation of erratic and insufficient power supply, they calculated that annual harvest of roof-top rain water in the region, if stored, would help sustainably generate sufficient power for a household. Based on known theory, they decided that a Pelton turbine (See Fig. 54) would be appropriate.


Fig. 54: Standard Pelton turbine with castings of split and notched buckets


Fig. 56: Students' modified Pelton turbine with wooden runner, innovative buckets


Fig. 55: Students' modified Pelton PVC bucket with a notch and W splitter

They started with the design specifications available to them from textbooks, and journal papers. But constraints of funding, workshop facility, and time, made it necessary for them to develop the Pelton turbine from alternate materials. This led them to develop alternate Pelton buckets out of PVC pipes cut in half, and W-shaped deflectors made out of bent steel plates. The W fitted in the PVC cups performed the role of splitters, as in a sophisticated casting of a Pelton bucket (See Fig. 55).

Though the students did not engage with the (real-world) eco-social context of their technology, they interacted with their own social (institutional) and techno-economic context, to find the appropriate materials and ways to work with them. This widened their design space and enabled them to benefit from the plasticity of the socio-technical connection.

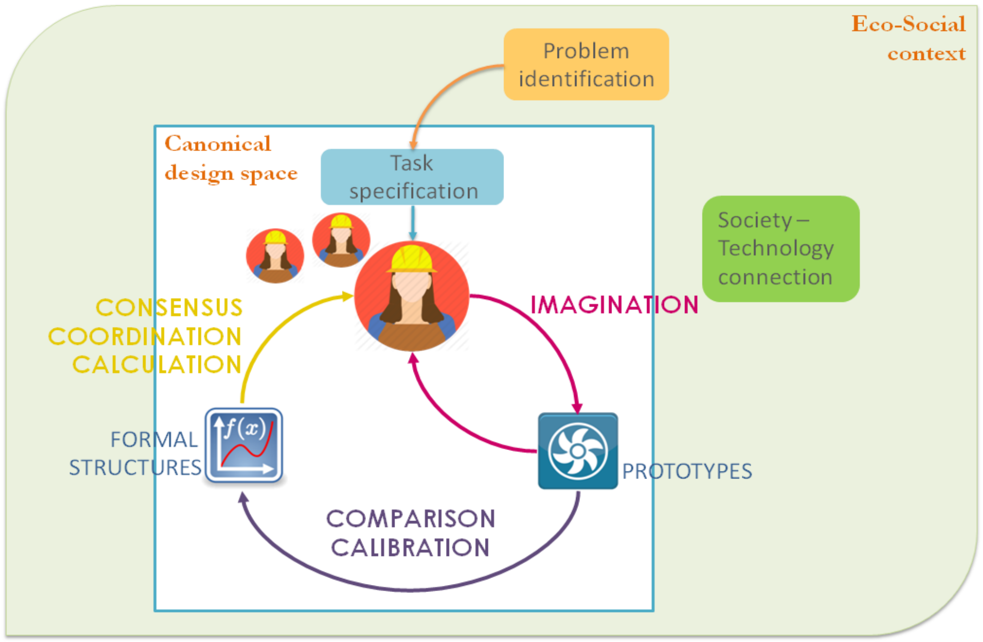

Fig. 57: Engineering Learner's cognitive processes while designing a pico hydro power system

The students thus arrived at a completely innovative material form of their turbine (See Fig. 56), by modeling the known *form* of a Pelton turbine using alternate materials, and not the *theory* of a Pelton turbine. The modeling was not a mere customization or tweaking of the given parameters. They arrived at the actual material form through imagination (See Fig. 57). Though starting with formal knowledge based on their training, when faced with a real design situation, the engineering learners demonstrated cognitive processes of design similar to those of the cases discussed earlier.

Formal structures helped them to compare the performance of their prototype turbine with known standards, and calibrate it. This also allowed them to anticipate the required specifications of the other components of their system, and communicate these to each other and to their workshop technicians. The formal structures also enabled them to arrive at a common understanding of their goals, build a consensus, and coordinate their efforts.

One of the students nevertheless strongly felt that use of computational fluid dynamics would have helped them arrive at a better (more efficient) design faster. This indicates that while imagination was the core cognitive process used to arrive at a prototype, its role either went unrecognized, or was attributed to formal structures (embedded in CFD) used in design. This also shows that despite the stated goal as well as potential of the students' novel, low-cost Pelton turbine towards affordably solving the power problem for many, the student's primary concern was about the technical efficiency of the design. This indicates that while imagination allows for the eco-social to enter the design process, imagination does not automatically ensure that this will happen. Sensitivity and training in eco-social problem formulation and design principles would be necessary to bring about this change. This further supports the view that the assumptions underlying the canonical training for engineering design need rethinking.

For example, by sourcing water harvested on the roof-tops, EL designed a low-cost technology that by default supported a decentralized, house-hold production of power. Though he considered this to be a renewable and sustainable source of energy, the value of such decentralized production in self-sufficiency and independence was not recognized. Since he did not engage with the socio-political-technical connection, his technology remained a lab project, instead of sustainably empowering the needy, and in turn becoming a commercially viable alternate technology, for example of the kind that Harish Hande has developed through SELCO in the domain of solar power. The wider role and value of technology in addressing people's problems is not appreciated by EL or the education system, because it is not connected to the real users, or the larger patterns it is embedded in. This indicates that students need explicit opportunities, encouragement, and training for eco-social engagement.

7.5.3 Comparison insights from the canonical model

A comparison, of the canonical schematic with the engineering learners' cognitive process and the cases analyzed earlier, provided the following insights about the assumptions in the engineering training process:

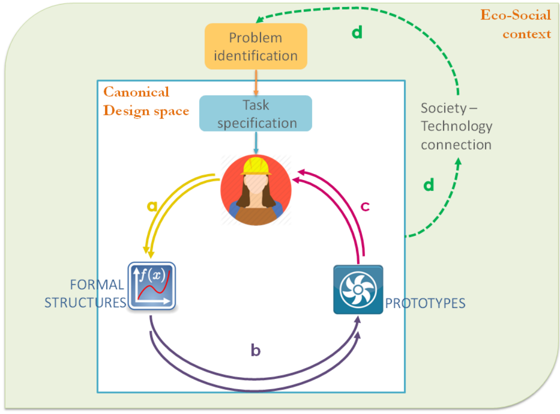

Fig. 58: Cognitive process in canonical design training (same as Fig. 27)

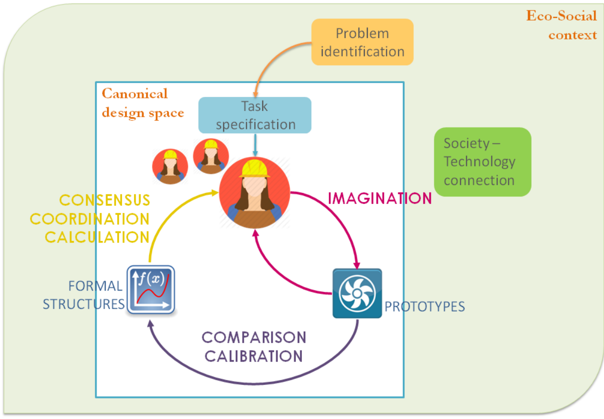

Fig. 59: Cognitive processes of engineering learners (same as Fig. 30)

- Imagination, and the interaction between the engineer and the prototype (c, Fig. 58), is central to the students' design process, despite is under emphasis in the canonical model.

- The canonical model does not properly differentiate imagination from the interaction between the engineer and the formal structures (a, Fig. 58), as well as the prototype and the formal structures (b, Fig. 58), thus leading to an attribution of the work done by imagination to the processes of a and b, and a misplaced emphasis on a and b in education, to the neglect of imagination. This process possibly leads to the formation an engineering identity based on technical rationality, where the non-technical is dismissed as non-engineering.

- The canonical model does not recognize the role of imagination in widening the design space to 1) include the eco-social, and 2) to engage with the plasticity of the society-technology connection (d). Without this engagement engineering education cannot enable students to design for sustainability.
- The canonical model assumes the direction of interactions as a-b-c-a (See Fig. 58), but empirical data, from both practice as well as training, suggests the direction is the exact opposite, i.e. c-b-a-c (See Fig. 59).
- In the mainstream industrial scenario, the design activity is located and embedded in a closed industrial context that forms a design space isolated from the (real-world) context of the problem. There is rarely any interaction between the eco-social context (where the problem and its solution are embedded) on the one hand and the engineer, the prototype, and the formal structures on the other. Assuming that engineering education trains students for mainstream engineering practice, this compartmentalization is a concern, particularly when training to design for sustainability.

7.6 Generic insights from the comparisons

The analysis of the different cases, as well as the canonical understanding of engineering training presented in this chapter, leads to the following *generic* characterization of the cognitive processes in sustainable engineering design.

7.6.1 Characterization of the cognitive processes in sustainable technology design

The key insights into the cognitive processes of sustainable design, from the analysis of the cases discussed, can be summarized as follows. (See Fig. 60).

- The Designer-Formal Structure interaction is neither primary, nor mandatory in technology design, as can be seen from GRI's non-formal design (Fig. 36) as well as EP's first design (Fig. 38). This is because the formal structures do not directly enable GRI and EP to generate or synthesize new ideas, without which solutions are not possible. This is also demonstrated by the other cases, of formal design (ESs, EEEs, ELs).

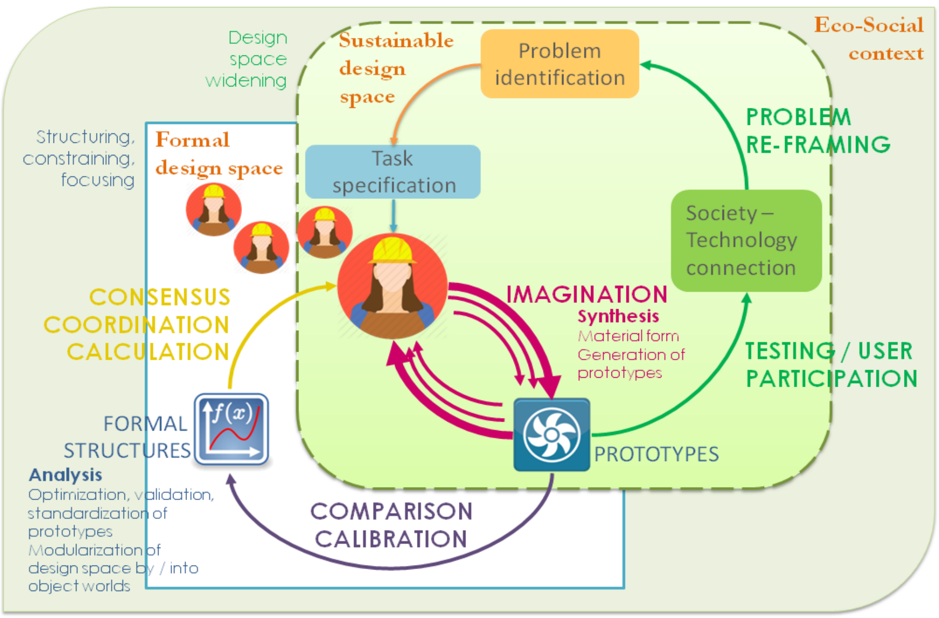

Fig. 60: Cognitive processes in sustainable technology design

- Formal structures also do not directly or necessarily lead to prototypes. Neither GRI, nor formally trained EP, begin design by using abstract formal knowledge. Rather, they begin by working with tangible forms such as existing gadgets or previous prototypes.

- Formal structures, where they exist, are used at the detailed design stage for calculations and optimization. The fuel cell scientists used CFD-generated graphs to optimize the exact tapering angle of the cooling duct, once they had worked out the shape in the CFD. During the conceptual and embodiment design stages, designers need concrete 'form' of formal structures i.e. artifacts to work with (designer – prototype direction in Fig. 60), and not abstract concepts and equations.
- Designers find in prototypes the embodiments of their conceptual ideas. The prototypes enable them to generate data about behavior, and provide feedback, in turn modifying or fine-tuning their conceptual or mental ideas/models of the correlations of components and forces. In short, prototypes or material artifacts act both as the solutions and as external representations to think with, as well as enablers of imagination (the 'mental simulation of physical structures and activity/dynamics through these structures'). Prototypes are not mere instantiations of formal structures. They are a part of the imagination process, and act as invaluable cognitive tools and strategies in the design process.
- As a result of this, the designers' empirical work with the materials and artifacts sometimes contributes to generation of technological knowledge in the form of thumb rules or heuristics (prototype to formal structures direction in Fig. 60).
- Designer - Prototype interaction creates a space (see the design space marked as Sustainable design space in Fig. 60) in the cognitive process to incorporate a variety

of non-technical/eco-social/qualitative considerations in the design process, which may be impossible to translate into formal structures, and thus be left out (in the isolated/closed Formal design space in Fig. 60). Thus, imagination allows for a widening of the design space beyond the formal space of technical input-output parameters. Generation of the actual material form (prototype) as well as the inclusion of eco-social context happens through imagination.

- For the formally-trained designers, the formal structures can be understood as supporting the cognitive process in terms of saving experimentation time and effort. The formal structures can be characterized to be acting as tools for the cognitive processes of (validation through) comparison, and (standardization through) calibration, which together leads to optimization, as well as speeding up of the design process (as less prototypes need to be generated). Formal structures also enable coordination of the design work, by enabling consensus-building within design teams. They also allow better coordination and collaboration, through component-based modularization of design work into various ‘object worlds’. They also allow the knowledge generated in the design process to be formalized, through comparison and calibration with other prototypes/designs/formal structures.

7.7 Discussion and findings

7.7.1 Assumptions in engineering education

In analyzing engineering design practice from a design cognition perspective, this characterization provides more depth and detail to the critique that engineering education overemphasizes formal structures (see section 1). Particularly, the analysis identifies the different cognitive components involved in engineering design, their cognitive roles, and some of the (erroneous) assumptions underlying the current curricular emphasis on formal structures.

Moreover, the canonical understanding underlying engineering education helps reveal the nature of cognitive processes assumed in engineering design training. It also shows how these assumptions prohibit/limit the eco-social from becoming part of the design process. The key takeaway from this study is that engineering practice is mis-represented by engineering education, in the following terms.

6. *The work done by imagination*. This goes unnoticed, unacknowledged, or gets mis-attributed to formal structures.
7. *The design role of prototypes*. The canonical model treats prototypes as instantiations of formal structures. The cases I analyze demonstrate that prototypes are products of, as well as *tools for*, imagination, which drives design thinking.
8. *The cognitive role of formal structures*. They play mostly a calibration and coordination role in practice, rather than a design generation role. Once a design is available, formal structures help lower the number of prototypes generated.
1. *The way formal structures limit the design space*. They constrain the imagination, by idealizing away key components of the design problem, and thus making the design unsustainable in the long run. More importantly, the idealizations also make unavailable other possible design trajectories, based on the ignored factors, and thus constrain the design space even further. In the words of Louis Bucciarelli[364], "The

364 Bucciarelli, *Designing Engineers*, 1994, p. 185.

scenario about science determining form, as ordinarily understood, misses the complexities of alternative forms and paths to a design”. The components of the formal structures may also lead to designs based on modules that map to these components, even though other modular configurations may be more viable. Finally, while formal structures lower the number of prototypes actually created, and thus speed up design, they also lower the designer's ability to learn from the prototype's behavior (as GRI has done), which lowers the range of designs and their recombinations available to the designer, with which she imagines.

2. *Misconstruing of design thinking*. The emphasis on formal structures leads to the active roles played by imagination being ignored, or attributed to the formal structures.

7.7.2 Findings: Imagination, synthesis, and analysis

Design process models since the beginning have discussed analysis and synthesis as two central aspects of the design process. Koberg & Bagnall[365] discuss two basic stages of design as “First, we break the situation or whole problem into parts for examination (Analysis) and Second, we reassemble the situation based on our understanding of improvements discovered in our study (Synthesis).” They expand the synthesis phase as “ideate, select, implement,”[366] Dubberly[367] summarizes that “Alexander (1962) and other designers have described analysis as a process of breaking a problem into pieces—of “decomposing” it. Synthesis follows as re-ordering the pieces based on dependencies, solving

365 Koberg & Bagnall, *The Universal Traveler*, 1972, cf Dubberly, *How do you design? A compendium of Models*, 2004, p 14.
366 Koberg & Bagnall, *The Universal Traveler*, 1972, cf Dubberly, *How do you design? A compendium of Models*, 2004, p 16.
367 Dubberly, *How do you design? A compendium of models*, 2004, p 22.

each sub-piece, and finally knitting all the pieces back together "recombining" the pieces." Lawson[368] calls the 'first analysis, then synthesis' as a non-designer, scientist approach, and "For the designers it seems, analysis, or understanding the problem is much more integrated with synthesis, or generating a solution". Cross points out that "This kind of procedure has been criticized in the design world because it seems to be based on a problem-focused, rather than a solution-focused approach. It therefore runs counter to the designer's traditional ways of thinking."[369] According to Newkirk[370] (1981), "synthesis begins at the very beginning of a design project". This shifted the focus from analysis to synthesis.

The characterization of cognitive processes in sustainable technology design in this study demonstrates that synthesis (of the material form) is the central design process, and imagination (mental simulation) is its core cognitive process. Formal structures are cognitive tools in supporting design process of analysis, through modularization of design space into object worlds, validation, and standardization of prototypes, through the cognitive processes of comparison, calibration, calculation, and coordination.

7.8 Conclusion

This analysis reveals many of the underlying assumptions of current engineering education, and shows why these assumptions are mis-guided. As imagination does not receive due emphasis, students develop an engineering identity centered around formal structures, which prevents them from considering the eco-social as part of design thinking. Given this curricular structure, sustainable design can only remain an add-on, or a trade-off. The study demonstrates that the process of imagination enables the non-formal (such as the qualitative

368 Lawson, 1990, cf Dubberly, *How do you design? A compendium of models*, 2004, p 26.
369 Cross, cf Dubberly, *How do you design? A compendium of models*, 2004, p 23.
370 Newkirk, cf Dubberly, *How do you design? A compendium of models*, 2004, p 26.

or eco-social) to be a part of the design process. If design training is restructured, to uphold imagination as the core cognitive process of design, the design process could start from the eco-social perspective. Only when this becomes a standard practice can the sustainability perspective truly enter engineering design.

This characterization makes it clear that the central cognitive process involved in design is synthesis, and not componentization, which is the key role played by formal structures. The synthesis role is played by imagination, which is unfortunately occluded by formal structures. The optimization-coordination role played by formal structures in effect also blocks designs that require wider perspectives such as sustainability.

This understanding, where the engineering design problem is treated as a distributed cognitive system, can help limit the emphasis on formal structures, and help engineering education move to a model where developing imagination is the central pedagogical focus. Furthermore, by widening the design space to include the eco-social, this may help reform engineering training, so as to enable students to design for sustainability, by systematically incorporating eco-social principles into engineering design. It must be noted, at the same time, that while imagination allows for the eco-social to enter the design process, it does not automatically ensure that this will happen. Sensitivity and training in eco-social problem formulation and sustainability design principles would be necessary to bring about this change.

Chapter 8: Discussion and Implications

Solving for Pattern is a promising process approach to design technology for sustainability. Implementing this design approach requires setting up of interdisciplinary institutes, to research and promote sustainability engineering

"In the terrain of professional practice, applied science and research-based technique occupy a critically important though limited territory, bounded on several sides by artistry. There are an art of problem framing, an art of implementation, and an art of improvisation – all necessary to mediate the use in practice of applied science and technique."[371]

In this chapter
The results from the studies indicates that grassroots technology design can provide interesting insights towards developing a new engineering pedagogy for sustainability. In terms of implementation, case-study-based learning, where case studies of grassroots technology design are integrated with technical modules, could be the first step forward. These modules would help demonstrate how the eco-socio-ethical are closely tied with the technical, and thus extend the current disciplinary modules and textbook exercises towards the alternate practice of 'solving for pattern'. Training based on such modules would be one way to transform the engineering practice for sustainability. The modules, along with grassroots projects and internships, would help seed a new engineering identity, based on alternate values and engaged with eco-socio-technical problem formulation. EE based on such modules would focus on social engagement, imagination and synthesis as core competencies, rather than formal structures. Designing engineering programs, and even institutes, that teach for sustainability in an integrated manner, by screening for, and nurturing, imagination and synthesis, and training for eco-social problem formulation, are the key policy recommendations of this thesis project.

Introduction

This research study was driven by the question: *how can we develop a practice-based understanding of sustainability engineering, to guide pedagogy?* To address this question, I analyzed case study data from the unique Indian context of grassroots innovation – where both non-formal and formal (non-mainstream) sustainable technology design

371 Schon, *Educating the Reflective Practitioner*, 1987.

practice co-exist – to characterize its main features. The key outcomes of this characterization analysis are:

1. A broader design process and overarching design principles necessary for sustainability engineering (Chapter 6),
2. A descriptive model of the cognitive processes that need to be involved in sustainable technology design (Chapter 7).

In this chapter, I first provide a brief summary of these findings (Section 1), develop an integrative perspective or framework that brings them together (Section 2), and then discuss the theoretical, practice-related, pedagogical, and research implications of these (Section 3). This discussion addresses research question 3 (See Chapter 3), in the light of the research gap identified in Chapter 2. I then outline the contributions and limitations (Section 4) of the study, and conclude with potential directions for future work (Section 5).

8.1 A brief summary of findings

1. *The connection between society and technology is highly plastic, and recognizing this plasticity enables design innovation*

Any engineering design seeks to establish a connection between society's needs and the functions provided by technology – the socio-technical connection. However, most designs implicitly start from, or build on, existing socio-technical connections, without recognizing that such connections are very fluid or plastic, and thus amenable to redesign. Once the plasticity of the socio-technical connection is recognized, the space of possible designs expands manifold. Particularly, the standard design categories (such as product, manufacturing, embodiment, concept etc.) and business categories (such as market, distribution, consumer, capital etc.), which are taken as default currently, can be recombined in novel ways, to significantly expand the innovation space. The default industrial model is thus just one socio-technical connection, and therefore one of the possible design trajectories. Assuming this model as default restricts the design space – the available directions to generate solutions – to 'within' the detailed-design phase of the canonical design process.

2. *The socio-technical connection is plastic, but only when the design process starts from need (problem) formulation*

In practice terms, the plasticity is available only if the designer begins at the problem formulation stage (need identification, problem definition), which allows for a much wider design space. Otherwise, the designer works with a pre-defined and 'frozen' task specification, which (implicitly) embeds the currently dominant centralization assumptions, including centralized manufacturing and distribution processes. This default approach creates many social and environmental costs that are conveniently externalized, leading to socially and environmentally unsustainable technological solutions.

3. *The idea of optimality goes beyond that assumed by centralized efficiency and revenue models, to include social and environmental factors*

The grassroots designers designed a product/process/system that could be easily handed over to individuals and/or small communities themselves, including the operation, maintenance, minor repairs, marketing, and income generation, even manufacturing and installation in some cases. This resulted in a very different business model (compared to the centralized efficiency and revenue model). The resulting system is sustainable both ecologically and socially, through local management of resources and processes, and more equitable distribution of wealth. This suggests that the default model is just a starting point, and there could be a continuum of socio-technical designs, going all the way to full decentralization, including full sharing of surpluses, or partial centralization, with an equitable sharing of surpluses.

4. *Sustainable technology aims at empowering people at the grassroots and sustaining their local livelihoods, a design principle beyond drudgery/cost reduction*

The factory model, where industrial wage-earning jobs are provided to people who have been forced to move away from self-owned resources, is an unsustainable model of employment. The demand for technology at the grassroots level, most urgently and importantly, stems from the need to protect/support existing, sustainable, and self-owned sources of income generation. Grassroots design thus seeks to develop technology that empowers underprivileged people, providing them self-sufficiency in their local livelihoods, and control over their lives.

5. *The key cognitive process that drives engineering design is imagination (mental simulation of structure and dynamics). The synthesis of the technical and the non-technical – which is the central requirement for any engineering design – is driven entirely by imagination*

Engineering design thinking, widely understood as just technical problem-solving, overemphasizes formal structures. This understanding poses a central cognitive difficulty for sustainability engineering, as it leaves no room in the design process for widening of the design space, to include the eco-social in the problem formulation. My analyses of non-formal and formal design cases of grassroots technology, as well as mainstream technology design, show that imagination (mental simulation of structure and dynamics) is the core cognitive process in design. This suggests that the cognitive process of design i.e. imagination – is well suited to the widening the design space, through the generation and synthesis of many socio-technical connections.

8.2 Discussion

An exclusive focus on techno-economic efficiency and profit-making as design principles, ignoring the embeddedness of technology in larger eco-social networks, invariably leads to unsustainable solutions. Trade-offs based on these principles do take a step towards sustainability, but such trade-offs are limited to socio-ecological considerations that support quantification for trade off. Furthermore, educational emphasis on formal structures, to the neglect of imagination, leads to a design space that cannot break away from these constraints.

The findings discussed in the previous section from the analyses of cases individually offer some ways to address these limitations of current technology design. However, to compensate for the dominant efficiency narrative, these findings need to be brought together into an overarching design perspective. This would help in developing a broader design approach to sustainability than the trade-off approach. I develop this design perspective based on Wendell Berry's idea of 'Solving for Pattern' (SfP).[372] I don't claim that this is *the* technology design perspective for sustainability, applicable across all technology design, but merely that this could be one perspective/framework among many that are possible. In the following sections, I discuss some aspects of this design principle/perspective in detail.

372 Berry, "Solving for Pattern," 1981.

8.2.1 Solving for Pattern as an overarching perspective /framework supporting sustainable technology design

Primarily in the domain of ecology and agriculture, philosopher and farmer Wendell Berry has captured and put forth this conception of sustainability, through the term called 'Solving for Pattern' (SfP).[373] Having arrived at this perspective through a characterization of grassroots technology design practice, and recognizing the need for such a perspective to take technology design beyond technocracy towards sustainability, I borrow and extend this term to the domain of technology design, in order to capture together both the perspective and its operationalization.

While doing so, it is necessary to point out that in using the terms 'solving' and 'pattern' together, Berry implies an entirely new meaning, which goes beyond the conventional meaning of these individual terms very common to the domain of engineering and technology design. The following section elaborates this term as implied by Berry, and as extended here to the domain of sustainable technology design.

8.2.1.1 Solving for Pattern (SfP)

Wendell Berry highlights that things are embedded and interconnected in the world, and any modifications (including new technology) restructure not only these patterns of connections and relations, but also the wider interconnections that these connections are embedded in. This makes it necessary for design to keep these larger patterns in mind. It is perhaps crucial to quote Berry himself here, to fully bring across the sense in which he uses the terms 'pattern, solving, and interconnectedness'. While discussing three kinds of possible

373 Berry, "Solving for Pattern," 1981.

solutions to "the problems of farming, then, as to other problems of our time", Berry explains how a concern for pattern leads to better solutions.

> *"Perhaps it is not until health is set down as the aim that we come in sight of the third kind of solution: that which causes a ramifying series of solutions – as when meat animals are fed on the farm where the feed is raised, and where the feed is raised to be fed to the animals that are on the farm. Even so rudimentary a description implies a concern for pattern, for quality, which necessarily complicates the concern for production. The farmer has put plants and animals into a relationship of mutual dependence, and must perforce be concerned for balance or symmetry, a reciprocating connection in the pattern of the farm that is biological, not industrial, and that involves solutions to problems of fertility, soil husbandry, economics, sanitation - the whole complex of problems whose proper solutions add up to health: the health of the soil, of plants and animals, of farm and farmer, of farm family and farm community, all involved in the same internested, interlocking pattern – or pattern of patterns."*[374]

In explaining the limitations of 'techno-economic efficiency driven' singular best solutions, Berry then comments,

> *"A bad solution solves for a single purpose or goal, such as increased production. And it is typical of such solutions that they achieve stupendous increases in production at exorbitant biological and social costs. A good solution is good because it is in harmony with those larger patterns – … It is the nature of any organic pattern to be contained within a larger one. And so a good solution in one pattern preserves the integrity of the pattern that contains it."*[375]

Wendell Berry further adds:

> *"… all who are living as neighbors here, human and plant and animal, are part of one another, and so cannot possibly flourish alone; that, therefore, our culture must be our response to our place, our culture and our place are images of each other and inseparable from each other, and so neither can be better than the other".*[376]

The notion of sustainability underlying this perspective recognizes that the patterns of interconnections, relationships and interdependencies on the planet are very subtle, intricate, delicate, and most importantly, based on reciprocation. The complex links and patterns they form are not easily revealed or obvious. As Wendell Berry explains,

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374 Berry, "Solving for Pattern," 1981.
375 Berry, "Solving for Pattern," 1981, emphasis mine.
376 Berry, *The Unsettling of America*, 1977, p. 22.

> *"… it is impossible to sacrifice the health of the soil to improve the health of plants, or to sacrifice the health of plants to improve the health of animals, or to sacrifice the health of animals to improve the health of people. In a biological pattern – as in the pattern of a community – the exploitive means and motives of industrial economics are immediately destructive and ultimately suicidal."*[377]

An approach such as SfP highlights the need for a sensitivity and capacity to trace and respect these patterns, when building technologies. The way to sustainability can emerge only through entering into a similar responsible relationship among humans, as well as with the rest of the living and non-living world on the planet, of restraint and reciprocation fundamental to these patterns, rather than designing technology merely for grabbing (prospecting, mining, polluting), and controlling.

8.2.1.2 SfP as a guiding perspective in sustainable technology design

Wendell Berry's idea of 'Solving for Pattern', described in the previous section is illustrated by the cases discussed in this thesis, and captures the broader perspective that could allow the interconnectedness of things in the world to guide the design decisions, instead of trade-offs based on quantification. It would lead to a more holistic and socio-technical approach to efficiency and sustainability.

Such qualitative aspects of the socio-technical approach to sustainability may appear to be vague and subjective, when viewed from a rational, instrumental approach. It needs to be noted though, that technology design is a process of negotiation between various stakeholders. As Vermaas, Kroes, van de Poel, Franssen, and Houkes argue, engineering is

> *"the result of social negotiation processes in which the various groups involved, including customers but also producers, articulate their wishes and needs. The function of the product that is to be developed is thus a social construction that is based upon what divergent groups consider to be 'desirable'."*[378]

377 Berry, "Solving for Pattern," 1981.

A socio-technical efficiency approach would make it possible for an engineering designer to be sensitive to those voices that are weaker at the articulation and negotiation of their real needs. This also needs to include the voices of the other species on the planet. ‘Solving for Pattern’ essentially brings in the understanding that meeting only human needs of some, at the cost of the well-being of other species, as well as the interdependence of species, cannot lead to sustainable solutions. The unarticulated, vague, and subjective get defined better through the negotiation process, rather than a designer alone trading off parameters based on her/his 'objective' understanding of the situation.

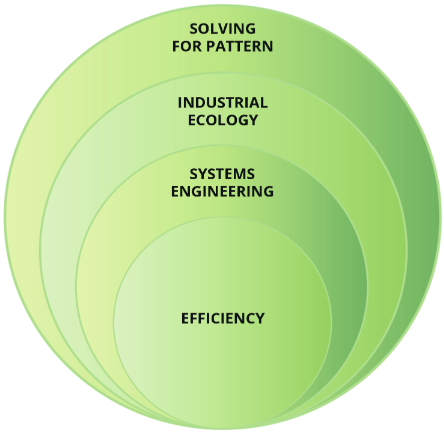

Fig. 61. From efficiency narratives towards SfP.

Furthermore, transitioning from purely efficiency narratives towards SfP may not be an instantaneous transition, and Systems Engineering and Industrial Ecology may be intermediate stages.

For example, a design thinking approach may start from these, and transition towards SfP to solve many environmental problems (such as groundwater pollution), which are created by the coming together of many misguided engineering (building) projects (giving rise to garbage dumps and untreated effluents), and thus requires designs that bring together many engineering and social components (such a bio-remediation through farming of plants such as Vetiver while generating livelihoods). Fig. 61 captures the intermediate stages, expanding to SfP as a wider approach.

378 Vermaas et al., *A Philosophy of Technology - From Technical Artefacts to Sociotechnical Systems*, 2011, p. 95.

8.2.1.3 Solving for pattern for a reflective design process

The term, coined by Wendell Berry, highlights the larger ecological patterns that govern any specific locale, and the ecosystems globally. I borrow the SfP concept and extend it to engineering design, to highlight how this view could be used as a design principle, to support a more ecologically-aware *process* approach to technology design. The SfP process idea, when applied to design, recommends that technology designs be treated as embedded not only in ecological patterns, i.e. local interconnections, but at the same time also situated in larger socio-cultural, economic, and political patterns.

This may appear to be a status quo position, giving rise to the question as to whether the solving for pattern process requires the continued maintenance of all existing patterns, such as every ecological pattern, as well as existing exploitative social structures.

In order to clarify this aspect, I highlight that the process of solving for pattern does not specify how to solve a problem, in the sense of specifying maintenance or disruption of existing patterns. Solving for Pattern, in using the word ‘solving’ as a process, suggests that when engineering solutions are generated by humans, they need to explicitly take into account the various patterns (and interconnections) related to both the engineering problem and the possible solutions. In this sense, the emphasis is on including in the design process a sensitivity towards the embedded nature of all engineering solutions. This process emphasis does not make any recommendation on whether the technology should maintain or disrupt existing patterns.

A close example is the design of bioengineering solutions, such as new genetically modified organisms. Designers of bioengineering solutions are required to explicitly take into account the different ecological and agricultural/social patterns such organisms could disrupt, and also require that such technologies meet stringent ethical and testing standards. The SfP view could be considered to extend this reflective process of engineering to all technology design, as all engineering solutions restructure ecology, and cumulatively, these changes lead to larger disruptive patterns, such as climate change.

The cases I studied demonstrate that, for sustainability, it is not sufficient to only aim for conserving or protecting the ecological interconnections. Technology design needs to also promote social equity and wealth distribution. Sustainability thus includes both ecological and social sustainability. For this reason, it would be necessary to develop technologies that seek to do both simultaneously – contributing to the abundance of ecological patterns on the one hand, while disrupting the unjust socio-economic and political structures on the other. Only then can technologies support the flourishing of all, together – which is how 'solving for pattern' understands or approaches the problem of sustainability. This position questions the possibly glorified popular view about disruptive technology, that:

1. Technology is required to always disrupt (both ecology and) society
2. Disruptions of technology, society and ecology always necessarily go together
3. Such disruptions are always beneficial, even when not done in a reflective way

The SfP process suggests that it is possible to do reflective design, based on the design principles identified by the thesis, such that both engineering practice and engineering education can move to technology designs that support the flourishing of both ecological and equitable social patterns.

8.2.2 Solving for Pattern and technology at large scale

Wendell Berry warns that "... enlarging scale is a deceptive solution; it solves one problem by acquiring another or several others."[379] He explains this as "a limit of scale, because it implies a limit of attention … [to] a pattern that a single human mind can comprehend, make, maintain, vary in response to circumstances, and pay steady attention to."[380] This, in other words, upholds solutions for a small and decentralized scale, of family or community size.

The findings from the cases of grassroots technology design support these design principles. Micro hydro power (MHP) projects are small in scale compared to mega dams, and produce power only in the range of 1-100kW. AM's sanitary napkin machines lead to cottage-scale or community-scale manufacturing units.

It could, on the other hand, be argued that such MHP systems cannot meet the large requirement for power across the world, nor the local manufacturing setups the demand for product quantity. Is the SfP perspective then only applicable to the limited sphere of small-scale technology design? When confronted with a similar question about 'small' Appropriate Technology, E. F. Schumacher had an interesting answer.

> *"What I wish to emphasise is the duality of the human requirement when it comes to the question of size: there is no single answer. For his different purposes man needs many different structures, both small ones and large ones, some exclusive and some comprehensive. .. For constructive work, the principal task is always the restoration of some kind of balance. Today we suffer from an almost universal idolatry of gigantism. It is therefore necessary to insist on the virtues of smallness - where this applies. (If there were a prevailing idolatry of smallness, irrespective of subject or purpose, one would have to try and exercise influence in the opposite direction.)"*[381]

379 Berry, "Solving for Pattern," 1981.
380 Berry, "Solving for Pattern," 1981.
381 Schumacher, *Small is Beautiful*, 1973, p 41.

Similarly, it may not be possible to answer this question unless many more cases of technology design are explored, small and big. But it may be possible to address it to some extent, based on the current cases, which lead to a counter question as to whether large-scale/quantity is really required, and required in the current centralized manner. If not, then decentralized units may be installed in as many places as necessary, to meet the quantity demand. This will be a more sustainable solution, as discussed in detail in the previous sections. In this sense, Solving for Pattern (SfP) as a perspective and design principle is not limited to small scales, and both small and large scale solutions could be developed based on this principle, even if the technology is family/community scale, but can be easily replicated or used in multiple sites. What would be crucial is to scale to a size where it would be possible to pay steady attention to the complex patterns and to vary in response to them. To illustrate this, three large-scale examples that could walk a path towards SfP are discussed below.

8.2.2.1 Organic farming in a solar power plant

The Cochin International Airport Limited (CIAL) at Kochi, India, installed solar panels to generate about 12MW power, which successfully supports the entire airport's power needs. The solar panels were installed over an area of about 45 acres. In 2018, CIAL was awarded the 'Champion of the Earth' award by the United Nations (UN), in recognition of their efforts to generate sustainable energy.[382]

CIAL also initiated an organic farming project over 3 acres of this land, in spaces between the solar panels. The water used to clean the solar panels is used for growing organic vegetable gardens next to the panels. The garden helps reduce the dust on the panels, thus

382 Times News Network, "Cial receives UN environmental award," 2018.

maintaining their technical efficiency, and provides gainful employment to people who live near the airport. It also allows for more utilization of the vast track of land and the sunlight it receives.

The project helps CIAL make money (as they save on power consumption and feed excess power to the grid), and the expense of watering the panels is compensated for by the vegetable produce, sold at the airport as well as in the city market.[383] This combination design has also created goodwill for the airport in the nearby villages.

This 3-acre model could be replicated over the rest of the 42 acres, where solar panels are installed. It may also be useful to develop manure from solid organic waste collected at the airport, and use it to nourish the vegetable garden.

8.2.2.2 Reversing desertification through a desalination plant

The Sahara Forest Project seeks to create a bigger version of the above design, with more focus on flourishing, as it is situated in a desert. Initiated in Jordan with Norwegian support, the project attempts to utilize seawater, concentrated solar power (CSP), and atmospheric CO2, to produce food and other biomass, fresh water, as well as energy in the desert. According to their estimates,

> *"A single SFP-facility with 50 MW of concentrated solar power and 50 ha of seawater greenhouses would annually produce 34,000 tons of vegetables, employ over 800 people, export 155GWh of electricity and sequester more than 8,250 tons of CO2."*[384]

In the process, using moisture released from the green houses, the project supports re-vegetation of the surrounding land, thus restricting and reversing the process of desertification, triggered centuries ago by the Roman conversion of forests to farmland for

383 Deccan Chronicle, "Cochin International Airport Ltd forays into organic farming, plans bigger," 2016.
384 Sahara Forest Project, "Restorative growth," nd.

food. The vegetation in turn reduces dust, and keeps the CSP mirrors clean. The SFP initiative aims to use restorative practices to reverse the trend of desertification through sustainable farming.

Selecting sites in low-lying areas, the project builds infrastructure to profitably bring seawater using gravitational force and electric pumps. The desert heat and CSP are used for evaporation of the seawater. The vapor provides humidity to the greenhouse vegetable crops, and superheated steam runs turbines to generate electricity for the operations. Evaporated seawater also provides fresh water for drinking, irrigation in the green house, and for cleaning the CSP mirrors. Unlike the conventional desalinization plants, where brine is put back in the sea, salts are recovered in this process. These minerals provide an alternative to mining of salts. A number of economic enterprises can be developed around this infrastructure, including cultivation of fast-growing biomass such as fish and algae in the salt water ponds, by harvesting the sun and sequestering CO2. This creates many skilled and unskilled jobs for local people.

This large scale project, illustrating a synergy of multiple environmental technologies to support flourishing, can be seen as a step in the direction of Solving for Pattern, where the large scale challenges of food, water and energy are addressed, by building on renewable resources, employing non-polluting processes, and achieving diverse outcomes, while also seeking to create conditions of flourishing in the desert. More importantly, the project is based on the understanding that environmental problems are interlinked, and therefore their solutions must be designed in a systemic manner.

Following an SfP design implicitly, the efficiencies of the technologies are valued for their multiple outputs, and not just the maximizing of any one.

> *"The synergies arising from integrating the technologies improve performance and economics compared to those of the individual components. In addition to its commodity outputs of food, energy and salt, the system also provides global climate benefits by sequestering CO2 in the facility's plants and soils, and by pushing back the accelerating process of desertification through the revegetation of desert areas."*[385]

8.2.2.3 Reversing migration through integrated agri-horti-forestry plantation

BAIF's Wadi Project is conceived and implemented in participation with tribal people by BAIF, a national-scale NGO in India. It is primarily an integrated agri-horti-forestry plantation project, where a small plot of land (an acre) owned by a tribal family is brought under cultivation using a special model developed by BAIF. This model starts with planting 60 fruit trees in the plot, usually 20 mango saplings, 20 cashew, and 20 gooseberry, or depending on the bio-geography, some other native fruit tree variety. During a five-year growing period, where no fruits are ready for market, the rest of the plot is cultivated with fodder and timber trees on the boundary, and intermediate crops and flower trees in the spaces in between. The model thus allows the tribal family a subsistence farm produce for most of its own needs in the early years, while at the same time allowing them to stay near their village, and not migrate to other places in search of work. With training and materials support from the NGO, water and soil conservation measures are implemented in the plot as well as surrounding hills. In five years, the family's fallow land is converted into income-generating assets. This model provides short-term as well as long-terms gainful self-employment. Entirely organically grown fruits and other produce is then collectively processed in smaller village-level units, and further value-added and marketed through a

385 Sahara Forest Project, "Technologies," nd.

larger federation of such units. The success of this formula (which includes many levels of techniques and farming/ restoration technologies) in sustaining tribal families as well as restoring denuded stretches of land in the state of Gujarat and Maharashtra, led to its large-scale implementation, with thousands of tribal families benefiting across numerous states of the country, not only through government-funded programs, but also through other organizations such as the Gates foundation.[386] The model may turn into a good case of SfP, as it lends to very-large-scale implementations, while at the same time remaining a flexible formula that can be adapted to the local variation of bio-geography, thus taking into account and working in tune with the larger socio-ecological patterns it is a part of, and acting so as to nurture and let it flourish.

While these three projects illustrate the possibility of SfP at a large scale, embedding the notion of flourishing, they also show that it is pertinent to question the assumptions and implications of large-scale interventions. For instance, projects such as BAIF's Wadi project show how interventions can be contextual, decentralized, and yet, implemented within large geographical areas. 'Scaling-up' as conventionally understood may not thus be applicable to SfP-driven interventions. The essential aspect is harmony with the larger eco-social patterns. SfP requires that technological interventions, instead of focusing narrowly on maximizing any single outcome of interest, finds a balance such that the larger patterns of society and ecology flourish/thrive, rather than get destroyed.

These three examples indicate a possible progression, from the current efficiency-driven design towards SfP. In this view, the current approaches of 'Green tech', systems

386 BAIF, "Agri-horti-forestry," nd.

engineering, or industrial ecology, can be considered as steps towards sustainability. SfP indicates where they fall short, and the direction in which these need to evolve.

8.2.2.4 Limitations of applying the SfP perspective to large scale

It may not be possible to apply the underlying SfP principles of eco-social optimality and decentralization to large scale industries based on mining of centralized resources such as oil and ores. Steel factories, coal plants, or oil refineries probably cannot be decentralized to co-locate production and consumption economically, at least as long as they depend on the current technologies.

However, the manufacturing of cement or paper could be reconsidered for decentralization. After all, the centralized communication technology of landline-based telephones and STD booths has been completely revolutionized in a few years, when technology was developed to support mobile phones through decentralized telecom towers.

8.2.3 Solving for Pattern and the building instinct

Solving for Pattern provides an eco-social design perspective that is in clear contrast to formal engineering design. This contrast now allows it be used to develop a better understanding of the standard practice. This view presents an ecological and biological approach to design, and makes possible the reformulation of approaches to sustainability engineering in fundamental and far-reaching ways. Particularly, this ecological approach helps analyze how the human building instinct -- the biological motive underlying engineering practice – has deviated from its biological function over time, and has moved into a runaway mode.

For instance, the biological principle of form following function allows us to consider the practice of building - engineering or designing any technology – as manifesting its design values (such as efficiency) in the technology it creates. Once manifest, the technology, and the values it externalizes, becomes part of society. This manifestation allows the values of design and practice to permeate social narratives, eventually leading to an overall cultural narrative (such as the efficiency narrative) based on these values. This cultural narrative then loops back, and reinforces the values underlying the designs. Over many cycles, this cycle creates a positive feedback loop that both reifies and expands the existing technology design model (See Fig. 62), which is currently one that significantly damages ecological and social structures that are benign.

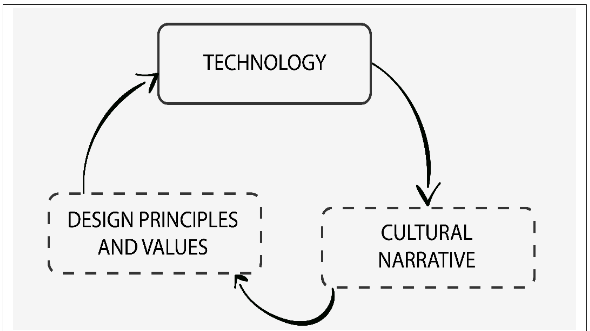

Fig. 62: A generic representation of 'building' technology, with values it is guided by, as well as helps create.

Looking back from this perspective, craft – the traditional practice of building based on limited and biological resources that are available locally – also manifested a value system, where use and reuse of natural resources, and thus their continuing availability, were key components. The design practices of the skilled artisans, passed on through apprenticeship, were inherently restrained, as they depended on the immediate environment, and therefore valued and conserved it. These design principles were imbibed by society, and was reflected in the larger cultural narrative, which was oriented towards sustenance and frugality. (See Fig. 63).

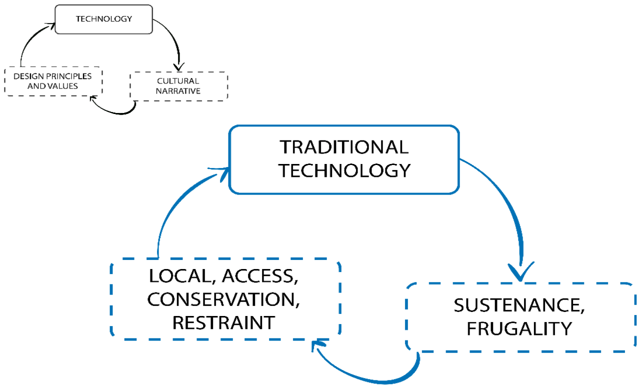

Fig. 63: The traditional building practice embedded values of sustenance.

The modern practice of engineering, through industrialization and formalization, harnessed much bigger sources of power than human and animal power (such as steam), and hence could build highly scaled technological systems, using resources from across the globe, which also became accessible through the harnessing of new sources of power. The more the output power available from a given input power, the more such scaling was made possible. Energy efficiency thus became a key value, along with a lack of limit on resources – when one resource was exhausted, another would be found, through plundering when needed. The design process changed from being need-driven to being technology-driven. The only constraining factor was cost, i.e. whether the technology justified the cost of acquiring the resources, including the use of violence.

The design practice was now guided by the technical efficiency value (output to input ratio), which seeped into society, turning efficiency into a cultural value. Through feedback, this cultural value led to automation and centralization of production, in order to achieve ‘economies of scale’ – efficiency at the level of business processes, and the economy in general. The resulting mass production required finding markets beyond local users. Combined with the centralization of production, the new and large markets led to a concentration of wealth. This expansion of the resource base and the consumer base then became a process by itself, leading to a narrative of abundance, opulence, and unchecked consumption, in contrast to the earlier one of restraint. It also created colonialism, and its related value system – of faraway places and people waiting to be plundered and technologized.

As technology became all-pervading, manifesting these and other such design

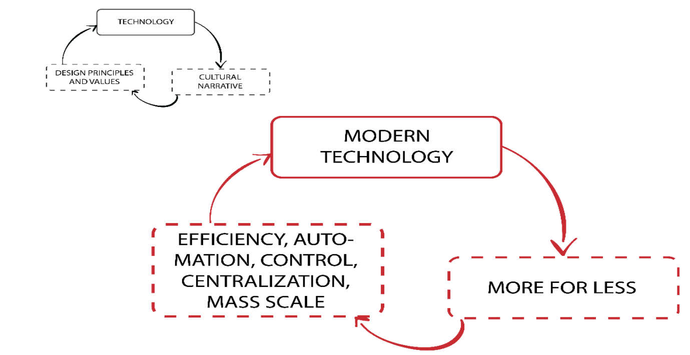

Fig. 64: The modern formal engineering practice where efficiency is a key value.

values, the cultural narrative adopted efficiency as a central value, always seeking 'more for less'. (See Fig. 64).

The reinforcing feedback loop based on this, and related values, created the runaway practice of constantly building technology, leading to ecological and social damage at a corresponding global scale, and a very unsustainable way of life on a finite planet. While some continue to put faith in this model driven by technological optimism – such as by trying to build technology to inhabit outer space, and arguing that technology will solve all the problems it creates – the above-sketched evolution of this mode of existence, and the rampant damage it has generated, suggests that this is not a sustainable direction.

The current configuration of the building instinct thus needs to be reshaped, such that both ecology and society can flourish. As Berry puts it, "A good solution solves more than one problem, and it does not make new problems" and "… it should not enrich one person by the distress or impoverishment of another."[387] This reshaping requires drastic changes to engineering design practice and principles, their manifest technologies, and associated cultural narratives. The SfP approach provides one way to visualize such a systemic change – a way to alter building practice, technology and values to support flourishing – and the cases of SfP practice I discuss offer examples that could pave the way towards this direction. (See Fig. 65).

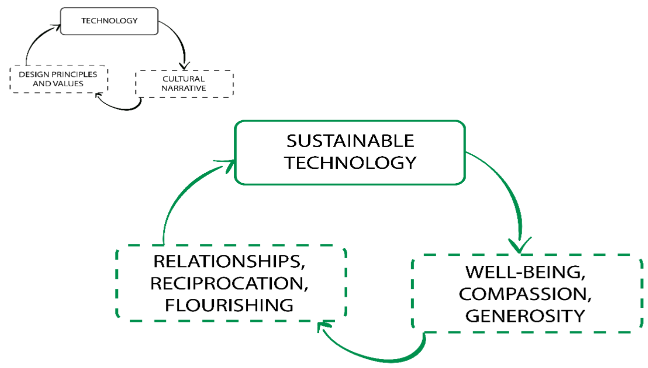

Fig. 65: The SfP building practice is founded on sustainability values.

In generic terms, the SfP approach to building – be it engineering design of products and systems, or a broader sense of technology-based practice such as farming – primarily visualizes technology as embedded in a web of interrelationships connecting society and ecology, rather than technology being isolated and independent. Building always alters eco-social relationships, to create favorable or adverse impacts on these patterns. SfP requires designing technology in full consciousness and sensitivity of this fact. Many of these relationships may not be readily obvious or apparent, but the process of building technology,

387 Berry, "Solving for Pattern," 1981.

if it is to sustain the biosphere and the human species, needs to be extremely mindful of this web of life. Rather than the hidden/implicit hubris of techno-scientific rationality, SfP urges a building process that is explorative, sensitive and benevolent, ensuring that the interrelationships are least disrupted, if not actively strengthened. Thus embedded, technology could be conceived to form and support positive or contributive relationships with the larger eco-social systems, rather than creating destructive, or merely neutral, relationships. The larger patterns of nature itself are expected to be the model for devising such relationships. Unlike most bio-mimicry based designs, this imitation of nature's relationships is for the thriving of all, not just human beings.

8.3 Implications of the thesis

The findings from this thesis may have implications for the emerging field of Engineering for Sustainability, as the work reported here provides an operational and process-level understanding of sustainability engineering. The following sections discuss some of these implications, particularly for theory, pedagogy and practice, as well as new research and methodological possibilities.

8.3.1 Theoretical implications

8.3.1.1 SfP as a technology design perspective

SfP, as a perspective or framework guiding technology design, could offer one way to reshape the very meaning and goals of technology, design, and building, beyond the limited contemporary definitions, and could help define sustainability engineering in a new way at the operational level. This design principle provides a hope that technology, in its broadest sense, could be designed differently, to enable a sustainable way of life for the entire biosphere.

Moreover, SfP could also enable a new practice perspective and approach in wider applications, beyond engineering-specific product building, to technology understood as activity, knowledge, or even volition.[388] It could be relevant for a wider sphere of life, especially because the runaway building values have percolated into the cultural narrative, to the extent that all kinds of systems, such as food, healthcare, and education, are now driven by the same unsustainable values.

8.3.1.2 The cognitive processes of technology design

The analysis of the cognitive process of design I present is loosely based on the distributed cognition (DC) framework, as it examines how cognitive processing is spread across internal operations, external representations, artifacts, and people, and how this distributed system helps achieve both innovation and coordination. In the context of research methods for design cognition, this approach presents a novel way to examine design cognition, and offers possible approaches to develop mechanism models of design thinking, similar to recent work proposing cognitive/neural mechanisms that support DC.[389] While analysis-synthesis-evaluation ideas have been presented, discussed, and critiqued in various ways in the design cognition literature, based on different schools of thought, and imagination has also been referred to (See Buchanan[390] for more details), these elements have not been put together systematically using a cognitive science framework, particularly not in

388 Mitcham, *Thinking through technology: The path between engineering and philosophy*, 1994.
389 Chandrasekharan, "Becoming Knowledge: Cognitive and Neural Mechanisms that Support Scientific Intuition," 2014; Chandrasekharan & Nersessian, "Building Cognition: the Construction of Computational Representations for Scientific Discovery," 2015; Rahaman et al., "Recombinant enaction: Manipulatives generate new procedures in the imagination, by extending and recombining action spaces," 2018.
390 Buchanan, "Thinking about design: An historical perspective," 2009.

ways that allow modeling of cognitive/neural mechanisms. More generally, the prominent approach to understanding design cognition has been information-processing theory. Field theories of cognition, such as distributed, situated, and embodied cognition, have not been used much to analyze design cognition. The analysis presented here could provide a good starting point to develop such a theoretical approach, especially to understand the role of model-based reasoning in engineering design.[391]

The model of cognitive processes in design I propose is based on an analysis of formal, non-formal, and student cognitive processes in design. This analysis could thus provide a framework to bring together design by novices and design by experts, and a way to understand the systematic development of design cognition, through practice as well as training. Also, this integration may allow a more systematic examination of how formal structures expand/constrain design thinking, thus making it possible to develop evidence-based approaches to support design education.

Further, the cognitive process model I present considers built prototypes as products of, and for, thinking. Such run-time use of the environment for cognition is a key focus in the study of situated cognition. Design by non-formal practitioners would thus be a good domain to study situated cognition, especially how the environment is changed to advance cognition. This approach could help advance our understanding of tacit knowledge and situated cognition.

391 Kothiyal et al., "“Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning," 2016.

8.3.2 Implications for the practice of engineering design, and building in general

The characterization of the grassroots design process, and the cognitive-level understanding of this process, provides insights into what a possible engineering practice for sustainability could be like. The SfP approach to technology development requires technical values (such as efficiency and optimization) to be subsidiary to the larger sustainability values of well-being, interrelationship, and flourishing of all. More broadly, sustainability needs to be understood as the central problem of engineering practice.

8.3.2.1 Design innovation through plasticity of socio-technical connections

Currently, engineering practice is incarnated (/concretized/embodied) in close connection to the current technology-business/commerce (activity of buying and selling) structures. But the practice of engineering was not always so tied, and need not be tied, to any particular model of technology-business/commerce. A restructuring of the current model is already under way, with software technology models that disrupt contemporary business models of design, manufacturing, and distribution. Examples include Kickstarter, Kiva, and online marketplaces that connect products and services to consumers and customers in novel ways, such Airbnb/Tripping/Homeaway, Uber/Lyft/Ola, Zoomcar/Myles, eBay, Amazon/Flipkart/Snapdeal, Fabfurnish/Urbanladder/pepperfry, and so on. Furthermore, Free and Open Source Technologies and creative commons are good examples from the software domain that demonstrate and contribute to a more just and fair technology development and use. They promote global values that can be adopted locally. AM's case demonstrates the empowerment potential of such disruptive models in the traditional engineering sector, especially in the case of engineering for health and hygiene (sanitary napkin) products.

Similar disruption, through a restructuring of the contemporary centralized mass production model, could be an effective way to reorient current engineering practice towards sustainability.

One way to reform and bring in such plasticity into the canonical design process, which guides mainstream practice, could be through the prioritization of various creative and participatory processes related to problem formulation, such as need identification, problem definition, scoping and framing. Such a change would require recognizing and supporting new engineering profiles or identities, such as social entrepreneur, development consultant, grassroots innovator or designer. Further, one way for engineering innovations aimed at sustainability to move beyond the current notions of ‘technology for luxury/comfort/convenience/drudgery reduction’ that remain enslaved to the values of consumption and abundance, could be to design technology ‘for supporting sustainable livelihoods’, thus subscribing to the values of ‘sustainable self-sufficiency and empowerment of people’.

8.3.2.2 Solving for eco-social needs, a possible new approach to engineering science research

Even engineering sciences – which seeks to optimize scientific results and understanding to develop technologies for which needs do not yet exist – may benefit from such a widening of the design space. A good example of this is the recent development of the ‘paperfuge’[392] - a low-cost hand-operated centrifugal machine for testing blood, to address the problem of limited electricity access in medical labs in Africa. The design used microfluidic technology, and also illustrated that the RPMs achievable by hand are much more than previously thought. The design thus developed a real-world application based on a cutting

392 Bhamla et al., “Hand-powered ultralow-cost paper centrifuge,” 2017.

edge technology, and also contributed back to the science of rotation, all starting from a social need.

8.3.3 Implications for the education of engineering, science, design, and for educational policy

Current engineering education (EE) seeks to perpetuate a limited notion of sustainability, where it is seen as a more efficient use of resources, particularly developing 'clean and green' alternatives to petroleum power. Optimization – involving trade-offs, rather than a broader approach such as Solving for Pattern – is thus the primary guiding principle for students learning technology design, even when sustainability is a stated concern of EE. This 'more-for-less' value system is embedded in EE, forming its hidden curriculum, and places a premium on the use of calculations and hi-tech design tools. After training, students reflect the same value - "optimization is the goal, and that is innovation".

Training to achieve performance optimality alone is highly limited from a design perspective. Given the current socio-economic context, such training would be the same as training to design for maximal profit. Current engineering education appears to have implicitly accepted the narrow optimality-profit combo as the only design value and norm. This approach to design is clearly not what engineering education would want to be taking, particularly now that sustainability is a key engineering norm. The hidden curriculum of 'more-for-less' blinds engineering students to wider design possibilities. It also tends to work as an implicit device for capturing/directing the engineering work force towards solutions and structures that are unsustainable.

This thesis project attempts to indicate some possible directions to address these educational issues. The possible implications at the curricular, pedagogical, evaluational, and policy levels, are discussed below, though acknowledging that the issues are far too complex for a claim to be made about addressing them wholly with this proposal.

8.3.3.1 Training to design for enabling sustainable livelihoods

Anil Gupta comments, “There are problems in our society that we have decided to live with almost indefinitely. The result is a feeling of alienation among the affected people.”[393] Contrary to doctors serving in rural areas, and lawyers doing pro-bono work, trained engineers and engineering students in society either do not see the problems around them, or do not know how to address them. Scholars like Bucciarelli[394] have strongly argued for bringing practice contexts into design education, to overcome the limitations of designing in the learning context of textbook problems. While this may not address the above problem, it would be a step in the right direction.

An engineering program that integrates courses, project work, and internships based on the approach of Solving for Pattern could provide an opportunity for training students to address sustainability problems effectively. Training for designing technology that enables sustainable livelihoods could be one such course. Contrary to partial interventions that seek to change the existing curricula or pedagogy by including modules oriented towards sustainability, such a course would integrally address the required pedagogical components of knowledge, skills (including problem formulation and problem solving), and values. Scenarios and exercises based on cases of grassroots technology design practice could expose the students to real livelihood problems. While courses on Ethics or sustainability may broaden the knowledge base, this would only result in a descriptive understanding. Case studies of practice, such as GRI and EP, when integrated with the module on Hydraulic

393 Gupta, “The grassroots innovators,” 2013.
394 Bucciarelli, “Designing and learning: a disjunction in contexts,” 2003a.

Machines and Design of Turbines, would help redefine the idea of engineering knowledge, skills, and values. Ethics could become a part of the engineering definition of excellence, rather than an extra course that required a process of "infusing ethics into engineering"[395]. Integrated into the curricular modules would be real world issues. Other elements of such a curricular structure could include:

i) a detailed view of some of the ways in which the SfP approach makes a difference directly at the level of the design process. For example, how diverse design considerations, such as decentralization, interact with various stages of the design process, and thus change the larger eco-social relationships.

ii) 'designing for the larger eco-social systems', as a contrast to the limited context of the industry (production/manufacturing), market (distribution), and consumers (consumption).

iii) contrast cases that highlight the significant roles played by forms of technological knowledge apart from formal structures, such as know-how and tacit/experiential knowledge.

iv) contrast cases that highlight how a failure to sensitively handle the interconnectedness and eco-social relationships that technology is embedded in leads to a sub-optimal technology. For example, a technology to process waste plastic at cottage-level may generate employment and address the plastic waste issue, but if it generates pollution in processing the plastic, the technology would not be sustainable, nor could the design approach be called SfP.

395 National Academy of Engineering, "Overcoming Challenges to Infusing Ethics into the Development of Engineers: Proceedings of a Workshop," 2017, p 9.

Such courses could make ‘learning by doing’ a necessary pedagogical component for all stages of the design process, including need identification and problem formulations. Special credits could be allocated to encourage non-mainstream grassroots projects and internships.

Designing technology for sustainable livelihoods could also emerge as a possible model for other sustainability engineering programs, where the knowledge-skills-values transacted would be built into the pedagogical design, which requires uncovering and examining the values hidden in every curricula. Such a course would also provide opportunities to combine diverse pedagogical strategies, such as active learning, project-based learnings, case/scenario-based learning, and more, thus allowing the curricula to overcome the limitations imposed by any one of these.

8.3.3.2 Nurturing imagination and eco-social values

All aspects of technological knowledge beyond the theoretical (such as thumb rules, heuristics, local/experiential knowledge, and trial & error methods), while critical to innovative design processes in the world, are largely neglected in engineering education. Given the dominant bias towards the formal, it is not surprising that pedagogical components such as project-based learning do not by themselves succeed in exposing or training students for the bottom-up aspects of the design process. On the other hand, the competencies required for sustainability engineering are still not well-understood and agreed upon in the engineering education community. It is clear though that unlike the science and maths used in detailed design, these competencies, including some qualitative skills and more, are often not theoretical and declarative. The current engineering pedagogical process and methods are not geared to train for these skills. The grassroots technology design practice I have characterized suggests problem formulation capabilities (especially for an eco-social context), imagination, as well as synthesizing capabilities as some of the core competencies that support sustainability engineering.

The grassroots technology design cases also demonstrate that engineers need to be able to develop and use various structures (real/virtual, formal-non-formal) to imagine with, in order to design. This indicates that not only do students need to learn (to use) the formal structures, but they should also be able to develop and practice other cognitive alternatives as fluently. This cognitive fluency involves more than calculation, as cognition here is understood to be distributed across these structures, and situated in the eco-social context. Since the cases help bring out these aspects, with real-time design process and consideration details, integrated case-based learning could offer a good avenue to build these competencies among students. Case studies are widely recognized as an effective pedagogical tool in such contexts, as they also help develop tacit knowledge.[396] The cases could thus provide ways in which designers can situate themselves in real-world problem contexts, or embed engineering design learning in authentic contexts.[397]

Most importantly, this suggests that selecting for, and nurturing imagination, is one of the crucial requirements to groom future engineers for sustainability. Currently, students are selected for undergraduate engineering education on the basis of entrance examinations or qualifying examinations. Most of these exams screen students based only on their competency in working with formal structures -- knowledge of sciences and mathematics -- and analysis skills. Since there is rarely any screening based on imagination abilities or skills,

396 Heymann, “Engineering as a Socio-technical Process: Case-Based Learning from the Example of Wind Technology Development,” 2015.
397 Jonassen, “Engineers as problem solvers,” 2014.

or the capability to synthesize multiple factors into a design, or selection for eco-social sensitivities or knowledge, the selection is based just on techno-scientific rationality, which is then reinforced by EE. Given such a mutually reinforcing and circular system, where selection, training, and assessment is for formal structures and analysis skills, it is very difficult to build in sustainability values and practices. One way to reform this system would be to revise the entrance or qualifying examinations, such that they also screen for imagination, as well as the sensitivities valuable for sustainability engineering, selecting those with a more balanced understanding of both eco-social and techno-scientific factors. Whether it is possible to train for better imagination and synthesis is an open question. However, since it is clear that training for formal structures is possible, sustainability engineering practice may benefit from selecting and nurturing students with imagination and synthesis skills, and training them to use formal structures, rather than expecting formally trained students to develop imagination and synthesis skills, which is the current approach.

8.3.3.3 Grooming for a wider engineering identity

In the current education system, students' engineering identity gets constituted primarily through their educational training for and competence with formal structures,[398] a focus that also encourages a hidden curriculum that leads to social disengagement.[399] Since neither imagination nor eco-social problem-solving receive any emphasis or recognition in the education system, students' engineering identity is often limited to the dominant pedagogical process of learning formal structures. Gary Downey[400] has posed the following crucial question for EE:

398 Lucena, "Flexible Engineers: History, Challenges, and Opportunities for Engineering Education," 2003.
399 Cech, "Culture of disengagement in engineering education?" 2013.
400 Downey, "PDS: Engineering as Problem Definition and Solution," 2015, p 442.

> *"Might the main challenge facing the making of engineers in the present be to re-imagine and re-define in its entirety the obligatory core and essential heart of engineering identities?"*

Designing technology for sustainability makes going beyond the limited formal (and industrial-commercial) identity an imperative. In training for values and ethics, educational practitioners and research scholars have identified case studies and role models as effective pedagogical tools, particularly for inductive learning in undergraduate education for professions. SfP cases of sustainable grassroots technology design could offer alternate practice-cum-role models, integratively addressing the pedagogical challenges of exposing and training students for real-world complex problem-solving, social engagement, socio-technical plasticity, and sustainability perspectives and values such as SfP. The cases discussed in this study outline a spectrum of role models, which bring forth a diversity of possible identities in the practice of engineering design for sustainability. While the DWT artisans have been innovators and private entrepreneurs, GR and AM are social entrepreneurs, and EP is a development consultant. These role models could help demonstrate that,

> *"... engineering is more than developing technical artifacts. It is a way of "mixing with the world" in a much broader sense than reflected in many engineering curricula."*[401]

These aspects can help contain the overemphasis on formal knowledge, and the resulting identity. Exposure to case studies of non-formally trained innovators may also enable better dialogue between practitioners and lay people. This may pave the way for effective participatory designs, where collaborations between trained designers, experienced craftspeople, and lay users, lead to innovative sustainable technology. The case of Danish wind technology illustrates the possibilities of such collaborations, and it is already part of

401 Heymann, "Engineering as a Socio-technical Process," 2015, p. 477.

Aarhus University (philosophy of engineering) curricula for undergraduate engineering students.[402]

Case studies such as DWT, AM, GR, and EP, when integrated with the respective modules in engineering curricula, could support the development of an alternate engineering identity, and thereby shift engineering design education and practice more towards sustainability. Such mental exercises would be one way to build among students the sensitivity necessary for understanding the larger patterns. The key difference from the current sustainability curricula would the focus of these cases on flourishing, which is a broader than the anthropocentric approach.

Designing engineering programs, and even institutes, that teach for sustainability in an integrated manner, by screening for, and nurturing, imagination and synthesis, as well as training for eco-social problem formulation, are one of the key educational policy recommendations of this thesis project.

8.3.3.4 Implications for science education

The practice of science is fast expanding into interdisciplinary, trans-disciplinary, and engineering sciences, where science studies and technology run in parallel and inform each other. Given this fast-developing research area, it has become imperative for science education to combine engineering and science, and there are active programs now to include engineering at the K-12 stage in USA[403] and other countries. The work reported in this thesis suggests some other ways for science education to incorporate this change, as outlined below.

402 Heymann, "Engineering as a Socio-technical Process," 2015.
403 Chabalengula & Mumba, "Engineering design skills coverage in K-12 engineering program curriculum materials in the USA," 2017; National Research Council, "Engineering in K-12 education: Understanding the status and improving the prospects," 2009.

The Indian Department of Science and Technology (DST) has already extended consistent support and recognition to grassroots innovators, through the National Innovation Foundation, and through an annual exhibition as well as Innovator-in-residence program at the Rashtrapati Bhavan. Similarly, support and recognition could be provided to these innovators through science textbooks and curricula. Similar to showcasing Citizen's science or Biodiversity Registers of Western Ghats in science textbooks, the technology design efforts of grassroots innovators could be included to showcase the value of generating techno-scientific knowledge outside sophisticated laboratories, and the value of learning by doing. Their stories would not only bring respect to the innovators, but also provide role models to the science students. This would prepare them to engage with the societal problems around them, and to persist in solving the problems using their knowledge and skills in formal and non-formal science and technology.

Secondly, environmental education curricula could include the cases of grassroots technology design, to highlight the role of 'building' or 'making' in the current state of society and the planet. The discussion around sustainability would be enriched by an understanding of design considerations and concerns of doing technology, and their implications. For students, understanding the nature of technology, and what kind of technology we want to do, is as important as understanding what kind of science we want to do, for sustainability.

As mentioned above, engineering is being introduced at the K-12 stages in the USA[404] and other parts of the globe. This effort, along with Design and Technology (D&T) education efforts, can expand school students' opportunity to do interdisciplinary science

404 Katehi, "Committee on K-12 engineering education," 2009, cf *Cambridge Handbook of Engineering Education Research*, 2014.

through sustainability-related projects in engineering, and design. Reforming engineering education in these ways is particularly important for sustainability. Adopting broader approaches, such as SfP, towards sustainability engineering right from the K-12 stages could help avoid many of the pitfalls of the current engineering and science education. It may also be productive in D&T education to draw upon real-world contexts drawn from the needs of technology for sustainable livelihood.

8.3.4 Implications for research and methodology

This study demonstrates that the multiple case study method could be used in design studies of practice ‘in the wild’. Ethnography is a limited tool while studying historic episodes, and protocol studies limit the study of practice to controlled conditions in labs. The cross analysis of multiple cases, as illustrated in this work, could be one way to look for converging generic principles, even when using the qualitative case study method. Further, combining the practice lens (thematic analysis with design episodes and transitions) and the cognitive lens (cognitive-historical analysis with designed artifacts) could be powerful while analyzing the interrelationships between design practice and thinking across time.

8.3.4.1 The simulation tool

The study also illustrates how data from simulations and similar virtual design spaces could be used to more deeply probe both the practice and cognitive aspects. Practice studies typically focus on field study data and and historical methods. They rarely involve controlled scenarios. The simulation tool we developed provides a quasi-experimental structure, where clear situations could be set up and tested with different participants, and log data and eye tracking data collected for further analysis. This virtual design environment is generic, and illustrates a new method for the following.

- Probing design thinking
- Prototyping for a training interface: Pilot testing of the simulation with engineering students indicated its potential as a game-based learning interface, also allowing students a virtual experience of MHP designing.

8.4 Contributions and limitations

A summary of the contributions and limitations of this thesis is as follows.

8.4.1 Contributions

This thesis is the first in India and among the few global systematic research projects to:

- Develop an evidence-based approach to designing curricula and pedagogy for sustainability engineering
- Characterize the formal and non-formal situated practice of grassroots technology design

- Study technology design practice in the unexplored domain of non-formal design (particularly, grassroots innovators)
- Characterize the cognitive process of sustainable technology design across formal and non-formal engineering innovators
- Analyze the nature of non-formal design thinking in the light of distributed and situated cognition (rather than the classical information-processing model)
- Bring together studies from three distinct viewpoint levels -- of practice (macro-level), design process (mini-level), and design thinking (micro-level), from across a wide range of scholarly disciplines that study engineering and technology -- to develop an understanding of the nature of engineering, as well as the foundational assumptions underlying engineering education
- Bring to light the implicit aspects of mainstream engineering, and its practice and identity defaults, against the contrasting cases of non-formal technology design.
- Probe technology design thinking using a novel context-situated simulation tool developed specifically for this purpose

8.4.2 Limitations

- The primary data collected was not in real time, as the key empirical cases of design practice were historical. This required participants to depend on memory, which is not fully reliable. This limitation was somewhat offset using the simulation studies.
- No cases of grassroots women technology designers were studied, as these were not readily available. The conclusions could change for such cases.

- The simulation tool, while helpful in recreating the basic design situation, set up a well-defined problem, and provided limited feedback. These factors could have affected the responses of the designers.
- Student data was collected only as a contrast case. It confirmed the understanding from literature. For this reason, it was not analyzed in greater detail. It is also not reported here in detail.
- The analysis identifies the limitations of the canonical design process model. However, at the current stage of the work, I do not present an alternative/replacement model.

8.5 Future work

There are many ways to take this work forward, the following are some of the ways that are being pursued.

- The study of grassroots innovators to understand their problem formulation. in order to learn to design technology for sustainable livelihoods.
- The design of pedagogical interventions to train students in eco-socio-technical problem formulation, particularly a theme-based, rich, model case study module.
- Integration of case studies and assessments as part of technical modules, to expand student understanding and values.
- Developing a traveling workshop for engineering colleges.
- Designing a model internship in grassroots design.

- Extending the advanced simulation, for probing as well as learning.

Conclusion

> *"The things we call 'technologies' are ways of building order in our world. . . . For that reason the same careful attention one would give to the rules, roles, and relationships of politics must also be given to such things as the building of highways, the creation of television networks, and the tailoring of seemingly insignificant features on new machines. The issues that divide or unite people in society are settled not only in the institutions and practices of politics proper, but also, and less obviously, in tangible arrangements of steel and concrete, wires and semiconductors, nuts and bolts".*[405]

It is no longer far-fetched to extend Langdon Winner's warning about 'building order' to the 'building instinct' itself, since the very survival of the human race and sustenance of life on Earth now balances precariously on how we reshape our building instinct, and in turn the technologies we build. This thesis project hopes to have contributed one step in the right direction.

405 Winner, *The Whale and the Reactor*, 2010, p. 29.

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Appendix 1: Case Study of GRI

Introduction

In this appendix, I present detailed description of GRI’s design episodes and transitions further to the data reported in Chapter 5, section 5.3. I describe in detail the background and context of the designer, and report the data related to his early design trajectory, current design process and techniques, his interaction with the virtual design (simulation) tool, and his comments and views on other designs.

A1.1 Background and context

GRI is based in the Western Ghats region of peninsular India. This mountain region receives heavy rainfall during the Monsoon months (June-September), and is thickly covered with evergreen and semi-evergreen forests, besides the plantations of coffee, tea, and areca nut. GRI studied up to grade ten in a local vernacular medium school, and then took up his family occupation of farming, mostly the cultivation of paddy, areca nut, and coffee in his ancestral land. Twenty years back, he lived in a small village with his wife and their son, who is now independently employed in a city.

Electricity is supplied to this region through the power grid laid down and maintained by the State Electricity Board. But there are places where the grid has not reached, like GRI's village twenty years back. Also, even where grid provides power, often during the Monsoons, there are power cuts lasting ten to fifteen hours per day. Furthermore, due to heavy rains and storms in Monsoons, trees fall down or the electric poles are uprooted, and the power lines break. When the electricity distribution network breaks down, repairs take months, and the region experiences a season-long power failure.

A coffee estate manager in the region summarizes the need for an alternate source of power.

> *"... the usual power supply what we get from the main grid, that's also very erratic because one is power cuts, second is maintenance problems… in the sense that one small branch falls on a wire, the whole thing is gone. So then again finding that problem, and rectifying it… that'll take some time. So this, anyway since nature has given us a lot of water. I mean you can see water everywhere. So we thought that was a very viable option.*
>
> *Second is the gradient is very steep. <> … umm… the difference between the bottommost point of my estate and the top-most point is a 1000 ft. So that itself is translating to a phenomenal amount of head." [140308_006]*

GRI wanted to solve this problem for his household. He had visited a big dam, where engineers used large turbines to generate power from water, and supplied this power through the grid to cities and industries. He wondered if the perennial stream near his house could be similarly used to generate power for his household. He had not heard of such a small power system.

> *"I visited some higher capacity turbine in 100 KVA, 1 MW. That's a different… I will visit it and see and almost all I will… decided. There is a higher capacity… Why not we will design very… umm same type… is smaller. For independently? That's a first time. I will image.. The 1st time. After then I will try. Why the higher turbine… [mb na??] turbine is compared to every entire state… whole state. But why not devise… design my own for my house or my independently? I will will yes!... twenty years back." [140307_007]*

So he poured all his energy and money into designing such a system by himself. From 1990 to 1995, while GRI worked in his family plantation, and later in the near-by town as a sugarcane farmer, he continued to work on the design of the system. In 1995, he had a working hydro power generator running on the stream by his house. It supplied enough power to run lights, fans, and domestic appliances in the house. It took him nearly five years to arrive at a satisfactory design of a micro hydro power system. He also incurred a heavy debt that took him many more years to discharge off. But more painful was that his father was very displeased with this activity. Many in the village blamed him for landing himself into all this trouble, and only a few supported and encouraged him. GRI then had to take his family, and leave his father's house. It was only after he was recognized nationally and rewarded, that his father took him back.

> *"But nobody supported means not easy.. [I] was almost all blame.. [chuckles] in the village, people all.. <> father first he will blame and kick out my family house first.. <> but brother supported." [170109_015]*

> *"After then.. till umm nineteen umm.. yes, ten to fifteen years I when outside.. return back to .. [na] link umm completely missed my family. My father is very angry.. yes.. [na] After then he will compromise .. also my award is come then he will compromise." [170109_015]*

Eventually, by word of mouth, and coverage in the news, other people in the neighborhood learned of his technology, and showed interest in installing it for their households. Encouraged by this, GRI struggled to set up a business that is today known for successfully installing micro hydro power systems in remote areas. Ten years back, he installed three more turbines downstream, on the same stream near his house, for other households, charging them INR 50000. Over the years, his innovative work was widely recognized and rewarded through various state and national awards, including the Grassroots Innovator award by National Innovation Foundation. He was also invited to present his design at state and central government exhibitions, and at the Festival of Innovation, as a Scholar-in-residence at the Rashtrapati Bhavan. Engineering colleges invited him to give seminars about his technology, sent students on study visits to his sites, or to conduct projects with him, and one university included his case in their syllabus. (Brochure).

> *"Ten years.. by independently I fight. After then supported by some government and [NIF: NGO name]." [170109_015]*

GRI claims that he has installed more than 300 such systems. He proudly says that, "per day 10000 kW power generation by my individual turbines", and "that's a contribution to the government".

There are many potential sites for MHP development. But mega-power companies don't address this demand. According to GRI, MHP systems need to be designed as per site constraints and opportunities to generate power at about 40-60% efficiency. But mega-power companies have a business model where they work with one standard design, and will get only 5-10% efficiency. So the economics does not work out for them. They have heavy, vertical turbines, made of pure steel or brass, and will last for a hundred years. GRI designs horizontal turbines made of MS or galvanized steel. His turbines will last for about 25 years, and the customer recovers the investment in about three years. He says,

> *".. lower cost. When you will adopt any brass or heavy/any steel blades you will use, that's a very expensive. That's burden to the customer.*
>
> *Yes. But does it improve the performance also? Brass?*
>
> *No.*
>
> *Or efficiency?*
>
> *No, no, no. only umm for life." [140307_007]*

So GRI wishes more entrepreneurs take up this activity and start a similar business, but so far no one has come forward. It is because there is an initial effort that one has to put in .. it doesn't give profit immediately. He comments that engineers want a cushy job.

> *"They will say that's a risky job. And he was almost all days in the… for every… he was get sufficient salary… Engineers are.,. any persons… he has a… get sufficient salary. He was not take any risk. So he was not trying.*

Okay. What risk?

Means… risk. Means… the fabrication and a every design. That is a very risk. So he was not a take any risk. But he was thinking… why I struggle. With all every month… he has average per month the salary. The engineer is thinking that's way." [140307_007]

His customer who has placed order with him for a second and bigger power system recommends him, because,

"... he is quite well-known. And his warranty and guarantee is much better than other people. And his product is tried and tested." [140308_021]

There are few other designs available in the market. One such off-the-shelf product comes from Nepal, and offers no service support. As per GRI, who is aware of all these designs, this MHP system supports only lighting, and no other gadgets.

"Any equipments it's not working. Any TV or umm mixie… any how it is not working. Only for only… only for lighting. But it is required very-plenty of water. Umm no… and otherwise it is take minimum 80 feet, means umm 50m head-minimum. 30 to 40. For the low head it is not working. <>

And he is not a one-time is giving it is not a that's a responsible to customer… that's not a any service… no. And another one… enquiry is no. Any just purchase & forget." [140308_006]

According to GRI it does not address people's needs, and most installed systems of this kind have become non-functional very fast. (Fig. 66).

Fig. 66 One of the other MHP systems available in the market, but seen to be dysfunctional at this site.

"That is a only it is a… it's a only it is one of the alternator… alter means a motor. A motor is there… it is directly connected to shaft connected to umm water wheel. Directly. And he will use only 3 capadi.. capacitor. <>

It's not… efficiency is not there. Only 10-20% efficiency. Yeah. The efficiency very less.

And constant voltage is provided?

No, no, no. constant voltage it's a lower. It's a vary… different… umm vary."

> *“power production .. 400.. 450.. 600 watts it will go.. then he will completely control.. control means again he will divert the power to dummy load. So almost.. this is a very risky job. <>*
>
> *And some person.. don't know.. open the valve .. get the power.. connect it to the load.. immediate bulb is burst.. the equipments is completely burn.. lot of loss happen..” [170109_006]*

An end user [the coffee estate manager], who had installed one such MHP system that no longer works, comments,

> *“what you saw in the 2nd unit, is a very shared design. It’s like umm even though it’s a very popular design, its’ just part of a may be a 8th std. or a 10th std. physics textbook. <> but GRI… what is happened is he has learned it by trial and error… that you need certain components, without which it’s not going to work. That is why the belt drives, the pulleys and all come into play.” [140308_021]*
>
> *“he’s [GRI] a … one is he is a very close locality .. he will come at my … whenever I call him. Do whatever umm maintenance is required and he takes input from me. The other guys have a kind of a … rigid… fixed design and more over they are doing, stuff… they are just modified off-the-shelf equipment, that’s one more thing if you have noticed. They have actually just modified off the shelf equipment. So there’s no real… umm… input from their side per se. <>*
>
> *Where as he [GRI] is using only one component that’s off the shelf. Which one? Only the generator. The whole drive mechanism, the water inlet, the umm calculation of the water required that’s coming only from [him.. GRI], where as the others, I just have to give them umm the end of a pipe. They just bring a motor off-the-shelf, rewire it, put it there.” [140308_023]*

The Ministry of New and Renewable Energy along with the state government has approved of these products for a subsidy of INR one lakh ten thousand. So many manufacturers have got into this business to get this money. The subsidy encourages customers to prefer this product. But GRI claims that the system is an ineffective design, and actually worth at the most INR thirty thousand.

> *“.. it’s only simple.. simple motor. Our regular motor. It’s.. is only eight to ten thousand and [na] within 15-20 thousand.. finish. Thirty thousand. All put together.” [140308_020]*

On the other hand, GRI's design still awaits approval for subsidy, because it has not been scrutinized and approved by a technical agency yet.

According to him, in 2013, his 1 kW system cost approximately INR 65-70 thousand, while a 10 kW system cost about INR 1.80 Lakh. He says a 2kW system is sufficient for a household with a TV, fridge, and mixer. While he mainly designs Pelton-like turbines, he has also designed and installed several water wheels for low head water situations like canals.

In the following section, I describe the process followed by GRI to design and build his micro hydro power system, by designing Pelton-like turbines. Since GRI's design activity occurred in the past, this description is a reconstruction based on his interviews, documents, and the artifacts that he built.

Also, no drawings, diagrams, or other external representations that he created if at all for his own use, or for others were available or mentioned. But while explaining his activity to me, he drew some of the machine parts he was describing, on my request.

GRI's design process can be split into two parts:

1) the early design trajectory

2) the trajectory after the final working system was in place

A1.2 GRI's early design trajectory

The historical trajectory of GRI's designs, developed over an initial period of at least five years, offer certain landmark stages or distinct episodes of design prototypes. I present these as key transition episodes culminating in his final working design.

1. Lighting a torch bulb
2. More power and DC storage
3. AC power
4. Grid quality power (Constant voltage)

A1.2.1 Episode 1 - Lighting a torch bulb

Background

GRI did not have formal knowledge of hydro power systems. His first design was based on the gadget he was familiar with - a bicycle DC dynamo. He had seen people pedaling bicycles on the road with headlights powered by dynamos.

> *“I am a farmer. I have studied only SSC. But I have interest... Twenty years back I have no shop [workshop], or my house. So I started simply with DC dynamo... ”*

But he wanted to use water to generate power. He reasoned that how one rotates the dynamo should not matter. As long it was rotated, it would generate power.

“Why it is not.. any how you know.. when it will rotate .. it any how any torque[406] is there..”

He asked himself,

“Why not other movement except by pedal or hand? Why not water on a fiber-fan? I have plenty of water..”

He knew of a device that used water to rotate a fan. The fan-like device was traditionally used to beat drums in paddy fields at night to keep away the wild boars. Although GRI did not name this device, he drew and described it.

“It has a fan-like component that freely rotates on an axle. It is fitted underneath falling water stream in the paddy field. As it rotates, it drives a gong to beat a tin, making noise that frightens wild animals away, especially at night.”

Reference to a similar device is found in the description of Sri Lankan paddy farmers, who call it the 'water ghost' or 'Diya holmana' (REF) because it makes noise where as no one is seen making it.

Solution

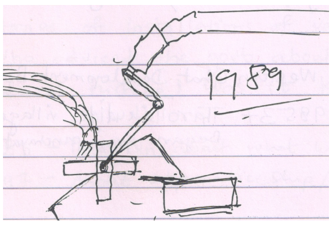

Fig. 67 Water falling on a fan to rotate the dynamo

GRI managed to combine the dynamo and a 'water ghost' like gadget, in order to use water falling on a fan to rotate the dynamo shaft. His drawing (Fig. 67) indicates this concept, in the form of the 'water ghost' directly installed under a small water stream, with its shaft connected to the shaft of the bicycle dynamo.

“I will afterward give one small pipe.. it will rotate.”

406 It needs to be noted that while in the interviews GRI uses many terms, such as 'torque', from Physics or the formal theory of hydrodynamics and hydraulic machines, twenty years back when he designed his MHP system, he had no exposure or access to this formal theory. Over the years, as he became well-known for his work, he had visits from and interactions with many formally trained visitors and college students. He may have possibly learned the terms trained persons use, to capture or convey certain meanings, through this communication.

Later, he took out the rim of the bicycle along with a dynamo, and attached plastic cups to the rim such that the rim rotated when water crashed on the cups. The dynamo shaft attached to the rim rotated, and powered a small torch bulb. He was able to generate small DC hydro power. Eventually improving this design, he was able to power more bulbs. (He did not comment on how he connected the five bulbs, in series or parallel, or if he lost any bulbs in the experimentation.)

“(I had) five torch bulbs burning in one year in my house.”

Observations

GRI's primary design goal was to generate power from water. At this stage, his understanding of the amount of power he needed was in terms of bulbs. His system was a complete solution that met this goal.

In order to design the system, he directly built the system, i.e. he did not design it on paper, or as a model. He combined two existing devices that embodied two functions/concepts that he needed to implement, modifying only the bicycle rim, on the lines of the 'water ghost'. The system acted as a prototype for itself. He worked with the components easily available in his neighborhood.

“Did you make any models? Of paper.. or something?

Models? Means umm..

For experimentation?

For experimentation? Paper.. no.

Direct live?

Direct. Direct.

Or any drawings?

No.. no. It is directly.. [chuckles].” [170109_015]

Considering that he was not formally trained, it is likely that his conceptual understanding of the dynamo was at a black box level. He learned about and used it in terms of its input and output, without knowing how it internally converted the rotation of the shaft into electricity.

His simple but complete system consisted of the following components:

stream water diverted through a pipe > cups attached to a bicycle rim > bicycle dynamo (shaft) > wires > bulb

A1.2.2 Episode 2 - More power and DC storage

Background

Having built a preliminary system to generate power from water, he realized that he needed more power to light the household bulbs. This triggered the next episode. He explored how he could do this, by using more water, and designing a system to run on more water.

Commenting on how he went about addressing this problem, he said that he did not have any guidance from any existing devices or books.

“Any turbine or any this type machine is not available in market or any [na] seen for solution purpose.” “Book is no available.. but I will put.. by trial and error, everything trial and error..” [170109_015]

Solution

GRI explored the junk markets in nearby industrial towns and replaced the bicycle dynamo with a DC dynamo used in motor vehicles. He added a DC storage battery to store the generated power. (Fig. 68)

> *"After then I do some improved version.. alternator.. motor vehicle alternator... DC dynamo. I will rotate it and store power in the battery and connect it to my house: 8 light bulbs. That is in two year."*

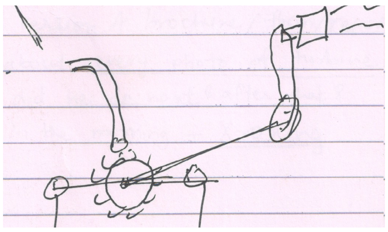
Fig. 68 A DC dynamo

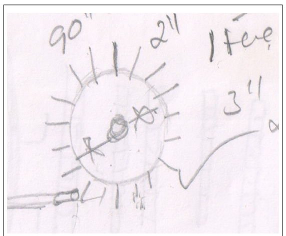
Fig. 69 Turbine 1

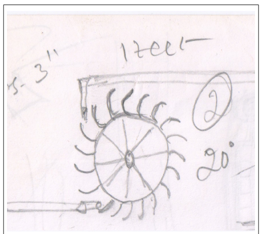
Fig. 71 Turbine 2

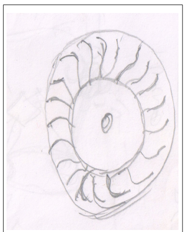
Fig. 70 Turbine 3

Turbine wheel

He needed a stronger wheel to handle more water and run the DC dynamo. So he tried to modify the bicycle wheel.

> *"Cycle wheel completely paste cement.. cement wheel. <>*
>
> *One is.. it is not completely through.. <> through means alignment.. it is not alignment.. wobbling..*
>
> *And another one is completely weight. Heavy. So it's .. it is not umm.." [170109_006 – 01:45]*

GRI went to a scrap yard and found a ready-made wheel (Fig. 69) – from a 'wind fan' i.e. a blower machine.

> *"This is available in.. it is fan.. means umm paddy cleaner and umm ragi .. means umm like as a big blower like same. This wheel. I will but it is completely it is already prepared. I not any alternation I will .." [140311_001]*

> *"It's ready available. First I will use. But is not umm it is not good. When it is water is crushed to the plate… water is fall down here… slipping.. it is not movement.*

But efficiency is .. very very less efficient

Only 10 to 15%.” [140311_001]

Water slipped from the blades, and so the wheel did not rotate well. Then GRI designed his own wheel, a 'spokes wheel', more like the original bicycle wheel, but better.

> *“After then I will use.. same.. wooden.. <> [Like a] Bullock cart wheel.. hmm same.. same. Like spokes. Yes. <> That's [Bullock cart wheel] very heavy.. very big. I will start with Pelton wheel.. mostly it is 20 inches or 24 inches. [170109_006 – 03:00]*

> *“I will completely make.. get one umm carpenter.. <> after then.. yeah, metal.” [170109_006 – 02:45]*

It was one foot in diameter, and had 24 plates, 3 inch each, made of MS steel. He further modified the angle of the plates by 20 degrees (Fig. 71). The shaft was made from a simple pipe used in plumbing. [140310_053]

> *“This is a spokes wheel.. This is Iron rod. This covered full by sheet. Iron sheet. And I will get the iron sheets from scrap. Iron sheets. That is a .. completely it will be open. [140311_001]*

> *“And after then I will change the … this type. 20 degrees. Light angle… light angle… so cups bend. Bend cup. .. Bend light twisted… light twisted.” [140311_001]*

> *“I had no any industry in myself. But other wise I am going to other industry… other workshop. I will a … different designs..” [140311_001]*

When he went to a workshop in a nearby industrial town to fabricate the sturdier wheel, he learned for the first time from others that it was called a 'turbine'. [140309_015] He says he did not go to look for ready wheels in the junk yard anymore, instead he tried several (ten) designs by himself, and eventually arrived at his final one (Fig. 70).

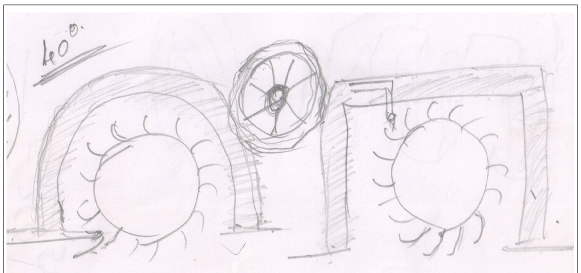

Fig. 72 Turbine casing and inlet designs

".. first I will experiment totally ten plants in my own purpose it will… I will design different type of ten plants." [140310_053]

"after then I will go into not junkyard. After that… after that only I will consider only I will consider pucca [fixed]… one purpose design." [140311_002]

The diagrams he drew for me indicate that he tried various positions of the pipe to hit the turbine with a water jet. (Fig. 72). Finally he settled for a pipeline at the bottom, and the jet hit the turbine's bottom plates/blades.

Turbine blades: shape and angle

He also tried out different shapes, and angles of the blades (Fig. 73).

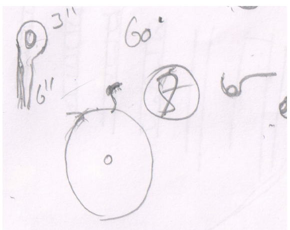

Fig. 73 Shape of blade

"I will start with .. same type direct.. direct means flat. <> After then.. half round.. half round." [170109_003 – 03:00]

He had also tried the rice mill elevator cups made of fiber or MS steel for lifting paddy in the rice mills, and easily available in the market.

"Buckets means first I will use.. this type is not.. rice mill elevator cups. .. After then we make umm iron.. iron cups." [170109_006 – 04:00]

"I will make the local.. by sheet I will fold.. after then I will make a buckets.. like as a half-round buckets. [na] But it is run a two years.. that's no problem.<>

But it is umm for domestic purpose, the 2kW is perfectly is producted [produced].. But lot of head is available.. more lot.. more water is available. But it is not .. umm efficiency is very below. It is umm that time may be 20 to 30 %." [170109_003 – 03:00]

He found that the flat and the half round shapes of blade were not very useful.

"Flat is completely .. when crush the water, it is completely split." [170109_003 – 05:30]"After then I will.. again I will again some different umm some change umm first Pelton wheel.." [170109_011 – 03:00]

"I will change angle, direction.. I will.. I will try.." [170109_003 – 03:00]

By heating and hammering the material, he tried to shape the blades into a spoon.

"hammering… here is … when it is complete heat and hammering. Here's a one depth is there… completely what is … crushed water is water is crushed to depth. Yes it is… same. Like a spoon…"

"6 inches length, 3 inches width. And this is 1 ½ depth… means… when water is hit to … this is half front… depth is direct depth." [140311_001]

"Spoon pattern is … it is… completely… it is… complete is … good. But it is umm he has fine in very… very tough… fix. Here is bottom is … tough.

Breaks very .. breaks… breaks. After then it is completely… it is no support. Only umm weld or only bolt. After then some time after 3 months or umm six see it is broken." [140311_004]

He found it difficult to firmly attach the blade to the wheel. To avoid breaking of the blade from the wheel, he explored the option of casting or forging. But at his scale of pieces required, it turned out to be an expensive option.

"I will try. But it's more come [na].. But casting is .. yes mold by … here is no manufacturing in my industry or other industry. It's only for… I will give the pattern to… in a industry in [industrial town] or umm in [industrial town]. Yes umm some foundry is there. But it is when you'll complete the give the order… but bulk order [na] But different type cups come only I will … only little. 12 or 20. Or 30 or 50. It is not possible. It is a heavy expensive." [140311_004]

Instead he devised his own method of manufacturing.

"Purchase the umm sheet. And you will cut it and you will bend. It is it's very easily. Within 1 or 2 days." [140311_004]

"This [the current curved shape] is very effective.. this is effective." [170109_003 – 03:00]

With this shape and angle of the blade, the water jet hits the edge of the blade. If it hit the center, it would rebound, but when it hits the edge, the wheel rotates smoothly.

"Center when it is hit, it is complete some time it is rebound. So it it.. this type.. it is easily move.. easily move." [170109_001]

The nozzle is placed at an angle and distance such that it hits a blade half-way between the middle and the bottom of the wheel, hitting one blade at a time.

> *"For example, a double.. means when it is hit.. it is complete.. the pressure is divide. So I will completely point to only one.. That's perfect."*
>
> *"So I will completely.. that is.. that is called angle. It's not cut the water.*
>
> *When the next one comes down?*
>
> *Yes.. yes! That is the [his company name] technology!" [170109_002 – 01:30]*
>
> *"It is possible only direct one hit. When it is going to the upper side, in middle gap, it will crush the water. So it is not cut the water. .. direct it is.. only one cup. It is not cut or any disturbance." [170109_003 – 00:30]*
>
> *"When it will crush the water here.. it will split. This is the space for .. split gap. .. immediately it will .. again it will going to up side.. it will completely wash out. .. Perfectly I will explain .. show .. at site. It's possible." [170109_003 – 02:00]*

In order to find out the best possible angle of the blade along the runner, he fabricated multiple turbine wheels, each with a different blade angle, and by installing them at a site, checked their relative performance in terms of RPM and voltage.

> *"One turbine I will completely install on the spot.. after then.. four types the Pelton wheel I will put ready to.. for testing purpose.. in the site. Same water.. same umm nozzle.. same head. It's not any changes. Only I'll changes only.. angle and direction of the wheel [means blades on the turbine wheel].. for different wheels. I will complete check the RPM. .. RPM.. the maximum RPM is finally..*
>
> *One is complete check the RPM. And another is check the completely output volt.*
>
> *Difference eh.. lot of difference. 30 % - 20 % - 20% - 30%. .. Sometimes it is completely 40% difference. .. when the.. when change the angles." [170109_003 – 04:15]*

According to him, a standard Pelton design is good for high head, but for low head it is not. It needs a minimum 60 to 100 feet of head. But his turbine design, (though more like a Pelton turbine), will also perform well in low head situations. If a cross flow turbine and GRI's turbine are compared in the same site conditions, he says his turbine will be as good, or could even be better by up to 30%. [170109_003 – 05:55], [170109_006 – 05:35]

Observations

In this episode, GRI's design goal was expanded to meet the real-world need: light the bulbs in the house, bigger bulbs than the experimental torch bulbs. His new design was a complete solution that met this expanded goal. He had 2kW power supplied to his house.

As this process extended over a number of months and annual precipitation cycles, GRI probably gained a qualitative sense of the seasonal variation in water flow in his stream, even though he did not measure the volume, or flow rate, and record the data. While engineers use hydrological data to get a picture of the annual rainfall patterns and likely fluctuations to estimate the water flow, this sense probably helped him decide the minimum water he could expect to generate power from, throughout the year.

He understood the amount (quantity) and quality of power that he needed (to generate) in terms of bulbs, and not in numeric units of wattage, or voltage.

His first system acted as a prototype for this next stage. He thought with the existing components, to compare and define the criteria of selection for new components. He used a component to think in two ways: using it to decide what the new component needed to do, and also what it needed to differently from the component he had. When he did not find such components easily in his neighborhood, he scouted for them at junk markets in nearby towns. He looked both - for what he thought he wanted, as well as what the stuff available there could offer instead.

Given the expanded requirement, he conceptualized his solution in the form of a readily available DC dynamo, and then worked with it, effectively ending up redesigning his entire existing system. While broadly the components remained the same, he essentially changed their specifications significantly. The DC dynamo worked as the technical goal and constraint for the redesign of his other components, through intricate loops of feedbacks.

His conceptual understanding of the ready components such as the DC dynamo was at a black box level, at a functional level. On the other hand, his finer understanding of the function and the form (concept and embodiment) of turbine wheel, blades, and water jet, and their interrelations, developed together, at an experiential and implicit level, as he experimented with various designs, shapes, sizes, and materials.

His still crude but complete system consisted of the following components:

stream water diverted through a pipe > some kind of spokes-cups wheel > pipe as shaft > connector > DC dynamo > DC storage battery > domestic light bulbs run on DC power

A1.2.3 Episode 3 - AC power

Background

There was more power, but in terms of usability, it was limited. On the one hand, DC power had its constraints in terms of charging time of the DC storage battery.

> *“Nine hours battery charging and output only three hours. That's a major disadvantage. … Night time, for example, you will start the power, burning lights for example five o'clock you open, start the lights, three hours only, eight o'clock it's finished. After that what you will do? ... When water coming to your turbines is started, (you want) continuous burning the lights.. any domestic purpose, any TV, mixie, any how/ of them.”*

On the other hand, GRI could only light bulbs. But they also wanted to run other household gadgets on power, now that it was available. For these, the DC power needed to be converted to AC, and that would have involved additional investment and maintenance.

> *“Another disadvantage is here. AC current is directly useful to TV, mixie, fridge, anyhow/of them, domestic purpose. But DC circuit: not easy to use. Again you convert it to AC. It is required the battery, and again UPS, and inverter. Again investment, and again additional maintenance. So it is a risky job.”*

Solution

In order to address this, GRI came up with the idea of replacing the DC dynamo with an AC alternator. (Fig. 74).

> *“After that I continue some mechanical improvements, and direct I will... why just not try for some .. thinking.. I'll take a small AC alternator and directly rotate it.”*

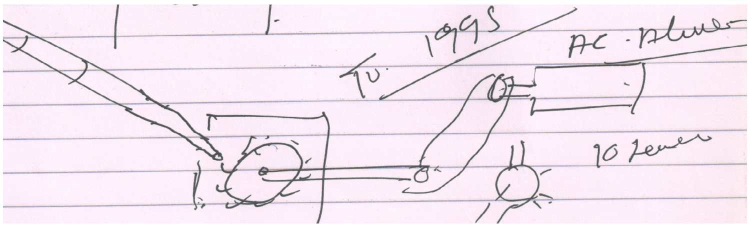

Fig. 74 AC alternator

Observations

In this episode, a broader household need expanded GRI's design goal, and in turn resulted in expanding GRI's technical goal (from DC to AC power) further.

Being the user himself, he implicitly brought socio-economic and behavioral constraints to the design - in terms of ease of use, time of use, maintenance, cost, and return on investment - not as add-ons, but as an integral part of the problem-framing in his design process.

He used the earlier system as a prototype to think with, and fine-tuned it for the AC alternator. He used the readily available AC alternator to perform the function of generating AC power.

With this, his understanding of the power he needed (to generate) also got modified. He understood power not merely in terms of bulbs, but also in terms of other technical qualities such as DC and AC, through the use of domestic gadgets that require AC power.

This understanding of AC power, and an AC alternator, probably remained qualitative, at a black box level.

His no longer crude, and complete system consisted of the following components:

stream water diverted through a pipe > improved cups wheel > wheel shaft > connector > AC alternator > power supply cable > domestic light bulbs, TV, fridge, mixer run on AC power

A1.2.4 Episode 4 - Grid quality power

Background

As long as he was lighting bulbs on AC power, the system worked fine. But when he had a TV or a blender running, switching the gadgets on or off seemed to create a problem.

> *"First I will.. directly I will put the turbine.. direct belt to the alternator.. When you will open the umm water.. rotated, and the power is generated. We were very happy, in two years.*
>
> *After then we will continue, then that time it is not TV.. it is not running.. that time. When TV is coming.. we.. we purchase one TV to my house. Then put the TV, immediately it will completely goes down, only .. the voltage. "What is the problem?" After then you will give the umm additional water. Anything.."* [170109_015]

The voltage dropped, even though there was no change in the water source that was driving the system.

“... when the light is putting, there’s no problem. After then you will put the … any load… for e.g. any other other… other things… means any umm charging or mixie [blender] or TV any… less come down of the production. But water pressure is constant. It is… it will not change. <clipped> 1st you will go production is voltage is 200, suppose. When you will switch ON the mixie, which is come down completely 100 Volts. It will be not working by 100 Volts it will not work in mixie. So it is not very… slowly it is rotated. And it is stopped.” [140310_044]

One of his customers who wants power in thirty houses in the coffee estate explains the same problem in the context of a power generator from a different vendor.

“what happens is… the quality of the power that is produced in that is very very poor. It’s not steady, and like if I supply it to say 30 houses, all 30 of them have to use all the load 24 hours. Like 1 person decides to [switch] off a lights, everybody else’s bulbs blow. <clipped> Or one person uses a mixie there, everybody else’s light becomes… dim.” [140308_009]

GRI found that the electric load variation significantly affected his output voltage. He needed to ensure that changes in the electric load did not damage the gadgets or the hydro power system.

Solution

GRI tried three different solutions over a period of time to resolve this problem: a booster (transformer), an AVR, and a flywheel. Since he did not know where to start, he asked an electrician. It was suggested that he could try the 'boosting method' i.e. he could use a transformer to boost the voltage.

“But I don’t know. But I … it is only suggested by electrician. After then I will for checking purpose I will purchase and I will put umm 2 transformer.. ” [140310_045]

He tried it out, but found that it was not the correct solution. When the load dropped, the boosted voltage caused the bulbs to blow up.

“But here’s a one problem [na] How many … [na] when it will be load is free, after then, it will voltage increase. Just bulb is on most of it is complete burn.” [140310_044]

GRI found out that automatic voltage regulators (AVRs) were used to solve this problem, and he could get one designed.

> *"I will inquire.. umm some electrical peoples. How do any control the voltage? It is similar, he will .. he will say. He will .. small.. easily.. easy, put AVR. <clipped> ... input is 300, Output is controlled by only 200." [140310_044]*

He invested a lot of money, and worked with AVRs for some sites, as can be seen in a 'Details of Project Report' (DPR) submitted to one of his customers (Fig. 75).

To
The general manager
Blue mountain estate
Shathaveri

Dear Sir,

As per your invitation I had paid a visit to your estate and inspected the whole setup I have come to an conclusion that the resources available in your estate are sufficient to generate approximately 25 K.V.A power.

Herewith I am forwarding a detailed project report with this letter for your reference kindly verify the same and send your feed back at the earliest .

Project Details

Si no	Particulars	Details
1	Name of the power generation site.	Blue mountain estate
2	Place of the power generation	Rex Khon feeld
3	Capacity of the power generation	25 KVA
4	Capacity of the turbine	35 HP
5	Power generation in volts	440 volts
6	Power generation in amps	15 to 20amps
7	Power generation in wats	10,000 wats
8	Power can be used for	15 HP pump set or 500 CFL lights
9	Power control by	AVR or Transformers
10	Power transmission by	UG cable
11	Source of the water	SB tank - Rex Khon
12	Discharge of the water for power generation	25 LPS
13	Available source in the year	365 Days
	Pipe line	
1	Quality of the pipe	PVC pipe(Phinolex)
2	Size of the pipe	8 Inches and 6 Inches
3	Number of leanthes	25 numbers
4	Gage of the pipe	10 KG
5	8 Inches butter fly value	1
6	Plange and fittings	

Fig. 75 Use of AVR to generate constant voltage (Detailed Project Report for a customer)

But he concluded that the digital AVR incurred a loss of power, and was not as effective as he wanted, in spite of its high cost.

> *" some vary is input the … into the AVR, and output is total receive 20% less in AVR… power loss. That's a major problem. One is a power loss. Second is heavy expense." [140310_044]*

> *"But the only it's a temporary solution. It's AVR or transformer is that's a temporary solution. The permanent solution it is not." [140310_045]*

> *"That's complete I will forget. After then easy solution is only is a mechanical." [140310_044]*

He decided to forget about transformers and AVRs, and went for a mechanical solution – the flywheels used in various machines, to control the runway speeds of wheels.

> *".. so I .. I think.. not use the one supporting wheel.. why not use.. that's how .. one small wheel purchased by.. it's not calculated.. totally on weight.. count weight to.. side. That .. that is some improved. "Ah, I think.. oh, so it is completely improved.." After then I go into the market, I purchase a one 25 kg one flywheel.. problem is solved. After then the blinking and the TV and all the light it is.. constant voltage.." [170109_015]*

> *"put a small flywheel inside. then it is rotates starts by force .. by force with water next will push the flywheel .. when it is rotate start the turbine and umm flywheel, the movement is very free. Constant voltage." [Voice103]*

He found that the flywheel balanced the RPM of the turbine wheel when the load dropped, and in that way helped keep the voltage and frequency of the alternator constant.

> *"When you will remove the balance wheel, it will be completely … rpm is completely… unbalanced. If imbalanced.. 1000-1400 or 900. Anyhow. When you will put flywheel, it is continuous definitely completely speed maintain." [140310_031] "The voltage is completely regulated. It is not blinking.. " [140310_032]*

Flywheels he could even source from the scrap market. If not, he could get it manufactured as per his design, for a required weight. On the whole it was a much cheaper solution.

> *".. the flywheel cost is only some within 3000 or 4000. But permanent solution. But AVR is completely available adopted, but it will maintenance … cost is 20,000 rupees." [140310_044]*

Observations

The need for safety of gadgets and quality of power expanded GRI's technical goal from AC power to constant voltage AC power. In this episode, he addressed the design challenge of 'control', rather than 'power generation'.

He tested readily available solutions embodied in specific existing components/gadgets, in the process traversing across three different domains of formal knowledge (electrical, electronic, and mechanical). GRI plugged each of these into his system, and applied his own criteria to test the performance. Considering not only the technical functioning, but also the cost, maintenance, accessibility, and the socio-environmental context, he discarded even some of the more sophisticated options, and decided that flywheel was the most effective solution. Effectively, he worked with three diverse concepts of controlling load variation and providing constant voltage that these components embodied.

With this, his understanding of the quality of power that he needed was also modified. He understood power in terms of domestic gadgets, but he was also aware of the technical qualities of this power. He talked of this power now, as of the same quality as that supplied by the State Electricity Board through the grid. [140307_003].

> *“That's the same power.. When is a [name of the State Electricity Board] supplies the power.. same quality, same power.”*

Fig. 76 Old turbine design for grid quality power

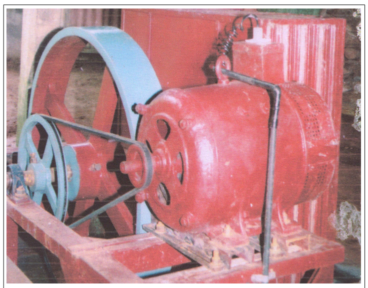

Fig. 77 Flywheel view

Innovating the technology by himself, GRI finally had a complete working system after five years, that supplied grid-quality power (Fig. 76, 77). It consisted of the following components:

stream water diverted through a pipe > a cups wheel > wheel shaft (with bearings) > a belt pulley > a flywheel > a belt pulley > AC alternator > power supply cable > domestic light bulbs, TV, fridge, mixer run on AC power

With this, he finally had power to run not just ten lights, TV, and fridge, but also other gadgets.

> *"Totally it was getting more power.. 50 lights, two filters, and one single-phase motor.. everything is [na]" [170109_011]*

A1.3 GRI's journey after finalizing the design

After GRI finally had his working power system design installed and running at his house, he continued to work on the turbine design to improve it further.

> "Again I will change the turbine, it will.. then it will provide ten.. ten kilowatt. Same head, same discharge.. <> 200 feet head, 12 LPS. But then it will.. same discharge, same pipe length, same [na].. ten kilowatt." [170109_011]

As others learned of his success, he saw an opportunity to convert this into a business. In the meanwhile, he had to face a notice from the State Electricity Board, objecting to his producing power for himself. A supportive Member of the Legislative Assembly (MLA) then moved for a resolution in the State Assembly, whereby people were eventually allowed to generate their own power where the State could not address their need. GRI was then cleared to build power systems for individual consumption, given he did no damage to the environment, and provided he was not selling power.

GRI implemented three installations during this period, mostly investing his own money, as customers were still not sure of his project. He accepted any payment they were willing to offer, and incurred financial losses, but gained publicity by word of mouth. These became his demo plants for prospective customers. It was still a side business, and he invested his agricultural income into it. During the years of agricultural loss, the business was entirely put on hold. All put together, he estimates his R&D investment at INR 5 Lakhs, which when sold at the scrap market fetched him only INR 80,000.

GRI needed land and capital to expand his business, but neither the District Industrial Board, nor the banks initially provided him with loan. Finally, through the MLA's support, he received funding from the State Finance Corporation, and started his own industry in 1997.

For about fifteen years since he started, he continued to learn from his own mistakes, and he used to be happy to find a mistake because it helped him learn.

For example, initially he used gunmetal bushings in coupling. But these demanded perfect alignment, and the slightest change would reduce the RPM. So he replaced those with bearings.

> *"First time .. two years run the turbine gun metal bush.." [170109_015]*

> *"Gun metal bush is.. it is perfect alignment.. it is perfect alignment. Sometimes it sure alignment changes, it will cross and it is direct affect to RPM. RPM decrease. So I will use for bearing. Bearing means regular bearing. It is not [Hillobach??] bearing. Some it is unbalanced.. it is running." [170109_015]*

For a while he used open bearings, but now he is committed to concealed bearings though somewhat expensive.

> *"First I will use the bearings, a regular bearing umm means open bearing. .. But it is problem created. When it is running the turbine, the thrust of water, sometimes this will… some… little water is leakage in outside. Then it will… comes to the bearing. But bearing life is… when it enter the water, bearing life is very less. After 3 months it will completely go out of [na??] style So I will decided… it's a concealed bearing .. different type .. This is a concealed bearing. Full closed. .. it's a warranty is … life is very good and maintenance very easy."*

".. umm remove the bearing and again place… [na??] very headache! In a remote areas very headache."

".. First I will test in [na??] one year… two years. Nothing any happen in two years, After then I will decide on that's a very good bearing it's… [na??]. Without headache it is running. After then I will completely use… " [140310_003]

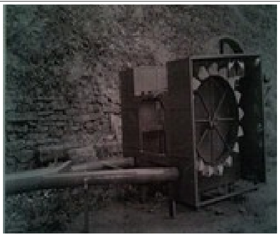
Fig. 78 Double jet design

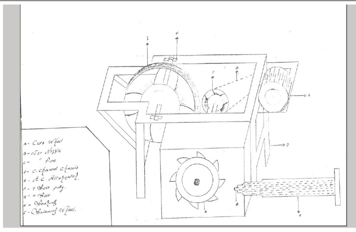
Fig. 79 Water wheel


Fig. 80 Giant wheel

He also experimented with many variations, as can be seen from old photos and diagrams he got drawn (Fig. 79), of his double jet design (Fig. 78), Water wheels and Giant wheels (Fig. 80).

Now his design is more or less stabilized. He has been invited to other States, and by the government, as a consultant for developing micro hydro power resource elsewhere. He has started receiving inquiries from near and far, and the business has picked up.

"Only in the last five years he has some income from this.. until then it was all umm.." [140309_015T - 140309_019]

He has also provided employment to local people, to help with welding, turning, civil work, and motor winding. These are individuals who have studied up to secondary grade, and learned the skills of the trades. They are not highly trained technicians, and certainly no engineers.

"Innovation is to serve to society, and you enjoy yourself in your life and your job.. means make it job.. [na] commercial.. make it job. And you will enjoy your life, your innovation, and you will supported another peoples to .. by job.. or you can make a small industry.. <> at least minimum five to ten people give them job .. [na]." [170109_015]

With the help of the electrician in this team, GRI designs and builds his low RPM permanent magnet alternators. He searched for off-the-shelf ones initially, but these were only made to order.

> *"I will try in 15 years, I will try. Any purchase in low rpm alternator 15 years. I will find out. Any agency or any… in a shop is not available.. <> .. regular rpm umm 1500 rpm every shop it's available. Every market it's available. But its low rpm as a permanent magnet as a not available. That' the only it is make [na] customized."[140310_036]*

He realized that he could use permanent magnet alternators to generate power when RPM was low, when he came across wind mill technology.

> *"Then five years back, I will.. going to one umm one of the industrial towns [name of place], I will see the one alternator.. the magnet alternator.. for wind mill.. for small wind mill. Then I will think "Oh! This is a very perfect for me .. it is very.. low RPM.. yes!" Then I will suggestion.. then purchase the body.. the motor body.. then get.. that's how. Then we will completely challenge.. how you give the head or water, definitely we will give the power." [170109_015]*

The electrician, educated up to 7 or 8th grade, was a winding expert. He and GRI discussed and designed their first low RPM permanent magnet alternator. They did not have any person to learn this from. So they did a lot of experimentation, also incurring losses in the process. (Fig. 81)

> *".. any one piece is for initial purpose or any show or any my umm for learning purpose, it is not available. Only for.. by taking.. everything is completely, again and again … trial and error and prepare and destroyed and again finally it's the only it's a any industry. We were not anybody questions or anybody show or anybody inquiry in the another shop… we'll not go. Only… here learn only by himself."[140310_037]*

> *".. totally 200 kg copper wire is completely destroyed.. Ya, for trial purpose… (chuckles) <> completely it is going to scrap. " [140310_036]*

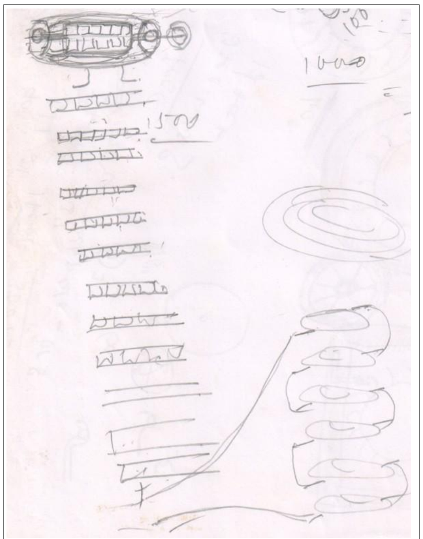

Fig. 81 Permanent magnet alternator design

But the design is now perfect. While an electromagnetic generator commercially available to GRI rotates but does not generate power for RPMs under 1500, the permanent magnet alternator generates power at much lower RPMs, and provides power at least for lighting, where higher RPMs cannot be generated. It is also maintenance free, because unlike an electromagnetic one, it uses no carbon brushes or diodes.

> *"only permanent magnet and coil. That's maintenance free." [140310_038]*

> *"Perfectly it's in Design… perfectly it's in winding… 5 % 10 plus or minus. No problem." [140310_037]*

GRI's industry offers MHP systems in the range of 1 to 40 kVA. On receiving an inquiry, GRI visits the site to understand the conditions and requirement. His 'Detailed Project Report's (DPRs) submitted to various customers record the details of his site study and corresponding estimates of power and costs. Particularly noted are: the period of availability of water, discharge in Liters Per Second (LPS), height of the water source from the turbine (vertical head), capacity of power generation in KVA, type and capacity of the turbine in HP, RPM, power generation in Watts, Volts and Amperes, and what the power can be used for.

On receiving an order and an advance, GRI designs and fabricates the turbine at his industry. This takes about two to four weeks, depending on the turbine capacity. Civil work for the reservoir, pipeline, and power house is conducted at the site. Once the turbine is installed, he measures the RPM, and designs the alternator. After installing the complete system, he conducts a continuous test run for 24 hours, and then the power production begins.

According to him, his system is sturdy, rust-proof, and of long durability. Safety is ensured through the use of Change-over switch, Tripper, and Earth Leakage Circuit Breaker (ELCB). Controlling the RPM of the turbine, by tuning the water inflow to the nozzle and using the balancing flywheel, ensures that there is no accidental high voltage supply in the system. He provides one year site warranty on his turbine, and also continues to provide service to the customers as and when necessary. His brochure proudly announces, “Our service is completely based on the requirements of user on such aspects like simple design and minimum investment. .. We are educating people on 'Renewable Energy Utilization' at both rural and urban areas.”

Over last decade, GRI has developed a diverse customer base, and an expertise in designing as well as business.

A1.4 GRI's design process for diverse customers

GRI's design process for a large diversity of customers and site conditions offers interesting insights. I present a few landmark episodes in his later design trajectory, to describe these.

1. Low-cost power
2. Seasonal variation of demand
3. Power for community
4. Remote troubleshooting, local maintenance
5. Mechanical power
6. Power for remote telecom towers
7. State-level drive for MHP installations

A1.4.1 Low-cost power

Background

GRI was approached by a vendor, who had a tea stall along the road in the mountains. His business depended on having power, and he could draw more customers by offering mobile phone charging facility at the stall, but he had little money.

> *“But some person say, no, I have no money. I have only some… some …. Some money. For example.. I have only 25000 rupees. But we will.. I want power. Yes. Some … ??”*

There are many such cases, where power is a major factor in enabling people to have a livelihood, a source of income. But the needs of such people in the remote areas are not addressed by the state power grid. Neither can these people afford to use generators powered by diesel. What they need is a low cost power system just sufficient to meet their power requirements.

Solution

GRI discussed the tea vendor's need with some engineering students who had approached GRI in the context of doing their engineering project with him.

Fig. 82 Low cost power for tea stall

> *“That time we will discuss the customer and the [na] we see, what, the what will… what we will do… I will discuss and design some… well… thought of the money… expenses. Who bears. I will discuss some time… some times… it will… when it is poor people, we will give to the … project to college. <Oh, Okay!>*
>
> *Yes, then students share the… some money.” [140308_005]*

The students agreed to pool their project money, and worked with GRI to design and build a power system on a stream right next to the stall. It was a low head site, but they managed to install the 5KVA power system for the tea vendor. It provided him sufficient power for eight months of the year. (Fig. 82).

Observations

GRI offered a reasonably low cost solution to meet the requirements of small households and vendors. This allowed him to serve such people, implementing the installation as a turn-key project. In cases where they could not afford it, he developed a business model wherein he actively raised financial support for them from various sources. This certainly generated business for him, but more importantly, brought together many hands to solve the power problem of the poor and the needy, who otherwise remain perpetually underserved.

> *"A… any organization… some person… is … some organization are there to umm. Some… for example, some temple… or government organization or NGO… you know support it." [140308_005]*

A1.4.2 Seasonal variation

Background

One of GRI's customers wanted to install a power system to supply power to the staff and labor quarters on his coffee estate. This was mostly single-phase power to run domestic gadgets, office equipment like AC and computers, and for lighting of the colony and the coffee drying yard. But in summer, he also needed to use the power to pump water to higher altitude in the plantation, for irrigation.

Since a coffee plantation has it's own annual schedule of activities, an aspect of providing power here, is the seasonal variation in water availability contrasting with the seasonal power demand. As per the General Manager,

> *“[GM] So in the rainy season actually I’m using lesser power. That’s because I’m doing only lighting of my labor colony. Where as in the summer, I’m doing lighting of my labor colony, I’m doing coffee processing and I’m doing irrigation. So I actually need power now. When the water flow is lesser. So I’ve guaranteed him 6 inches [of water]. So what is the maximum I can do it of six inches.*
>
> *[GRI] So I… umm … declare a slogan, “Give the water, take the power!”* [140308_018]

On the other hand, during the rains, there was another challenge. Heavy leaf debris, sticks, iron-ore-rich abrasive sand, and soil washed in with the water. Furthermore, the customer placed a premium on lower maintenance, longer life, and safety of the power system.

Solution

The coffee estate being located on a mountain offered a steep gradient. Taking advantage of this, GRI designed a 15 KW micro hydro power system, for the maximum available water in summer. He designed the power distribution system such that power supply can be switched between the different areas of consumption, such as the coffee drying yard during the working hours and the colony at night.

Fig. 83 Removable nozzle

GRI designed a settling chamber for the sourced water, and also designed the nozzle and the turbine cover such that both could be easily removed to clean the debris as frequently as necessary (Fig. 83). 'Provision to change nozzle' became an added feature of his design. [GRI_Qt_11Dec06-1]

He also offered a different business model alternative to customers who had sufficient funds and technical knowledge, such as this one. In this case GRI did not take it up as a turn-key project. He left to the customer's contractors the civil work for the turbine house, the pipeline, and the laying of the electric cable to the colony. He just fabricated the mechanical system, and install it. In order to ensure lower maintenance, longer life, and safety, he selected better quality pipes (HDP compared to PVC used elsewhere), and a better though more expensive electric cable. They decided to lay the cable underground, to avoid damage during storms. Since the customer could afford it, GRI also selected the latest maintenance-free alternator – the brush-less, diode-less one. Before installation, he tested it at his workshop to ensure satisfactory performance.

Furthermore, in an opposite site condition of low head water from rivers (and canals), GRI designed MHP systems for temples situated on the banks. These MHP systems support lighting at the temples, and allow them to reduce their grid power consumption. In the words of his customer, a chief priest one of the temples,

> *“This is probably for the first time in the country that a temple will generate its own power. The project was taken up at a cost of Rs 5 lakh. The turbine is expected to run for eight months; there is not enough water to generate power from February to May. The surplus power, if any, will be given to [State Electricity Board]. The trials will begin once the water level rises in the monsoon. The temple was spending about Rs 14 lakh annually on electricity bills. We hope to save a substantial portion of this amount even after the maintenance cost of the turbine.”*

Observations

GRI offered a lot of flexibility both in his technical design, and his business model. His designs took into account the technical and the contextual requirements and variations at the customer site. As necessary for a successful entrepreneur, he kept himself updated about the various technical alternatives available and their pros and cons. He also demonstrated the skills to work collaboratively with the customer as well as his other contractors.

A1.4.3 Power for community

Background

This is the case of a small community inside a reserved forest area in the Western Ghats, where grid power was not available.

> *".. so this is in the middle of the wild life. So umm there are.. there are strict rules that there cannot be power lines in that part. But these people have been living there for hundreds of years. So they are.. they need to be given umm basic needs.. facilities."*

> *"They were apparently first given solar power, but that doesn't really work here.. the sunlight will be low because of the tree cover and other things. So they used to get power.. proper power for three months of the year. So after.. I mean.. [GRI's industry name] became more umm popular, then they decided to contact... " [140308_036T]*

Solar, wind, or hydro power were the only ways of generating power allowed in this area, and solar technology had been provided. But heavy tree cover made both solar and wind power impractical. GRI was then approached to build a micro hydro power system for the community.

Dealing with the community was more complex. GRI had to gather requirements from each of the households, and all of them had different questions about the power. There were also concerns of distribution of power.

> *"They ya get the information from them… and as well as… he [GRI] gives the information to them… to the entire community. And he says, even after the end of the project, he again sits with them. He says okay, if you use more, then the other persons will get less. I mean he … he explains all those things."*

"they haven't had any formal education, so they know… so it's much more difficult to explain to them what is … what will go wrong when there is more bulbs, or what happens and so those kind of difficulties are there…" [140309_020-T]

Compared to designing the system for an individual household or estate, a community project also had more technical challenges, because many families would consume water from the source for different tasks.

".. see, if it's a individual house, okay, if they don't have water flowing they know. I mean here, it's not just they have to have water flow, but also at that particular level. I mean the particular volume and so on. So those things he has to guarantee all those things. So those… there are technical difficulties as well.." [140309_019-T]

Solution

GRI designed a 10 KVA system for the community. Going out of his way, he also helped raise funding for this with project students, from a temple trust, and an major NGO in the region. (Fig. 84).

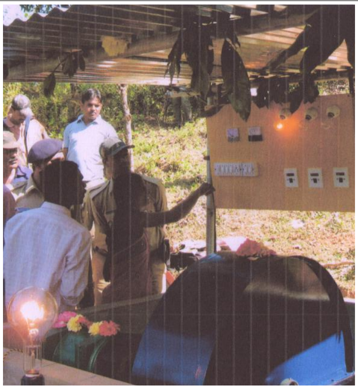

Fig. 84 Community project

He developed a way to work with the community, by establishing a rapport with them. He explored if the costs could be minimized and also if income could be generated in turn for the community, by involving them with the civil construction work for the system.

"And he has been.. he has been doing this from the first time."[140308_036T]

".. in other projects there's a deputy commissioner, there's a police superintendent… they all come… and they sit together with the village people, and then they discuss, okay, so these are the things to be done. Are the villagers willing to do that? Or does he have to do it with his team? So they discuss all these things." [140308_036T]

Especially in a government funded project, he could pay them for the civil work, and they also did it more promptly. Sometimes they were better than the external teams, and GRI collaborated with them.

For example, in this case, they came across a very hard rock where they needed to lay the pipeline, and the rock had to be broken. But blasting was not allowed as this was a reserved forest. External agencies quoted heavy charges. The community then took up the task as a challenge. They were not technically trained, but they had their own way of doing the job. They lit a bonfire on the rock with the jungle firewood, and let it run through the night. Then they poured salt water on the hot rock. This developed cracks in the rock, and then they were able to break it. It took them about eight days to lay the pipeline.

GRI conducted a survey of possible micro hydro power sites in his region. So he is aware of the need for power in such remote places, as well as the opportunity in terms of water flow. Sometimes he approaches NGOs or government bodies for funding to implement MHP systems for communities at such sites.

> *".. less often that people approach him, more often that he approaches people.." [140308_038T]*

On the other hand, when he provides power to a village, then the neighboring village comes to know, and they approach him for a similar power system.

Funding also comes from corporate houses like Infosys and Accenture, though his first effort is with the government. Especially in strife-ridden regions, (say Naxal areas,) and for the marginalized people, government allocates extra funds to provide basic amenities of life. GRI's hydro power projects for these communities are sometimes supported through such funding routed through the deputy commissioner of the region.

He recommends that the community form a self help group to look after the day-to-day operation and maintenance of the system, including minor repairs. He also trains the local people for this during the installation period.

Observations

GRI worked hard to provide power to the remotely located and marginalized community. He developed a business model that not only brought him business but also brought income to the people. For this, he built his implementation model around the skills and resources of the community, while also providing hand-holding and training support to build their skills and organization.

A1.4.4 Remote troubleshooting, local maintenance

Background

GRI systems were often installed in remote locations. In one of his initial installations, the system functioned very well for the first three months, but then had some issues. The customer complained of low voltage.

> *"Noise start and voltage.. low .. low.. <> Lights are coming but blinking.. <> And any domestic purpose any mixie, TV is not working.. " [140310_004]*

Solution

GRI found that in spite of sufficient water, the required RPM was not generated in the generator. The system was heating up.

> *"the rpm is not coming. Just it is a.. a frequency is change. Then it is blinking. <>*

> *When it will heat up.. it's a.. it is not perfectly rpm is well-developed. Means for example, thousand five hundred regular rpm is.. generally 1500 rpm an alternator.. 1500 rpm is correctly pucca it is voltage from 220 to 240 voltage. When it is come down, rpm is come down, for example, 1000 rpm.. " [140310_004]*

> *"When rpm is.. gets down.. definitely it will.. when it is a between.. it will come full tight if it is.. movement is very tough.. for movement, when it will be tough movement, then it will completely heat." [140310_004]*

GRI's remote diagnosis was that either the bearing was spoiled, or on the alternator side, either the copper winding was short-circuited, or the diode was broken.

> *"… the sound.. turbines sound is created.. Definitely it is going to.. bearing I will decide. Definitely. I will bring one new bearing. Yes, after then alternate site is when heat, or blinking any thing.. any happen, immediately I go to diodes." [140310_005]*

So he sent his technician with the necessary spares and the problem was rectified. Since the spares were easily available in local shops, eventually, the customers no longer needed a technician for these minor repairs. Customers were happy to save the technician's visit fees, while GRI is happy that he designed with local components, because he does not have to rush for every minor repair.

> *"But one special is my turbine is a … any happen repair… but it is available in local market."*

> *"Customers very confidence.. components first one.. one.. or two times he will informing to me. But after that he's already.. he has.. that' no problem. <> He will not waiting.. person.." [140310_005]*

Observations

GRI designs for the specific needs of his customers, taking into account the maintenance needs and constraints in such remote areas. Sometimes, the simplicity of his design has even allowed people to use local alternatives to keep the system running till they source the requisite replacement. In an earlier design, where he had used contact bushes instead of ball bearings, the contact bushes needed to be oiled daily for lubrication. Once someone ran out of oil, but managed with honey instead, because it was easily available. In another situation, the belt broke, and would take a few days to fix. They had ropes used to tie their cattle, and that worked as a stop-gap arrangement.

A1.4.5 Mechanical power

Background

The largest Pelton-type turbine that GRI designed was 42 inches in diameter. The 10 feet diameter turbine that he has designed, he says, would not be called a Pelton wheel.

> *"Definitely it is not Pelton wheel.. after then it is called Water wheel. Means is completely shape change. After that it is a Giant wheel turbine.. that's different. That's a very low head and low RPM. It is not suitable to.. in the high head or high RPM. <>*
>
> *You will expect Water wheel maximum RPM is 100 RPM. <>*
>
> *The Giant wheel is maximum 50 to 60 RPM. [170109_011]*

Such a low RPM cannot help him generate electricity.

Solution


Fig. 85 Hydro-powered flour mill

He nevertheless knew that he could generate large mechanical drive from low RPM situations.

> *"But the efficiency.. but umm.. sorry but the strength .. what is the we will call strength.. it is very high. Very high. Suppose, when it will be rotated, it is possible.. he was.. check the wheel.. definitely couldn't.. very strong.. very strong. But Pelton wheel.. it's possible.. but Giant wheel and Water wheel.. it's impossible." [170109_011]*

According to him, while you may not be able to generate electric power from these in the cases where the

RPM is too low, the strength of the Water wheel or the Giant wheel is very useful for water lifting for irrigation, and also in coffee estates for coffee pulping. He has designed and installed some such systems as well.

Also, with the modified Pelton design, he has developed the option to drive a mechanical grain grinder i.e. a flour mill. (Fig. 85).

> *".. I will.. it's one atta maker in my house? It is another purpose.." [170109_011]*

Observations

Identifying the need for mechanical drive, GRI has provided hydro-power based simple technological solutions for drudgery reduction in remote areas. This has in turn also saved the conversion losses from electrical back to mechanical power.

A1.4.6 Power for remote telecom tower

Background

As the network of telecommunication through mobile cellphones expands across the world, and especially in countries where grid supply is not available in remote places, there is a need to supply power to the remote telecom towers. Such towers are accompanied by base stations that require at least 5kW power for the telecom system and air conditioning.[407] While most systems are powered by diesel generator sets, there is a drive to support these through alternate and renewable sources of power such as solar, wind, hydro, and bio fuels.

> *"In India, which has about 400,000 base stations, the government has mandated that 50 percent of rural sites be powered by renewables by 2015. The decision comes as the*

407 Tweed, "Why Cellular Towers in Developing Nations Are Making the Move to Solar Power: Renewable energy is beginning to replace diesel in cell-phone networks," 2013.

> *Indian government, which heavily subsidizes diesel, looks to lessen the country's reliance on foreign oil and reduce greenhouse gas emissions. By 2020 75 percent of rural and 33 percent of urban stations will need to run on alternative energy".*[408]

While the specific power requirements differ as per the configuration of the tower system, a mobile tower requires more power than a household, and also more amperage for charging the batteries or to supply to the load directly in case of battery failure.[409]

Possibly due to the drive and compulsion to use renewable power in mobile towers, GRI was approached to develop MHP system for a mobile tower site in his region.

> *"Almost all the mobile tower is worked by DC current, it's not AC. So we will.. production of power for charging the battery., but charging the battery it is not easy.. it will get more amperage." [170109_011]*

Solution

Considering the requirement for high amperage, and availability of water, GRI designed a low RPM turbine to generate about 25 kW power.

> *"The Pelton wheel RPM is only 75. After then without any.. transmission .. mechanical loss.. I will design the alternator.. 300 RPM. 42 poles. Very low head." [170109_011]*

Currently the BSNL (Telephone) department uses the expensive option of diesel generators where grid power is not available. Apart from pollution and cost, this also allows room for corruption. Based on a survey GRI conducted in his State, around 300 potential sites can be developed for providing MHP to mobile towers.

Observations

For sustainability, the government has a policy to encourage green and clean power. He explains why MHP is a sustainable solution.

408 Tweed, "Why Cellular Towers in Developing Nations Are Making the Move to Solar Power: Renewable energy is beginning to replace diesel in cell-phone networks," 2013.
409 Balshe, "Power system considerations for cell tower applications," 2011.

> *"Completely eco-friendly.. <> No noise. And no pollution. And you will not destroy any greenery, you will not.. any take about one single tree.. you will not cut it. Same as it is same situation, it is implemented. Same. Take the water.. natural.. and again it is going to regular stream. You will not break up.. check dam.. any nothing. Or any submerge.. nothing. Check dam.. or big, big dam.. nothing. Very simply, we will put the pipeline.. <> .. not any disturbance to nature.." [170109_010]*

While finding a site for the power system, he chooses it such that no trees need to be cut for the pipeline. Furthermore, he also advises his customers on utilizing the generated power better by avoiding distribution losses and wastage. In his correspondence with a customer, he wrote,

> *"To increase power consumption with better voltage, we recommend to use CFL bulbs instead of filament bulbs. We found out fault with existing wiring in some of building like Managers bunglow, Laborers quarter etc., and that causes to waste lot of power." [GRI_Qt_2Jun96-1]*

Unfortunately most government initiatives for green power are only equated to solar power technology, and the MHP option is only now started being considered. He strongly argues that for remote interiors, technology such as his MHP is a better option to solar technology.

> *"Almost all the officials are going to.. only.. one word is.. give the solar. Solar panel.. you put the solar panel.. But almost all solar panels are .. implemented in the remote village .. almost all collapsing. <> No maintenance.. who has maintenance? One year battery.. one or two years.. after then who is maintain it? But it is available throughout the year.. water is very free.." [170109_009]*

> *"Zilla Panchayat [District Council] is provide the every.. each process independently.. umm solar panel and umm 12 volt battery, and umm 3 Lakhs.. it will provide. It will glow umm three months or four months. After then it will discharge.*
>
> *But.. umm solar maintenance will be easy, no, compared to?*
>
> *Compared to other.. easy.. but.. I will.. I will agree.. but after then.. one year after then, it is a reinvestment to battery.. again 8-12 hundred rupees. For example old one battery is 8 to 12 hundred rupees.. that's a problem. But I will implement the turbine in the village, after then five years back, ten years back implemented.. just is a just is a servicing. That's a service period.. very easy. <> Within five.. five – ten.. ten thousand.. entire village glowing [na] turbine.. Maintenance very easy.. very cheap.. damn cheap. <> Per year, maximum two thousand rupees.. maximum. <> Initial cost is some.. but in*

comparison, same.. Comparison solar to micro, same. <> And solar panels.. batteries only providing lighting, isn't it? But when he put the turbine, he will use all equipments.. TV, light, something houses like as a mixie.. all." [170109_010]

A1.4.7 State-level drive for MHP installations

Background

In many parts of India, where the mountains have perennial water streams, and low grid connectivity, the state governments and renewable energy initiatives are interested in developing micro hydro power systems. They have budgetary provisions to support the installations of MHP systems for remote communities.

Solution

GRI was invited to the State of Meghalaya, where the mountainous region has perennial water streams and water falls. Various NGOs and the government are interested in developing this natural resource to generate green power. After the visit, GRI had a plan to help them start the process.

".. engineering persons is there. I will.. first I will implement some 5 to 10 turbines here.." [170109_008]

".. it is completely royalty based. After that I will complete one turbine.. umm some percentage .. after then technology transfer.. purely I will technology complete give.." [170109_008]

"I visit five sites.. last umm.. previous visit.. I will umm five sites. Five sites are complete different sites. One is completely it is very [na] city.. nearby.. very nearby. Capacity is.. here it is.. falls is by step by step fall down.. verticals.. 500 feets fall down from top to bottom. I will suggested five stage.. five stage implement the turbines.. five stage. Stage by stage.. stage by stage.. After then you will completely come back and it's a synchronize. Totally it is get power.. each turbine is power generated 25 kW. 25Kw into 5, 125 kW. 125 kW synchronize and make one big [na] you are connected, after then the entire city get power for streetlights. Throughout year is water supply. Thats' fantastic!" [170109_008]

"After then I visit some two villages.. same! This is [na] it is come to.. fall down directly fall down.. by sky! (chuckles). And same.. just community basis. Put the turbine.. small small small small. That's very.. very funny.. in the hill, one rock is there.. one rock, this

> *same type rock.. 10 by 8 or 10 by 12 some rock. .. has built a one small house on the rock.. it's very poor people. .. Yeah very nice site... [na] means 24 hours, 365 days it will fall down.. the water. It is no power. With a small very.. 1 inches pipe .. put a 1 inch pipe.. it's a very small turbine for independently. Independently he was get the power in the house. Lot of NGOs, lot of donors is there.. our government is supported. Within.. mostly within 60 thousand rupees, one turbine is ready.. [na] sufficient.. problem solved." [170109_008]*

When asked if his design for this site could be used for many houses in Meghalaya, he said it was possible. He was also approached by a remote village from the State of Kerala, where the Gram Panchayat (Village Council) has allocated a funding of INR 40000 per house for development of independent MHP systems based on perennial water resources. He has planned to develop a system, and install the same design for all the houses. Since the budget is small, the design will support only lights and TV per household.

> *"Almost all the same.. same.. similar same. But this is only for lighting purpose. It is not for [na] production amperaty [amperage].. he was not required any mixie vixie. Only lighting.. LED light, and TV.. same.. He will not expect any another.. But expect but he is not.. who is bear the money? That's a problem." [170109_008]*

A1.5 Summary of observations across design episodes

1. The technical composition of GRI's system changes from simple to complex. The number of components increases and the system becomes complete in terms of addressing all technical aspects.

    i. stream water diverted through a pipe > cups attached to a bicycle rim > bicycle dynamo (shaft) > wires > bulb

ii. stream water diverted through a pipe > some kind of spokes-cups wheel (??) > pipe as shaft > connector > DC dynamo > DC storage battery > domestic light bulbs run on DC power

iii. stream water diverted through a pipe > improved cups wheel (??) > wheel shaft > connector > AC alternator > power supply cable > domestic light bulbs, TV, fridge, mixer run on AC power

iv. stream water diverted through a pipe > a Pelton-like turbine > wheel shaft (with bearings) > a belt pulley > a flywheel > a belt pulley (with bearings??) > AC alternator > power supply cable > grid-quality AC power (to run domestic gadgets, irrigation pumps, streetlights), and also mechanical power

2. As the design goal expands and gets technically more complex, the previous solution space acts as a prototype for the new problem space. But the new solution changes this solution space completely, by eliminating certain components and the concepts they embody, from the design space. Dynamo changes into an alternator, DC changes to AC, AVR changes to a flywheel.

3. GRI directly works and thinks with the components and then the prototypes, rarely making any drawings, measurements, or calculation-based decisions for fine-tuning the design specifications.

4. GRI's understanding of power, and various components also starts with the socio-environmental and adds the technical. He primarily understands power through its functional role in running various gadgets, and thus has a qualitative understanding of the characteristics of power, apart from a quantitative one. His conceptual

understanding of the components is experience-based, and conceptually at a black box/performance/behavior level. In this respect of designing without a theoretical understanding, GRI is not an exception. The historical development of batteries and induction coils also demonstrates that these were designed before Maxwell offered a theoretical understanding of electromagnetism.[410]

A1.6 GRI's design techniques

While designing and implementing an MHP system, GRI uses various methods and techniques. Some of these may be unique to his practice. In this section, I describe three such methods/techniques.

A1.6.1 Pipeline laying

GRI mentioned that he used a water level to design the pipeline, but he also elaborated a different method.

> *“[I] The design of pipes.. how did you do it?*
>
> *[GRI] The water level.. water level.”*
>
> *“Completely you will put the pipeline. .. After then.. using small umm inside the pipeline, a ball or a.. [hmm a marble] marble.. marble. Put inside .. in a marble.. top side. Then it will come to this side.. down.. umm.. [na.. flow?] very gradual. After then you will put the support .. That's a one technique.. that's a pipeline technique.”*
>
> *“That's a calculation. How many time it will take to .. umm.. pull the .. in between the umm pipeline.. and in umm for the down side .. how many times it will take. .. that will*

410 Michael Faraday discovered the principle of induction, Faraday's induction law, in 1831 and did the first experiments with induction between coils of wire. The induction coil was invented by the American physician Charles Grafton Page in 1836 and independently by Irish scientist and Catholic priest Nicholas Callan in the same year at the St. Patrick's College, Maynooth, and improved by William Sturgeon. (Induction coil. https://en.wikipedia.org/wiki/Induction_coil). James Clerk Maxwell, [who] in 1861-2 used Faraday's ideas as the basis of his quantitative electromagnetic theory. (Faraday’s Law of Induction. https://en.wikipedia.org/wiki/Faraday%27s_law_of_induction).

relation to .. rpm. .. Slowly it will come in .. it's a gradual turbine. Suddenly it'll come.. definitely it is fast. Torque. Calculation of torque.. rpm and torque.. 2 pound, 1 pound. 3 pound. This type."

"What's the timing.. the put in.. he will he will call.. I will put the ball inside in the pipe. Just I will.. just I will stopwatch. Then.. "

"After 50-60, after then, some design .. it is.. tough.. after calculations.. the efficiency calculations. Turbine efficiency is 50%.. Almost.. the marble is coming the low speed.. decrease the efficiency.. 30-40-50 [I assume he is talking of marble speed/efficiency here]. But average 50. 40 is maximum. Below in 40, it is not efficient.. it's not worth."[Voice105: ~ after 15/16 min]

When asked what will happen if the penstock was nearly vertical, with no gradient, he said but where is such a spot. In western ghats, all sites are like what he has. So when asked if he could install the turbine in a waterfall, he said then he could give even 80 or 90 % efficiency. [Voice105]

A1.6.2 Telescopic shaping of the pipeline (penstock)

".. umm high head is available in 200 feet. Vertical head is.. telescopic method pipeline, starting 6 inches and 4 inches. After then it is 2.. 2 inches. After then input only 1 inches for turbine. But suppose it will less head. Only 10 umm 5 meters head. Then it will completely I will.. if plenty of water is available, I will design only 24 inches pipe to.. till to turbine. 24 inches. Or 12 inches. That depend on the umm capacity of the turbine. For example 20 umm 5 meters head is available, 24 inches is pipe is.. foot, after then discharge.. the heavy discharge is available.. definitely it will completely the production 20 KVA. After then, same 10 meters head, you'll get the 12 inches pipe, after then you'll get the power, only 10 KVA. Same. But same I.. 300 feet is available, telescopic method you will get the pipeline, same it is 20 KVA power? Get.. is possible"[140310_051]

".. the piping continue to turbine, starting 4 inches and 3 inches, and after then, to [k?] turbine I will use is .. Umm.. I will.. we will show, if it is telescopic.. starting 4 inches, after then 3 inches, after then th.. 2 inches. It will.. creates a power.. gravity pressure is increased.. very increased. High pressure.. it will create."

"Means tapered. Tapered. Tapered m.. means umm cone type. Starting is very big and then some point it will be small, small, small, very small. This will like you say it is going to it is direct it will short to the least.. turbine.. that's the purpose."

"First I will give in a slight.. I will.. 2 inches pipe, slightly. It will umm production starts. But, it will be less. Only 0.5 kw. But lighting is sufficient, no problem. After then, it is

required, some domestic purpose for you is.. house.. a TV.. and every equipment.. again.. pipeline.”

“Yes, it is one in basic method. Basic means method it's a it's a simply.”

“.. when you will use umm more much water in the turbine, definitely [na] more electricity is produced”

[I] “Is it flow or is it pressure?

No, pressure. Pressure.”

“Automatically is RPM increases. RPM increases. When RPM is [seen] to increase, automatically power increases. That is one after one, one, one, one, one, one relationship.” [Voice103]

A1.6.3 Testing

GRI starts his design by visiting the site to know the water availability, preferably in the lean period, and by understanding the requirements.

“.. if there is a good water flow, then they [GRI and his team] don’t do the water-wheel testing, because they know they’ll get enough rpm. But otherwise they do check the rpm first, before they.. because if the rpm is too low, then they cannot really umm scale it to umm see the alt.. all the alternators, they require 1500 rpm, so if the rpm is only 100, with the water wheel, then they can not scale it by 15 times, because then there will be lot of loss..” [140309_027T]

After designing and manufacturing, when installing the system, GRI needs to know the RPM and the voltage generated. He uses the tachometer and voltmeter to measure these.

“First I will complete checks tachometer… rpm set and voltage setting … with … umm voltmeter. I will set with umm tachometer and voltmeter and [na] both at a time. I will connect.”

Once he gets the required RPM and voltage, he wants to test the system with load. Initially he used a simple heating coil as a test load.

“First I will test in for… only heating coil. I will use... heating coil. Means generally heating coil… means … heating justing purpose 1 kw, 0.5 kw, 2 kw. That’s a very some

tough one. It is very complete burning. And umm very heat and some area unfortunately… it is not show any … any customer.”

But it used to be very inconvenient. Once, while aimlessly exploring an old electric shop in a city, he stumbled upon two Mysore lamps, amongst the old stock from a lamp factory now closed. He immediately saw an opportunity and purchased the 2kW lamps. He now uses one of these lamps as the load for testing.

“I will check with this will light. When it is glow perfectly, that’s perfect and completely it will.. it will possible when it is come to glowing the whole bulb, it is complete.. definitely it will come to the 1 kw.. ” [140310_034]

“I will keep two I will.. kept carefully. Like as a my baby. But one day one is suddenly is broken.. very.. after then I have kept any any safely.” [140310_034]

He adds that, for a customer eagerly awaiting the inauguration of power supply from water, the heating coil had no visual excitement or magical effect at all. The Mysore lamp on the contrary brings the miracle of light to life!

“But it is very… when it is glow the bulb… customer is happy! (laughing) “Oh! It is well. The current is coming. The production starts.” [140310_035]

A1.7 GRI's design considerations for the virtual MHP system

GRI explored and imagined the virtual system with reference to his real world contexts, experience, and knowledge of design. Despite this, when working on the simulation tasks, he mostly worked on the basis of the feedback generated by the

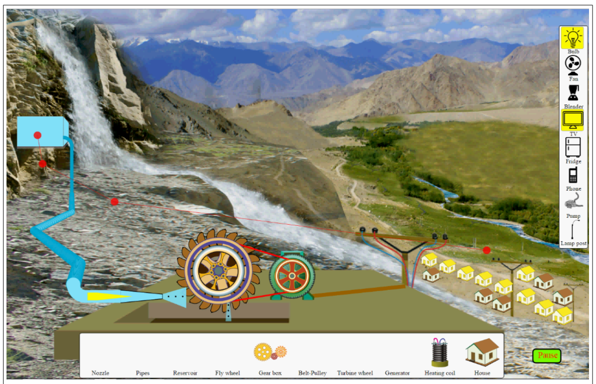

Fig. 86 Simulation interface

simulation interface (Fig. 86). This is anticipated as there are no real values of parameters or gadget ratings provided in the tasks.

For these reasons, it is important to understand his choices and actions in the simulation with reference to his comments and explanations in the interview that followed. This is particularly important for the numeric tasks 3 and 4.

A1.7.1 System construction

GRI explored all the components, houses, gadgets, and parameter settings in the simulation in various ways. His first choice of components to design the system was the pipeline, nozzle, turbine and generator. Having found no performance difference in a gear vis-a-vis a pulley, he settled for the pulley.

He commented that the nozzle in the animation has a problem, because the water jet looks more like spray, and it will not give good torque.

“spray.. split. It is not completely.. not torque.. point.”

A1.7.2 Load variation control

GRI did not use the flywheel in all the task situations, and did not actively look for a load control component or a dummy load such as the heating coil.

He explained that he uses a flywheel in his real-world system to stabilize the turbine, only if site conditions and requirement composition (such as high amperage gadgets) make it necessary.

“Sometimes more head is available.. flywheel is not required.. ”

> *"What is the requirement of the beneficiary? He wants.. light is common, TV is common. And some fridge.. this is amperaty [he uses this word for amperage or current rating]. And blender. Takes more amperaty. Then flywheel is compulsory. When you use amperaty, definitely use the flywheel."*

He further explained how he decides the specifications of the flywheel in tandem with the specifications of the turbine designed for those conditions, based on thumb rules.

> *"The inner spokes .. very less weight. Outer is completely weight. Central is very less."*

> *"For e.g. Pelton wheel thickness is 3 inches.. width.. flywheel 2 inches."*

Rather than using a device such as a heating coil, GRI preferred to design his real-world systems such that when load drops, the excess generated power is diverted to street lights.

> *"Below 10kW .. nothing happens. 10-12% varying. After that, when load completely switches off, that will be overproduction. Then you will convert it to dummy load.. like heating coil or diversion lights. I will say suggestion.. street lights. That's a easy solution."*

He further explained that he does not use a heating coil, as the villagers do not know how it works.

> *".. when you use a heating coil, it is very sensitive. In the villages, it is .. [to] know about this what is the action or cost.. not known. Give more water is very easy.. any uneducated man also can do it."*

But he has used the heating coil option to divert excess power and control load variation in a productive way at one site. During the months of cold, the heat is used for drying clothes is a heating room designed for the purpose, when idle power is diverted.

> *"But I will.. one turbine implemented at.. in one resort at in [name of a place: Madicherry] .. there is one kind of.. I will complete umm turbine .. 5kW turbine. 5KW turbine is power generated.. to .. the entire umm supplied to the resort. In the mean time.. in the free load.. thats time.. I will divert it to the.. power to the heating coil.. for drying the cloths. <> This time it is definitely temperature below ten [degree Celsius].. every year throughout year.. it's very cold.. very cold. So it is one .. one shirt is dry for take a three days. Same situation.. so it is .. make one clothes room. After then completely*

surrounded by heating umm cables.. in the free time directed to the heating coil.. heating room.. immediate.. five hours or six hours .. clothes dry." [170109_011]

When asked if the excess power, when the load dropped, could be used to pump back water to the reservoir, he emphatically denied the possibility. According to him, all the generated power would be consumed in this task, if at all, feasible. Besides, there was plenty of water, so no need to pump it back.

"It's impossible. You cannot be thinking about it in dream. Impossible..

So the pump is .. it's not a question of voltage.. its get more amperaty [amperage]. But it is not.. here is not production amperaty. 1kW.. 1 HP power is required. It is over amperaty. But it's power capacity is only to 2 to 3 kW. It is not possible."

[I] This is only for in-raise current or even for running?

Again.. please?

[I] The first starting current or the.. even the running current?

No. It's a running current. Here is no induction.. no any nothing .. it is not. But almost al the grid.. almost all the bigger turbines require induction. When it will be rotated, after then it will give the supported by induction power. Here is no.. it is self-induction. <>

The maximum amperage produced out of your system is 2 amperes?

No no. I will maximum .. is [na] 20 amperes.

[I] So then why is it not possible to operate the pump? <>

Simply it means the.. umm when .. what is the umm capacity of the power.. is output.. this maximum is for pump only.. it is for lifting and .. for cycling. It's not used for another purpose. So I think will not [sustain ??]

[I] What I am saying is, supposedly, your generator capacity is 10 kVA.. 4-5 kVA, and your load connected goes down to 2kW. Then, for the surplus 3 kilowatt, you have to reduce the flow of the water. But somebody has to go there. Instead of that, can you not switch on a 1HP or 2HP pump, and pump back some of the water back to the reservoir?

But umm.. I will not try.. the question is [okay].. but I will not try.. But it is umm mostly .. <> mostly it will take umm down.. <> again to the.. affect to RPM or efficiency mostly.. efficiency. <>

When you will give the amperaty load to the motor, it will umm turbine is .. it will tight.. again it will require.. another more power." [170109_011 – 11:00 to 13:45]

When the question was further elaborated that in mega power stations, part of the generated power may be used to lift back some of the water back to the reservoir, for load balancing, and asked what he feels about it on theoretical grounds, he replied,

"Just I will.. <> .. that's a matter of thinking.. yes.. [laughs] But here .. lot of water is available.. so here it is not question here..

[I] The question is, when you attach the heat sink or some kind of load, it is just wasted. Instead of that, where water.. water resource is limited..

Then it will be.. yes.. definitely.. definitely.." [170109_011]

A1.7.3 Power consumption

Given the option, he selected the gadgets TV, bulb, and lamp post as the most preferred for his users. His choice of gadgets indicates that he commonly designs for these applications, and is most familiar with them. He did not change the number of houses (12), but he was more comfortable supporting seven rather than five houses in task 2.

Based on the uses or needs of his customers in real world, he explained his choice of gadgets.

"Light is compulsory.. fan is occasionally.. and blender.. TV is very common. Fridge is not compulsory. Only option is lighting and TV.. villagers or any householders. First priority this. After you get sufficient power, after then, fan, mixie [blender] .. enjoy that. But first .. basic.. light, TV."

When asked "not even mobile phone?" he replied,

"When it is available for lights, then it is simply same, no problem."

He indicated that in a real-world situation, mobile charging requirement is already covered when power to light a bulb is available. So he did not have to select the phone gadget separately. Also, in task 2, he mentioned that the lamp post on the street could be supported by the same system design, as it could be run on the idle power available when in the houses the bulbs and TVs were switched off at night.

He commented that there would be many options to support all the houses and the selected gadgets, and so he did not remove any houses. Thinking in terms of the real-world situation, and not the constraints of the simulation, he explained that lower wattage LED bulbs now being available, could reduce the power required per bulb.

> *"What is the requirement? You will completely split. After then definitely it is sufficient. Lot of options is there. .. For e.g. Some places lights are 10 or 20 W. Use less.. I will suggest the LED bulbs. It is possible."*

He emphasized that in the lean period, he did not want to reduce the number of houses to less that the 12 in the simulation, because it cannot be done in a real village.

> *"That's constant. Anybody not compromise... all the.. suppose you give [to] one or two houses.. other remaining shoot him (he chuckles.)"*

> *"The requirement is constant. The source is vary. After then we will compromise."*

A1.7.4 Power generation

While setting the parameters, GRI varied and set the value of head first, and then the discharge (by varying the nozzle diameter). In the (visual/non-numeric) tasks 1 and 2, he increased values of these parameters to generate more power, when he added more houses, more gadgets, or gadgets consuming more power, and the other way round. His actions in parameter setting reflect his awareness of the correlations between head, discharge, and power generation. He finally set near maximum nozzle diameter, but medium head.

In the (numeric) task 3, when he set the head to 15 m and discharge to 15 lps, the system feedback indicated that he was generating 795 W less than the required 3000 W. GRI assumed the simulated system to be the replica of some real-world system, with certain component specifications, and not an idealized system with 100 % efficiency. He understood the problem situation as: the components of the simulation system are so designed as to generate 2205 W for 15 m head and 15 lps discharge, but he is being asked if he can generate 3 kW instead. Based on his experience, he answered that he could change the specifications of the components, and raise the power output not only to 3 kW, but to 5 kW, for the same water availability.

In the (numeric) task 4, for the pre-set head (4 m) and discharge (16.25 lps) values, his answer was that the system would generate 10 kW. (This is more that ten times the theoretical power.) He did not use any equations or explicitly estimate the theoretical power. Instead, he asked for additional technical details, such as the gradient and the diameter of the pipeline.

Task 3 and 4 show that he did not design with any equations, or make any calculations, to arrive at the answers. For him, the numeric task 4 did not make any meaning, and he might have given a random answer. Even though GRI seemed to bring real world context to the virtual system, he did not bring any numeric values of head, discharge and power from his real world sites to tally with the task values. This implies that either he does not think of site conditions in numeric terms (measured in meters and liters per second), and so his sense of head, discharge, and power is so embodied that he cannot bring it to this numeric task. Or he does not think of potential power from a site in terms of head and discharge alone, so he cannot reduce it to those two parameters.

GRI commented, with reference to the simulation scenario, on how he designs in real world.

> *"By experience. It is not measurement. .. for e.g. you will calculate by 6 inch pipe, water is available in throughout year.. calculate approximately for e.g. it is available 30 feet head.. 5 kW. Thumb rule.. thumb.. means roughly that's it."*

In the context of generating 5 kW in task 3, he explained how he would be able to do so. He would change the component design specifications, so as to i) increase the RPM to the generator through telescoping the pipeline, reducing the size of the turbine wheel, and increasing the pulley ratio, and ii) for the RPM so generated, he would redesign the alternator to generate more power.

> *".. increase the RPM very simply.. for e.g. this pulley.. mostly .. I'll just rough calculate.. diameter is 12 inches. Decrease.. 10 inches will do. Definitely 10% RPM is rise."*

This he claimed on the basis of his heuristical knowledge/thumb rules in terms of correlations of component performances and specifications, and possibly a reference system that he designed. He thought of these changes in relative terms, as percentage changes in component specifications, or RPM and power generated, with reference to the numbers assumed in the simulation.

To generate more power without more water, he suggested reducing the diameter of the turbine.

> *"Reduce. Must be it is 20%."*

> *"It will be possible.. change the [turbine] diameter? .. I will fix 18 inches.. it will be 12 inches. [He will make it smaller from 18 to 12 when less water is available.] .. It's completely in this RPM.. in this RPM by less water. That's the problem solved. Yeah, definitely."*

When queried about his calculation for task 4, he asked for additional technical details.

"One question.. what is the gradient? Another one.. what is the diameter of the.. your.. say pipeline?"

He explained how he thought about generating power in spite of low RPM from the turbine, by designing a suitable permanent magnet AC alternator.

"Then five years back, I will.. going to one umm one of the industrial towns [name of place], I will see the one alternator.. the magnet alternator.. for wind mill.. for small wind mill. Then I will think "Oh! This is a very perfect for me .. it is very.. low RPM.. yes!" Then I will suggestion.. then purchase the body.. the motor body.. then get.. that's how. Then we will completely challenge.. how you give the head or water, definitely we will give the power." [170109_015]

When asked about the number of buckets on the turbine runner, he asked for the diameter of the nozzle, and indicated the number of buckets he would use for that nozzle diameter.

".. nozzle 1/3rd the width for e.g. 1 inch nozzle.. 1/3rd.. means 3 inch width of the Pelton wheel. .. even every one gap.. bucket to bucket.. 3 inch again. .. 36 inches means 3 feet diameter completely including 48 buckets" .. "it is calculated by totally diameter of the turbine divided by totally circumstation [circumference] of the turbine."

This gap comes about 2.3 inches for 48 buckets, or 3 inches for 37 or 38 buckets approximately. GRI talked of even number of buckets.

".. when crush the water into the bucket, it will rebound.. water is completely rebound. That's a problem. .. it is completely cut.. it is not taken the pressure. But cut in between.. notch [nozzle] and cup .. perfect it is.. free moving. Then if this calculation is wrong, it will cut off the pressure."

For less number of buckets than this number, he stated that water is wasted.

".. suppose one bucket is coming this time, it's.. RPM is very less. That time, one torque is waste. One or two torque is waste. Water is.. totally orbit is complete less.. it will affect the efficiency."

He explained how he arrived at the efficiency of the system.

"For e.g. 1kW.. I will put full load.. switch on all the lights. I will calculate the voltage.. convert amperety. Then it will be available.. 1kW is .. 800 W. 100 W five bulbs glow.. 500

W load. Divided by 800/500.. what is the difference is efficiency.. (makes oral calculations) means 60% is the efficiency of this turbine."

"But available water is completely.. more it is available.. it is increase the.. in the level of the efficiency."

A1.8 GRI's evaluation of students' design of MHP system

The engineering students' (ELs') design of turbine was discussed with him. The students designed for a site with head 9m and discharge 1LPS. When asked what power he would expect to generate from such a site, GRI made some mental calculations and immediately answered 0.5 kW i.e. 500 W. He assumed 40% efficiency. When asked if it was good head, high, low, or medium, he answered it was medium, and the discharge very poor. But he would start by designing the turbine first, and install and test it at the site.

"After then you will check the RPM, and the pressure, after then you will completely design the alternator. Then you will get the power.. is possible. <> Mostly it will come to only 300 RPM.. <> 200 RPM you will expect at the Pelton wheel.. after that.. transferred to alternator.. 300 to 500.. maximum 500. <> after that it will get only 10% efficiency." [170109_006 – 10:00]

"Totally overall.. totally calculation.. when you'll have completed all.. RPM, head, discharge, requirement.. totally .. final is efficiency." [170109_006 – 12:00]

The students were actually able to generate around 40-50 Watts. So GRI's estimate was about ten times more. GRI commented that he could take the challenge and definitely generate 0.5 kW that he estimated.

In order to estimate the RPM the student's turbine may have achieved, he asked for the runner diameter and head. On converting the runner diameter from cm to feet, he estimated the RPM as 150.

"RPM is good, that's no problem.. 150 RPM is okay, not a problem. But after then .. completely transfer the.. to alternator.. that's umm <> and another one.. the alternator is

mostly not a regular alternator.. it is converted umm reversible motor.. it will get [need] minimum 2000 RPM." [170109_006 – 16:00]

He suggested that if a permanent magnet generator was designed instead, it would work. It would need to use minimum 12 poles.

He would use the nozzle diameter of 0.5 inch. Also, the number of buckets used by the students (36) was high according to GRI. In spite of the notch in the bucket shape, he thought that the buckets would cut the water jet. As per his design, about 15 buckets [blades] would be sufficient instead. This he estimated using the circumference of the runner wheel, and the gap he wants to have between two buckets. [170109_007 – 03:30]

"Total you will calculate the circumstation [circumference].. after then you will divide the gap.. final show.. it is the number of buckets.." [170109_007 – 04:00]

For him, the turbine design would work, the alternator was critical.

"That's okay.. major problem is .. alternator." [170109_007 – 00:30]

"This wheel is umm not any changes.. good.. it is umm almost all is working.. <> Changes in.. only for the alternator side." [170109_007 – 03:00]

When asked if the splitter would be effective, he commented that it is only used for high head. It is not useful for low head. He did not comment on the specific role of the splitter.

Appendix 2: Case Study of EP

A2.1 Background and context

EP graduated with a B. Tech degree in Civil Engineering from one of the leading institutes of technology in the country. According to a critique,[411] most students from such top institutes aspire to either go abroad for higher education, and/or join 'cushy', high-paying jobs (in multi-national and software companies), that may eventually have little to do with engineering, and sometimes have very little connection with the ground realities in the country. Very few move to career profiles that let them innovate or utilize their training to address larger societal problems. EP represents this latter group.

EP served as a consultant to a state government for eight years, and then worked in the watershed program at a research institute. After this he worked with various Non-Governmental Organizations (NGOs), and also started an NGO of his own. During this period, he designed and built around 15 or more micro hydro turbine projects for communities deprived of grid-based power supply, in remote interiors of the country.

Though he was trained as a Civil Engineer, as he engaged with the micro hydro power design, he had to cross over to other disciplines.

> *".. actually we have a subject at.. called Hydraulics.. so hydro-machinery, hydraulics is a subject. And we have done experiments in the lab. So we very well conversant with the turbines. We know. So after that, if you refer to the literature, you already know the shapes, you can design according to that. The only problem I had was, I was a civil engineer, to I had to get into mechanical.. part.. " [150410_014]*

This he did in informal manner, learning by experience, and from various sources outside of college.

411 Sohoni, "Engineering teaching and research in IITs and its impact on India," 2012.

".. You have seen a turbine. But how will you fabricate it? You know you are jumping to another field which is mechanical engineering. And mechanical engineering is very big. There are lot of processes, of umm you know, making things out of metal, non-metal.. you know, all that. And you have to know each and everything. That I've learned by interacting with a lot of vendors. Lot of vendors. <>

I've done so many things myself. So those experiences are very useful experiences.. learning.. of course. And given anything today, this component.. one knows actually how it is to be made.<> You keep on learning.. all new things are coming in the market today. <> Very complicated, it's not easy. It's not easy to do." [150410_016]

Involving the college carpenter and a casting maker he knew, EP himself made his first Pelton wheel.

"but, in the beginning I made it myself .. didn't get it made, I fabricated the design myself. <> everything.. step by step. I did it myself. All alone by myself. I did.. grinding.. winding.." [150410_014]

"Electrical parts are very easy.. actually, if you.. umm if you buy a vehicle, it gives you detailed diagram.. you know, how your alternator is aligned and all that? <> Any auto repair man will tell you. You have to connect it like this. Very easy to do that.. how to connect this, how to connect that, and then rest of it.. then you can.. that was my first learning actually." [150410_014]

".. all this I learned.. bit by bit I improved the efficiency of things. Initially we were not umm.. we assumed something.. We did not get.. got enough power. Then we realize water is not flowing through or there is a problem somewhere with the nozzle or problem with the blade. Then we started getting more and more conscious. Then of course reaching back to literature to study it properly, and improving our system." [161228_005.2]

According to him, micro hydro power, where available, is the cheapest, and the most simple and sustainable mechanism of delivering not only power but also development at the grassroots.

"Micro hydro is actually cheapest. That is one.. the greatest advantage. It's cheapest source of power. In solar, one has to put in lot of money to generate that amount of power .. and.. night time it is difficult.. because you have to store power. Here there is no [not audible] it's continuously available, 24 by 7. .. plus it is very clean. You are not using batteries, you are not doing any [na] absolutely clean power. Here, you have civil structure, plus moving parts. So slight maintenance problems are there in this. And, with wind.. wind has is.. this.. erratic.. you know, you can't say at this time wind will be there. You can't predict. Wind has a problem like this.. so 24 by 7 is a difficulty. In solar as well as in wind. So, 24 by 7 is very easily obtained with this, at the worst prospects." [150410_002T]

He recounts how he initially experimented with wind power.

> *"So those day we had a lot of people coming from Australia, trying to sell wind generators, actually. <> So we started looking at that. In fact we even built a wind mill. And ercting it on top of a pole, we used to keep waiting for wind to blow (chuckles). So when the wind did not blow, once we even ran with the wind mill. Then we realized that its not going to work. There has to be something else…umm….something which is more reliable. <> So we visited field and then I saw these water mills. Watermills. So then I realized, ya.. that puts water and it makes it run.. there is a shaft running, what else do you want?" [150410_014]*

> *"There's no other scheme, you know, that's better than this hydro power. For small power generation, you don't have to give any cess. Water is free. And when water is free, your generation is say about say a Rupee, 50 paisa, or maybe 25 paisa a unit. It's so cheap electricity. And sometimes you need not generate electricity even. You have to run the shaft, and with shaft you can run anything that you want to." [150409_001]*

> *".. see for instance, hydro power can be of immense help- in that you don't generate electricity. Just use shaft power. You don't need to generate electricity to create livelihood. You can generate many options even without.. but they don't promote this.. they go straight away into generation of electricity. <> .. you should look at the need, rather than, you know, giving a modern name to it.. <> If your work is getting done by mechanical power, then why would you want to generate it [electricity]? <> First you generate it, then you convert it to mechanical, by using a motor. You connect an alternator, and a motor. Haven't you added two new devices unnecessarily? Who will maintain those?" [150410_003]*

> *"I don't think there could be any system, solar or any other.. that you can get so much work done with.. <> they can't have a project like this, it's impossible with solar. Because it's for 4/5 hours, peak.. peak you get just for about two hours." [150410_005]*

But there is no political will and support for micro hydro power.

> *"Even if you go to non-renewable energy ministry, they will say we are interested in mega watt, or high generation of power. But they don't realize even small generation can benefit the village, you know, in a very big way. It can open lot of avenues of employment for people." [150409_001]*

> *"It's a misconception that micro power stations are very expensive. This is a lobby that is afraid of the micro-hydro producers. The reason is, see people have.. local people have more power. <> So the 'mega' or 'big' minded, they'll always try and negate the small ones. It's expensive, this, that." [150410_003]*

Having worked in diverse situations, he describes various facets of the socio-political situation interacting with the technology.

“.. this village is having.. there’s a stream. It can just generate enough power to [na] this entire village. <> And in summer, there will be so much water, that they can actually sell this electricity from the grid. But they will not allow that. Instead they want to have a huge power station somewhere, which will block the way for the smaller ones. So this is a very strange politics that is going on, and umm, people who have been working in the area, they.. they know it very well what is the politics involved.” [150410_003]

“.. no government is interested in doing training program for the small hydro.. they are not done, actually.. they don’t promote training of man power. You don’t have man power to install small hydro power stations..” [150410_004]

“.. local people don’t rise to occasion. They are doing things on their own. If they get together, they’ll do fantastic things. But the problem with the society’s it does not get together. So it gives chances to people coming from outside or other power force actually. The big contractors come immediately.” [150410_003]

Furthermore, climate change is a visible phenomenon for him, and it has impact on the design of micro hydro power systems.

“Because water is like that .. you never know how much water is going to come. So climate change is having a lot of impact on this. <> We have older projects.. there we can make out. Where we expected one cubics or 1000 liters.. in the river .. it is not now 1000 liters. It has come to 800.. 900.. 800. <> What we expected in the lean season.. that discharge is not available.. it's decreasing.” [161227_004]

Also, as he realized after his first project, no trained people, i.e. trained engineers, were “interested in getting into all this”. He, on the other hand, never took up a 'regular' industry job. It was not easy, but he managed to sustain himself, through fellowships, government consultancy contracts, as well as NGO projects.

“I realized that I can’t leave it just at that, I have to still pursue it further and take it to the community level. And how do you do it? So I started looking for donors. And I didn’t have any NGO of my own, so the best thing was to work with an NGO.. which would have a good donor also. But I was given a very measly salary… you know when I did some interesting community projects <> Sometimes there has been difficulties because there was not, you know, connectivity.. one after another.. it was not like that. There was a break in between, for instance. Then that.. like that it went.. ” [150409_004]

“that’s why I say.. if you make it remunerative .. if you make this whole exercise remunerative even for those who run the power station, you know, only then they’ll be able to shell out some money, isn’t it? If you want to run as a private business? So .. if you have to look for returns.. if you provide technology that gives you returns, so people will also able to give you some, you know, good returns that way.” [150409_005]

He found local people working to solve their own problems when motivated by an interest. Early in his work, EP had this experience.

"That.. we raised some funds and made turbine for them and all that, installed the turbine also. And also requested somebody to donate us overhead transmission wire. The wire reached and I could not reach there for some reason.. I was busy in something else. And one day my friends said that "lets go.. to that village and see. What is happening to that. We can go and help." And to our surprise, when we reached there, these people had set up the lines, and the 'Ramlila' [a festive Hindu drama] was going on, in that village. And there were about 10 shops.. each shop was given a bulb." [150409_001]

"You can think of some livelihood which- which the village thought- but I was not very much involved in the community exercise actually at that moment. We thought that village Pradhan, or head of the village, is taking care of all this. Actually it was not getting into our thinking process.. that it is very important to have the community with us." [150409_001]

But he also acknowledges that people need training, and it is not always very easy to address this need in the demanding project schedule.

"When you go to a village, how much time do you have on hand to do all this? If it's a year-long project, you may spend just about 10 days, 1 month. Isn't it? What can you teach [a novice trainee] in one month? <> What would be the practical experience.. of that learner? It has lot of limitations. In one month you can't sandwich all things in his mind." [161228_002.70]

"And he will forget also. He forgets. Recently I've seen this happen, I had trained him about the oil mill.. he forgot how to open it. He was using a hammer to do it.." [161228_002.70]

"Critical [part] is.. settings of these. These come ready-made, you have to do the settings. They are not able to do the setting properly. <> .. whether it is responding properly to the behavior of this alternator. Other thing is, when you shut off the load, whether it is taking up or not. You know, synchronizing properly or not. And there should not be any short circuit in between." [161227_005]

Nevertheless, EP finds ways to maximize the training opportunities, so that the local people are equipped to maintain their power systems and livelihood machinery well.

"Once we installed the [oil] mill, actually I called the manufacturer. [Asked him that] you open the entire mill. Get [the village] people to assemble it back. Run it. Stay here for a couple of days. Get them to run it. So what are the problems they face? For example, there was a mustard one, and the mustard was getting stuck. So how is he to open it, clean it? He should learn this. So he [manufacturer] staye for a couple of days,

then left. I stayed on. Then he [village trainee] goofed up. He.. he skipped certain things. He didn't remember. Made him open it. I told him this is where you are making a mistake, this is how it will open. So in this way, making him open and reassemble it again and again. Now .. they don't ask me. I'm persona non-grata now! I feel happy. That I am no longer required here. Right? They can look after things themselves. That is more important." [161227-005]

He tries to identify the local craftsmen like carpenters, masons, electricians, mechanics, and even accountants and managers for the projects. There are differences of technical skills, and opinions.

"We were installing the pen stock at a site, umm steel pen stock. So pen stock, made of steel, there are expansions and contractions in that. Because it gets heated up, it gets cooled down. So I told, at one place you must put an expansion joint. <> So umm.. they said, "What is that, Sir?" Then quietly somebody says, they study in Delhi, wonder what they teach them there (chuckles). I heard all that. So I said "Okay brothers. Hum.. We have a difference of opinion about this. Let's do it this way, it's noon time now, let's install the pipe. Okay? Let's not put the expansion joint. Leave it like that. And see, here we put a marking. This pipe covers the length up to here. Let's see tomorrow." So we came in the morning. The morning is cold. So the heat [was different] in the noon and morning. They found that the pipeline has gone back. So they said "How did this happen?" I said "It has shunk.. check later on, it will be back to the marking." So.. those experiences they don't have, that's why they don't understand this. So when they get experience like this, they start understanding."

EP found local youngsters to work with him, and trained them such that they could be on site, and get installations done. But the income from this activity was not enough for them, and government is not supporting the micro hydro.

".. they are very good actually, I tell you, some of the boys! <> He is from umm adjacent valley. <> But the problem is.. you get from us say about 7000 – 8000 rupees.. you know that time. He is only 5th pass. But there is.. there are heavy demands at home.. <> If your power station does not pay, people will not work. They won't run it either." [161227-005]

EP continues to use his engineering ability to innovate machines, processes, and products to create more livelihood opportunities, for the marginalized mountain people.

"I have also my own problems and- we keep on looking for technology for instance. <>

He observes, surveys, and designs new methods. An example of the innovations he is making in the process to produce wool-felt products through a local women's group.

> *"This is after very thorough survey in the market and seeing how it is done. So we looked at a method by which, you know you have some kind of fancy label sometimes - labels you know or some cut-outs. <> So you have to make some kind of a die, on which you'll put that, then some force will come, to cut that piece, isn't it? So we adopted that idea into it, which nobody was using. So (chuckles) we were quite successful in that.*
>
> *We're still improving upon that because women are not used to it, you know they hammer it sometimes roundly, and they tend to break it. There are a lot of injuries (chuckles) to the die.<>*
>
> *[Interviewer] Who told you about this?*
>
> *M.. I looked for it in the market, right. And I had to think.. how should I do it." [150409_002]*

He is very passionate and committed to designing technology such that it solves problems for the rural, marginalized people, and such that they get employment based on local resources, and their drudgery in the work is minimized.

> *"Pico is say upto 5 kW only. So in pico, you go for small lighting purposes and all that – for small purposes. But if you have to go for livelihood, then you have to enhance the, you know, capacity. <> You have to go say five onwards till about ten-ten-fifteen. <> If you go to oil expellers, they require more than 5. <> So lighting these days you don't require much load actually, you can switch over to LED bulbs and all that. That's not a big load. The big load is only in the livelihood, actually." [150410_001]*
>
> *".. program does not stop there, by installing and supplying power. It has to be over a period of time, to see actually where umm there have been shortcomings, and how to you know overcome these shortcomings." [150411_004]*
>
> *".. so I'm still you know, restless till I have completed this and made it very convenient for people to.. you know work on it." [150409_002]*
>
> *"Now we're trying to tie up now with some friends, that we will have some kind of a system by which we will know, you know sitting at distance, how this thing is running. So this is my last step actually in this. So once I have that then I'll be satisfied that I've contributed you know, enough in this area." [150409_001]*

A2.2 EP's historical design process

In the following section, I describe EP's process of designing micro hydro power systems. These key episodes can be identified from the historical trajectory of EP's designs over several years.

1. Modified water mill
2. Pelton turbine and digital load controller
3. Cross flow turbine
4. Electrical and mechanical power
5. Power for community
6. Multi-purpose power
7. State-level drive for MHP

A2.2.1 Episode 1: Low cost power - Modified water mill

Background

In 1975, fresh out of college, EP was asked by one of his professors whether he could develop a power system for a research lab in a non-electrified, high-altitude region of a protected National Park. The professor's team was working on high-altitude plants, and the material they collected got spoiled due to germination by the time they got back to their labs in the city. To avoid this, they wanted to set up a lab and conduct experiments where they were collecting the samples. The lab would require electricity, but grid supply did not reach the research site. They needed some other solution, and one major constraint was the lack of funds, since the research project had not anticipated a need for continuous power when budgeting. Thinking it would be an 'adventure', EP took up the challenge.

Solution

There was a small rivulet flowing near the lab tent, receiving water from seasonal rains, as well as from snow melting in the summer. The region had traditional water mills installed on such perennial streams, mainly to grind grain into flour.

> *“You can analyze it...you have never seen it.. you see it, and then you.. it's the way water is falling.. It is imparting force to the.. Umm this thing.. blades and this is making the wheel run. The scientific process, isn’t it? You learn little bit of science, you can understand that very easily. But it was new, it was very simple, alright? In fact umm it was really really ingenious.. these water mills.” [161228_002.123]*

He took a crude measure of the rotations per minute (RPM) available, and rather than connecting an alternator to check if it would be sufficient to generate power, he estimated.

> *“.. one day I just sat down there, and I noticed the top stone. Then after putting the mark on that, let me see in one minute how many regulations it is…making. So we assessed, not very accurately because it also runs very fast, so that moving eyes is also very [na]. So that was about 250 RPM. So I said we are getting 250 RPM, but if we reduce the turbine size, that will run faster. So reduce the turbine time umm little bit, and if you are getting the gear ratio good on top, then you’ll be able to take it to 3000 RPM, very.. [na]. So this is how it was done.” [150410_014]*

There would be a chute fitted in the stream, to direct the water flow on to the wooden blades of the locally made water wheel, which had a vertical shaft. Excess water would be diverted through a side channel using traditional wooden gates.

EP decided to modify and improve this wheel design and build a micro hydro power system for the research lab. He replaced the straight wooden blades of the turbine wheel with curved ones. This modification improved the rpm as necessary.

"The turbine.. we adapted a local turbine, and we made it ourselves. We made it slightly different, improved version. Actually they were using blades which are straight. If you have curved blades, then you get more impulse, and you get more force from the turbine."

Using car spare parts like bearings and axle, he made some small changes to the turbine, and also made it portable. He added a big starter gear and a smaller gear to increase the shaft's RPM by ten to twelve times, from 300 to about 3000. This was coupled to a vehicle alternator that charged a DC battery.

"... and we had a gear. Gears are there. And then we were using this very good alternator, with that. That used to generate electricity.. with same .. similar system as you have [in] car."

"... and it was basically a battery charging system used in the cars only. So this is how we used to run that."

Thus water falling from the chute rotated the turbine and the alternator shaft coupled to it, generating about 700 Watt DC power. This was successfully used to light up the lab tents, and to power electrical instruments, and a small incubator.

Afterwards

Though the micro hydro power system based on the modified water mill provided enough power for the lab and the resident researchers, in the month of October, when it grew too cold, and many guests arrived, the team did not have enough power to provide warmth nor enough ration, so the lab had to be closed. But in the process of setting up the power system, several key learning points emerged:

- The team realized that many villages don't have grid electricity, but it is quite possible to generate electricity locally from available water.
- EP felt "some sense of achievement" .. and that "it's so easy to do it".

- Villagers realized that it is so simple to generate electricity from the water they already have.

These points eventually led to EP's involvement in more micro hydro power generation projects at the grassroots.

> *"So, after this we jumped on to another thing.. .. how do we run a small power station in a village?"*

Even as he worked on other projects as a government consultant and with Non-Governmental Organizations (NGOs), he continued to build micro hydro power systems for remote villages.

Observations

EP's design goal was to generate 'sufficient electrical energy for lab illumination and instruments'. EP had formal knowledge of technically sophisticated turbines and generators. But due to constraints of funding, he identified a rudimentary design concept as well as its embodiment in the local traditional water mill. This provided a stand-in for a turbine to generate shaft rotation from flowing water. Another stand in, an existing vehicle alternator, was used in place of an AC generator, to convert the shaft rotation into electrical energy at required voltage and frequency ratings of electrical devices.

> *"Readily available in the market. We.. that also from the disposal market (chuckles). We didn't have money, we couldn't go for.. you know, new and fancy stuff."*

In this case, the social factors (the activity context that the electricity supports: a temporary research lab that could shift its location or wrap up) were embedded in the task specification and cost constraints, which drove the design. Once specified as a task, these social factors influenced and constrained the design choices and decisions, but were not explicitly noted as part of the design goal. It is possible that the social factors were implicitly considered by EP while designing, because he was a part of the academic world that specified the task, and was thus aware of those unarticulated factors.

Over the following episodes, as EP becomes more involved in this domain, social factors started becoming explicit in his design goals.

A2.2.2 Episode 2: Seasonal variation - Pelton turbine and a digital control system

Background

EP had studied the Pelton turbine, and knew that it can handle variations in flow and is good for high head situations. So he designed technically sophisticated Pelton turbines for such sites, starting from 1978. One such site was near a twin tribal village, in a remote area in the middle of a reserved forest, home to wild animals. Grid-based power supply did not reach the 67 households, of about 380 people. In 2005, an NGO, working with the marginalized communities in the region since 1979, envisioned a micro hydro power project to solve the power problem of the twin villages. The NGO aimed to provide electricity as well as ensure inclusion, social and gender equity, and sustainability, in the process. The project was to be implemented with community participation, was and to be handed over to the community. EP was engaged as a consultant for this project.

Solution

EP designed, fabricated, and built a micro hydro power system near a waterfall about two km from the village.

For this, a Pelton-type turbine was fabricated by EP in his own city. The source of water - the waterfall nearby - would vary throughout the year, but it offered a good head. In order to cope with the seasonal variation in the input flow, EP provided two alternators, generating 10 kW for low flow and 25kW for high flow. To manage the variation in electric load, EP designed a Digital Load Controller (DLC) and each house was fitted with a variable load controller with manual reset. Each household got two bulb holders and one tube light, one plug-point, one fuse, and one isolation switch. About ten streetlights were also installed in the village.

Afterwards

A report of the project by the NGO states that the technology was sound, and the power system started providing electricity. Quoting a villager, it says that the "electricity has not only brought practical benefits such as the ability for children to do homework at night or villagers to simply see in their homes after sunset, but also a basic sense of equality with urban people. The electricity has also enabled new community activities.".[63] The report also adds that although it was planned that the project would be handed over to the community for maintenance, there were several glitches. "The corpus was not collected because initially the project needed to be technology driven in order to meet donor timelines. The timeline did not allow enough emphasis on developing the community's stakes. .. No corpus or tariff was collected, leading to community not valuing the system and no fund for future repairs and maintenance."[412]

412 Vaghela, "Powering Dignity," 2006.

Observations

EP's design goal in this episode was to generate sufficient electrical energy for a village, based on a water source with high head but also a high seasonal variation in flow.

The technical choice of a Pelton type turbine and a DLC took into account the technical parameters, maximizing the opportunity in high head water source, and efficiently compensating for water flow variation and load variation.

In the case of the turbine, the characteristics of the local water source indicated two technical choices for the type of turbine. Either a 'pump as turbine' or a Pelton wheel. The 'pump as turbine' is less expensive and widely available. But it can accommodate only one flow rate and its efficiency is low. A Pelton wheel on the other hand can handle variations in flow and high head.

> *“It had a very nice waterfall actually, coming from 100m. 100M fall is a very good fall actually. … And we had a very nice Pelton wheel, very nice one. And which could run with very small amounts of water.”*

EP chose the Pelton wheel. It was a sophisticated design and the process of fabricating it was complex and meticulous. He manufactured it in his city, and took it to the remote site.

> *“To casting of those blades is actually done by that process [investment casting]. But high precision matching is needed in those. <> [na] there are a lot hassles. First you have to make a wax pattern, then you have to do all this work, right? You need a lot of precision in this.” [150410_011]*

The other issue was to regulate the generator output in case of variable load, such as during night and day, in a village.

> *“I happened to have some problems with the control systems. So control was the main problem actually those days for me. … Actually what happens is, in a power station, suppose you are generating 40 kW power, and you .. you utilize just 5kW...”*

When the generator load drops like this, to maintain the generator output frequency constant at the required frequency rating, the turbine RPM needs to be held constant. This could be done by proportionately varying the impinging water by controlling the water flow. But automatic varying of jet diameter would involve mechanical power and a feedback system to trigger it.

> *".. the water control is actually by moving the valve. Valves require a lot of power for movement."*

In order to avoid this, EP developed a digital load controller to balance the load drop. Heating coils were kept immersed in water, and excess power in the system was diverted to heat these coils, whenever load dropped. This protected the system and kept the output frequency constant.

> *"There's a frequency sensor. If it is 50 (Hz), it's ok. If it crosses 50, that means there's surplus power in the line. So automatically some switches get opened, and some heaters get on."*

> *"So water.. water is wasted, but your power station is safe."*

The entire design process involved community participation, as labor during construction, and (expected) continued involvement in the maintenance of the service later on. But since the Pelton turbine was fabricated in the city, the community had no experience of handling technical issues related to it. In later projects, the NGO emphasized training local people to fabricate the turbines locally. Digital technology such as the DLC would require a trained and equipped person for its maintenance, troubleshooting, or repairs, and this could be expensive or not readily available for the community. This constraint remained implicit, unarticulated, and thus unaddressed.

EP also commented that the villagers are familiar with materials such as wood. But they need to learn the characteristics of machined steel, plastic, and so on, to be able to maintain the system well.

> *"There people are used to working on wood and soil and things like that. We've introduced steel for instance. It's umm machined steel.. machined steel. So that has a different requirement. You know, you just can't misuse it. <> The pipeline we have here.. once they had fire in the jungle.. so the upper plastic portion of the .. pipe got burned.. (laughs)." [161227_004]*

Such social factors remained externalized in the design, and were not explicitly a part of the technical design. As a result, though electricity was generated, the community did not own the project enough to create a corpus fund for maintenance. Eventually the NGO had to recommend halting the power generation till this issue was resolved.

A2.2.3 Episode 3: Local, easy maintenance - Cross flow turbine

Background

Even in a typical remote mountain village, high water head may not always be available. For low head situations, if the discharge is also low or seasonally variable, then the jet diameter needs to be large. As a result, the runner diameter needs to be large, and a Pelton turbine becomes too big. Alternately there need to be multiple jets. Also, both the Pelton turbine and the digital load controller are too expensive, complicated to manufacture, and difficult to maintain. Repair services are not locally available.

> *"So if you use these kind of technologies [not audible] more and more complicated. And the capability in rural area is not you know such that you are able to take care of complicated technologies. .. And similarly control systems are again all electronics based control systems. Something goes wrong in control system, you are in trouble, you have to go down [to the plains]."*

Solution

When good flow of water was available throughout the year, EP designed cross flow turbines that work well at low heads. A cross flow (Banki or Ossberger) turbine is simpler to design, fabricate, and maintain. “Though less efficient, its simpler structure is less expensive than other low-head turbines of the same capacity. Since the water flows in, then out of it, it cleans itself and is less prone to jam with debris”.[413]

Observations

EP's design goal in this case takes into account the constraints imposed by the social and environmental factors, alters the technical choices, and offers an effective solution. The design goal includes the social constraint of locally available technical capabilities.

> *“... we should make equipment in such a way that can be opened easily. So there had to be some change in it. Every time we used to think which part umm, you know, is difficult to remove, and simplify it actually... ”*

His turbine selection takes into account factors other than efficiency while selecting a simple-structure and low-cost cross flow turbine.

> *“You see, you can run up to four meters.. you can very easily run your cross flow turbines. There is no problem in that.”*

Further, through this design process, EP brings down the overall cost, even at the scale of micro power. He argues that it does not have to be a mega-scale power system to minimize the costs.

> *“If you make it very sophisticated.. the micro one, and add many things to it, then it becomes expensive, otherwise it's not expensive.” “It's a misconception that micro power stations are very expensive. This is a lobby that is afraid of the micro-hydro producers.”*

413 Wikipedia. (2016, February 01). Micro hydro. [Web site]. Retrieved from https://en.wikipedia.org/wiki/Micro_hydro

A2.2.4 Episode 4: Electrical and mechanical power

Background

The renewable energy ministry, along with international funding agencies, implemented a power supply project in remote villages around 2006-9. It aimed to demonstrate how renewable sources of energy can reduce poverty through improved quality of life and increased livelihood opportunities in remote, non-electrified villages that are not likely to get electricity from the grid.[65]

EP's NGO was an implementation partner for the project in a remote mountain district, based on their track record in micro hydel and in community based, innovative, low cost engineering solutions in difficult locations.[65]

Solution

Based on the water availability, EP designed a system of two turbines running side by side: one turbine for electricity generation, and the other for motive power application when no electricity generation was required.

> *"Thinking is that when there is less discharge there will be less generation of power and which could be use mostly for lighting purposes and when there is a high discharge we can generate more power and probably runs machines from electricity.. that was the idea." [161228_016]*

The mechanical drive saved loss of power in conversion from electrical and back to mechanical, effectively raising the efficiency of the system.

> *".. when you generate electricity your efficiency is not 100 percent, your efficiency is 80 percent or something, okay.. then you will run motor, the motor will have an efficiency of about 80 percent. So what was the percent available over there? It's 64, right? So you already have a loss of 36 [percent] <> If you run it with the shaft, you save 36 percent .. there is a lot of advantage in that" [161228_015]*

EP designed scaled-down machinery for livelihood generation, drudgery reduction, and income earning based on local natural resources, through wool washing, wool carding, spinning, oil milling, flour milling, and rice threshing.

> *"... after doing the [village name] project it was a very big realization that unless people are making money out of that, you can never run this power station. But if they are able to make money out of it, it is the best scheme actually."*

He also involved local labor in the project implementation, and trained some villagers to be grassroots engineers for the fabrication, construction, and maintenance activities.

Afterwards

EP's projects are now conceived on the model of energy for livelihood generation. According to EP,

> *"Now if a village comes to me for a micro power station, I insist for a livelihood component if they want me to accept the project ... if you provide technology that gives you returns, so people will also be able to give you some, you know, good returns that way. So we never used to think like that earlier. It was just electricity."*

> *"The toughest part is community, and the livelihoods actually .. it is the toughest part in this."*

Observations

EP's design goal here expands to explicitly take into account not only socio-environmental constraints and opportunities, but also the overall context and the role of electricity or power in people's lives.

> *"... there are two things actually in this .. whether you want speed or you want power at low speed. .. "*

Some of these social and environmental factors now get explicitly stated, for example building the technical expertise of the local people, designing for easy maintenance and repairs, and running machines that support livelihood activities like wool carding.

> *".. if you're able to generate electricity in a god-forsaken place, it's a great thing. If you are able to provide electricity to ten households, it's a great thing. If you are able to provide electricity to one village, it's a great thing. If you are able to provide livelihoods to the people with electricity, it's the greatest thing.. that you can do. If you can make people just self-sufficient by this, it's the best thing that you can do. <> So there have been steps like this."*

A2.2.5 Episode 5: Power for community

Background

In the community project, EP now explores the actual needs of the village, starting with the demands of the villagers.

> *"So normally it has been seen that the demands are very vague actually. They are not very practical about demands. Oh they will say you open a factory here. They don't realize that this has small power, you can't open a factory." [161227_005]*

He explains that he now employs the method of Participatory Resource Appraisal (PRA). In one village project, it afforded the chance to get 'down to real stuff', in a meeting with about 60 odd men and women. EP said it was a great thing to do.

> *".. actually I enjoyed it!" [161227_005]*

An analysis of this discussion revealed problems and challenges faced by the villagers, as reported in EP's presentation slides.

> *"Wheat - inadequate milling, rice - no milling, millet - inadequate, mustard - no milling, wool - no mechanized processing, milk - no processing facility, aromatic plants - no processing, fuel for cooking - scarce and difficult to obtain, irrigation facilities limited, power required to lift water, news and information dependent on word of mouth, education in schools poor quality, computers are not used, teachers don't like to stay, village is not electrified." [161227_005]*

They had to estimate which of these could be addressed by the power they would be able to generate. It would not be enough to support electricity-based cooking in all the households. So that was out. But the rest of the demands could be met. Even if the power was limited, it could be time-shared.

> *"So broadly these things we had figured out. Now we need to find out what all we can do with the power we generate? Right? I may not have big power say umm fuel for cooking.. I can't provide electricity to all households for cooking. That is.. write off. Rest you can see, you can do. Then if there is a limited power, then you can umm allot time for it. Time allotment.. so this is what you do for this much of time.." [161227_005]*

But any one of these businesses or mills would not run for 24 hours, nor through the year.

> *".. in villages the best way is to give them many options. Wheat [flour mill] is not going to run for 24 hours. Oil mill is not 24 hours. Rice mill will not run for 24 hours." [161227_005]*

Solution

So they decided to design the power system such that it would generate both electrical and mechanical power, and support a variety of businesses, services, through the year, with a possibility of uploading excess electricity to the grid.

> *"So when it is customer dependent, then if you have many things to run, at least something is running! Okay? If one of your mills [businesses] is running, you are earning. So for this.. when you design in this way, these are multi-purpose power stations." [161227_005]*

EP recommends this mixed-basket approach as the best for the villages, to earn income from one or the other sources. He also points out that the villagers agreed, and the project got underway, because a funding agency was supporting the investments in the power system.

> *".. we didn't make them invest a lot of money. If they had been asked to invest a lot, they might not go for it. It would have taken much longer time actually for them to realize ..*

> *when we did small work then they realized this has a capacity of growing further." [161227_005]*

This allowed the villagers to see that it was indeed in their interest to have such a multi-purpose system, and then they started building on the idea. But left to themselves, they would have probably taken longer to see its merits.

Observations

EP's design goal here expands to: explicitly and methodically understand, document, and report the local resources, needs, and demands of the villagers in a participatory manner. This also enables him to convince the funding agency about the appropriate technical solution, and justify the investments, while motivating the villagers about the project.

A2.2.6 Episode 6: The industry model - Multi-purpose power for a small group

Background

EP also found that it was not easy to navigate and negotiate the entire village community, with its undercurrents based on caste and class politics.

> *".. community plays sometimes.. it can also play a negative role.. where people with self-interest.. lot of people with self-interest come, and they can ruin the program. <> So they will not try to maintain, but they try to accrue all the profit through that and you can't run a power station like this. In some villages, it has given a lot of pride to people that we own this power station ourselves. But running a power station still becomes difficult.." [150409_001]*

> *"you also realize that.. as I carried the machine there for installation, up front he [the villager] announced that the [na] machine will not function.. and I insisted [na] and installed the machine [na], and it has been having good potential, but the headman [na], he had no interest in running it.. so as a result, we left a bad impression and the turbine did not run." [161228_015]*

> *"I have done many power stations. I've done small ones, done with community, umm done with the community and the.. umm lot of livelihoods.. There finally I decided that community is not my cup of tea. One cannot sort out the tussles within a community." [161227_003]*

In some places, it was difficult to get communities to join hands to build and maintain MHP systems for such reasons. On the other hand, the government or NGO agencies interested in supporting such project through funding were often shortsighted in their goals. Their mandate was restricted to providing electricity, but not beyond. Unlike EP they did not engage with the relevance of power to people's lives.

> *"What else you can do with electricity [na] that is the point actually, whether you want to light bulbs, upload it to the grid, use it locally to get work done with machines, they are blank absolutely. If you tell them that we will link this to livelihoods – no no, not livelihood. Just build it as it's been written, that's it.. so that's how they are doing it." [161228_001.26]*

Solution

EP found a way out by deciding to work with small self-help groups.

> *"So many people have worked and they found that community.. you know, have lot of problems.. [na] So people have started coming down to smaller groups. We can do self-help groups." [161227_003]*

In his latest project, six villagers have formed a group. One of them owned a traditional water mill, constructed by his grandfather, along the road side. The group has opened a joint bank account to keep aside a corpus for maintenance of the power system.

> *"It takes a little while to form a Self-Help group.. you take a couple of months to establish Self-Help group." [161228_001.21]*

> *".. you have to engage them in some activity.. the activity continues over 2-3 months, people come together, meet and discuss, they will start saving 5-5-10-10 Rupees a week or per month, their kitty grows, right?" [161228_001.22]*

EP designed and implemented a micro hydro power system, so as to improve the existing mill, and to provide additional 5 kW electrical and 2 kW mechanical power. Utilizing this power, the group plans to run a set of businesses that will offer various products and services to other villagers and passers-by. The flour mill is already in business.

> *".. electricity, oil mill, operation.. umm oil mill operation, then millet processing, compressor, jet pump, RO – water purifier, cooking unit. <> 2kW mechanical power only exclusively for grinding. <> The [other] grid-powered mill is shut down now.*
>
> *[Interviewer] Shut down?*
>
> *Shut down. All the grain now comes to the this person [the micro-hydro mill] <> Runs for the whole year.. People don't make oil for the whole year at one go.. [since] if they would do that, the stored oil goes bad." [161227_003]*

He argues that while the trend is now to generate and upload power to the grid, his livelihood and income generation model is far better. Generating only electrical power from micro hydro can get you INR 4 per unit, if you sell it to the State electricity grid. According to his calculations, instead if you generate both electrical and mechanical power, and run diverse businesses, the generated income is about four times more. You are not selling electricity, you are selling value added power.

> *"..Now this game has come of supplying to the grid. You sell it to the grid.<> .. from grid you get 4 rupees. <> See, if you have grid connectivity for 8 hours, you get forty eight thousand rupees.. okay? Projected. If you consider all of it, it is five lakh twenty thousand rupees.. okay? If you had grid connectivity for 24 hours a day, hmm, you would get twenty four thousand rupees. So you compare the difference between the two, it's a huge difference. This is almost four times .. of this. <> Because you are running industry! We are not selling electricity (chuckles), we are processing electricity and then selling it. So we are making a profit because of that as well, isn't it? <> We are running it as an industry.. this is an industry model." [161227_003]*

Furthermore he adds that he finds this model better for other reasons as well. One such reason is that rather than just taking the benefit of government subsidies, when people invest more, in terms of money and efforts, and start earning from it, they are far more involved with the system.

> *"Actually I found this better.. umm problem is that when you build a power station, it has so many external subsidies, that people don't take it very seriously. But when you design*

and install such machines that generate income, then they are.. they.. they realize this is a great source of earning. <> People get attached to the system. Then they will not let others touch their system! Shew.. get back.. (chuckles)" [161227_004]

Another reason is that small power is very important in generating and sustaining local self-employment.

"I am not in favor of putting in the grid. Because there is so much of requirement of power, you know for doing small small employments, in number of places." [161227_004]

Even when the discharge goes down in winter, the businesses running on mechanical power will continue to run, if a little slowly. So the flour grinding, millet processing, oil expelling, and car washing services will continue. The electricity-driven restaurant, purified (RO reverse osmosis?) water, and mobile charging may not.

".. [he] will pour grain, but will not make it very tight. [na] not full pressure on that.. so he will operate it slowly and lightly to grind flour. And the flour will be lesser. Instead of two, one jet [of water] will run [drive the turbine and flour mill]." [161227_004]

"Some services it does provide, doesn't it. And it is creating employment in other ways. This is a better goal rather than thinking of.. electrify the entire village.." [161227_004]

A2.2.7 Episode 7: State-level drive for MHP installation

Many customers are interested in exploring the micro hydro power alternative because it is cheaper compared to the power they use. Small scale entrepreneurs working with local resources such as broom grass or Moringa trees, from the states of Meghalaya, Sikkim, Odisha, and so on, have approached EP for developing micro hydro power systems and machinery based on it.

According to EP, that is the best way to use micro hydro.

"So that's a use of power. Brother, you have a watershed, there is a small stream flowing through, these all are potential source sites. They are like gold flowing in the .. if you can utilize it that way. Isn't it?" [161227_005]

A2.2.8 Summary of observations across design episodes

This historical analysis of some of the key transitions in EP's design process indicates an increasingly explicit understanding of social factors, and the connection between society and technology, and an explicit incorporation of these into the design process.

The following salient points emerge from this case study:

1. EP's design process indicates a progressive transition from purely technical design goals to the inclusion of non-technical or socio-environmental requirements in his design goals. The composition of EP's solution accordingly changes, from merely technical to socio-technical.

    i. stream water diverted through a chute > modified traditional water mill > car alternator > DC storage battery > lab instruments

    ii. waterfall water diverted > Pelton turbine > gear box > two AC alternators > household gadgets

    iii. waterfall/stream water diverted > Cross flow turbine > pulley-belt > AC alternator > household gadgets

    iv. waterfall/stream water diverted > turbine > pulley-belt > AC alternator and mechanical drive > electrical gadgets and mechanical devices/machines for income generation

2. As EP's design goal expands and gets socio-technically more complex, the previous solution space acts as a prototype for the new problem space. But the new solution changes this solution space completely, by eliminating certain components and the

concepts they embody, from the design space. Pulleys and belts are preferred over gear boxes, and power generation is diversified into electrical and mechanical.

3. In the case of grassroots needs, the problem definition or understanding the requirements is very complex, especially for a designer external to the context, as the needs are not always explicitly stated or directly technical. The material and social structures interact with the technical. In the process, the needs and constraints emerge clearly.

4. EP's conceptual understanding of the components as well as electric power is initially purely formal, theoretical, and quantitative. But it expands into an experience-based appreciation of the qualitative nature/characteristics of power, in terms of it's specific applications for grassroots people. This shift towards qualitative understanding with expertise is counterintuitive, in terms of standard narratives where expertise is equated with formal knowledge.

5. EP's MHP system design evolves from being technically sophisticated and highly efficient, to being socio-technically relevant and effective. EP's design incorporates, from the very beginning, all the components necessary for the technical functions to be performed. But the components are progressively replaced or modified, in terms of technical complexity, to suit the socio-technical functions. For this reason, the system becomes really complete for him only after adding the components to provide mechanical drive along with electrical power.

A2.3 EP's design considerations for the real and virtual MHP systems

In the following section, I describe in detail how EP now designs various aspects of his system. I try to characterize EP's current generic MHP system design and considerations across diverse design situations. Particularly his interaction with the simulation system for virtual MHP system design throws light on some of these aspects.

When it comes to MHP system design, it involves the generic concepts of conversion of potential energy of water to kinetic energy, to rotational energy of shafts, to (electromagnetic generation of) electricity. EP's generic preliminary embodiment now consists of diverted water > turbine > pulley-belt > AC alternator and mechanical drive > electrical gadgets and mechanical devices/machines for income generation. But the definitive embodiment and detailed design involves many specific parameters and considerations related to the site, coupling, as well as control.

In this section, I report EP's embodiment and detailed design considerations, in the light of the generic conceptual design.

1. Conversion of potential energy of water to kinetic energy: Design of the site and the civil structures

2. Conversion of kinetic energy of water to rotational energy of shafts: Design of the turbine and other mechanical components

3. Conversion of rotational energy of shafts to electrical/mechanical energy: Design of electromagnetic and electronic components

A2.3.1 Design of the site

The concepts of head (vertical height of the water source/tank, in meters) and discharge (volume flow rate of water, measured in m^3/s) of the water source formally capture the potential of a site for power generation, and thus MHP system design. They are also the parameters used to calculate the theoretical hydraulic power available. Higher head and higher discharge indicate higher potential of power generation.

EP is formally trained and knows this theory. For example, in order to increase the power to be generated at a site, he fine-tuned the design by changing the location of the reservoir (forebay) tank to increase the head.

> *“... it generates 18 amps of current. 18 amps. So 18 amps into 250 is how much? How much does it come to? Which is slightly less than 5 kiloWatts. So I told them that you raise structure by 2 feet more so this [power] generation will be equivalent to this. 5 .. in 5 .. it will reach 5.. so it is acceptable for us.” [161228_001.28]*

While exploring the simulation, he experimented with various values of the reservoir height and the nozzle diameter, effectively varying the water head and discharge, to find out the power generated in the virtual MHP system. He talked of the head variation as 'velocity control'.

> *“Can anything be changed with the Velocity control?” [161227_009]*

This indicates that he was viewing head as the stand-in, an implicit indicator and control, of the velocity of water: $v = \sqrt{2gh}$. (This derives from the principle of conservation of energy, which states that the Potential Energy PE of water converts to Kinetic Energy KE as it descends from a head of 'h' meters, with a velocity 'v' m/s. This equivalence is given by the theoretical equation $2mgh = mv^2$, where 'm' is the mass of water in kg, and 'g' is the gravitational acceleration in m/s^2).

Simulation Tasks 3 and 4 show that he used these equations, and made calculations, to arrive at the answers. While he did not seem to bring any numeric values of head, discharge, and generated power from his real world sites to tally with the task values, he applied efficiency considerations to his answers.

As the system feedback indicated surplus power generation, he commented that he had assumed 100% efficiency in the calculations, and may be considering it 80% would give the correct answer. He was perplexed when the system kept showing either a surplus or a deficit, but not an exact answer. He explained it as the system showing settings taken from some very exact real world system.

> *"Sometimes a little surplus and sometimes this. Why have you designed like this? This seems like modeled on some very exact machine. This is designed on the basis of some exact machine." [161227_009]*

If his sense of head, discharge, and power is to an extent embodied, he did not bring it to this numeric task, and approached it in a textbook manner, keen to derive an exact and accurate answer. He thought that using the exact value of gravitational acceleration ($g = 9.8$ m/s^2) instead of the ball park value of 10 may get the accurate answer.

> *"I'll change this.. I have been using the value 10, which we shall generally do. Let me do that. Let me use 9.8 in this. Then it will be better." [161227_009]*

Despite using equations to calculate the theoretical hydraulic power, he made it clear that the design of the MHP system will define the power generated, and not the head and discharge.

> *".. this will depend on your turbine and alternator configuration. There's no set rules like this, that you have height and you have flow rate this much, I'll give you so much of power. Alright? So umm I disagree with this." [161227_009]*

Some such complex aspects of his design, beyond head and discharge, indicated from his other interactions with the simulation, as well as from his interview data, are further described.

In the simulation Task 2, he noticed the month as February, and immediately commented,

> *“Okay so now less water is available. The same components will still run.” [161227_009]*

In the sub-Himalayan mountain ranges where he builds MHP systems, water streams receive rain water from July to September - the Monsoon season, and from snow melt in the summer. But in winter months, the streams are lean. Because of such seasonal variation in discharge, EP prefers to look for high head sites. These support power generation even when the discharge dwindles in lean season. Even low head sites work, if the seasonal variation in discharge is minimal. But such sites are few, and low head sites suffer poor power generation during low discharge periods.

> *“.. there are turbines in low head, it is not as if turbines are not there. But there are the problem of part flows.. that you designed for 80 or you are running it for 100 liters.. okay? In the lean season, it might drop to just about 20 liters. At 20 liters, the efficiencies are very low in turbine.” [161227_001]*

In order to get sufficient idea of parameters such as seasonal discharge variation, EP refers to various maps, charts, and graphs by Survey of India. These include the hydrological charts of data collected over decades. But EP mentioned that he also talks to the villagers, conveying the kind of sites he prefers, and surveys the sites they suggest.

He collects valuable information from the villagers, who, he asserts, are also 'thinking', and who know the 'real situation'.

> *"they are good sources of information to us. So that helps us also in planning.. don't build it here, this had flooded once, make it over there. <>*
>
> *They'll tell you also that this land may be available [na]." [161227_005]*

He needs to translate some of their descriptions to extract useful information. But some inputs may remain vague.

> *".. he does not understand velocity part. He understands this volume of water is available. So two inch water can be moving like this, or two inch water can be moving like this. [show with his hands]. There's a big difference between the two." [161227_005]*

EP does not rely solely on the maps, graphs, and second-hand data about the sites. He needs to see for himself before finalizing any site.

> *"After assessing the site condition, only then we'll feel you know, that we can do something here." [161227_005]*

He may not measure the flow every time, but makes it a point to gain an embodied sense of the seasonal variation in the flow and discharge of water at a site by visiting it whenever he happens to be in the region.

> *"Actually.. actually, you should assess it for one year. So when we discuss a site, we keep visiting, observing. You have that site in mind, and you know how much water is flowing.." [161227_005]*

He gathers invaluable information about the water source and the potential power generation through observing any traditional mill already running on the water.

> *"How much water is available.. what is it doing? Is a water mill running on it? Ya.. so that gives lot of ideas, that with this much of water, this will run, more than that will not run. So that is one thing, you have learned that there is some potential here." [161227_005]*

Apart from the potential of water, EP also wants to get an idea about the motivation of owner of the mill and other individuals interested in building an MHP system. He needs to check the legal aspects of land ownership, sharing, disputes, and availability of land for an MHP system at the site.

> *"Whether he [owner of the traditional mill] is interested or not. Alright? Whether he has enough water or not? If you have gradient, means you have to do something with channels.. whether he is interested or not.. in this or not? Or he wants to run on the basis of Self-Help group. As of now you don't know what it is like." [161228_001.7]*

> *"Then there are some other issues, such as, land or water issues, there are disputes, you stole my water.. it is your water.. my water, it's my property, and so on. You will need to verify all that at the site." [161228_001.22]*

EP also talks to the village elders in case they have memories of any undocumented but out-of-the-ordinary events such as major floods in the water stream. He needs to know the flood lines, to build the system out of harms way.

> *"Floods will definitely give a lot of water, but they are also prime cause of damage. <> So…thinking of flood is most important thing during power station. <> It is better to go slightly away from the river but not so much that you are loosing the [na] head also.." [161228_018]*

Despite the exhaustive effort, it is not always possible to gain sufficient information.

> *".. sometimes we are unable to survey field properly, you know. We expect so much of discharge will come but discharge is not there. These things are the most complicated of all. <> and with climate change, everything is changing, isn't it? So .. you expect a certain amount of discharge, but discharge is not available there, then what will you do?" [161228_005.4]*

But EP also considers another aspect when he looks up a site: what income generation activities exist or can be supported in its vicinity.

> *"First thing is whether there is a potential for generation of electricity or not, first thing is that. Then what is the potential, total potential? Then what potential we can utilize in the village? Is it over that or it's less, that we work out later. If it is over, try and put it in grid or do whatever you want to do. If it is less, you minimize certain activities, at least some comfort is there in the village." [161228_002.2]*

A2.3.2 Design of the civil structure

Textbooks document the need and ways to minimize friction in the water channel. At the same time, EP needs to think about getting it constructed using local labor. So he designs a rectangular shaped channel for minimum friction, which is also easy to construct. He does not aspire to make it very sophisticated, but ensures that the slopes are as required.

> *"You might have seen other trapezoidal kind of channel like this, you might have this kind of channels pentangular channel or you have seen triangular channel, so they have different frictional coefficients. So you decide according to that."*
>
> *"We build only rectangular channel because it is easy for people to make it." [161228_002.4-10]*
>
> *"Not to loose 'head' in the channel, that is important." [161228_018]*

EP designed the settling chambers, without which silt would damage and stop the turbine. There were detailed experimental reports by Central Water Commission (CWC) with respect to silt size, water velocity, and the design of chamber required for silt settling. But EP designed his chambers such that they were sufficient for his sites, though not highly accurate. He used his judgment, developed on the basis of the experiments he conducted himself.

> *"We have done it at an approximate level, we have not done it on a very scientific basis. <> We have done this for large particles, they have done it for very fine particles.<> Actually these are all old experiments I have done. So we have seen that particles with size less than 1-1 settle down. But exactly how smaller than 1-1 settle down I have no idea." [161228_001.53-60]*

EP prefers to design the pipeline (penstock) such that the velocity of water through the pipe is limited to three liters per second, to avoid friction losses.

> *".. in the pipe, we don't allow speed more than.. Don't allow more than three liters per second. The flow should not be more than that.*
>
> *.. when water flows and when water flows in the pipe, the velocity [at] contact is almost zero.. zero. The velocity only increases in the middle. Velocity will be the highest here, and here it will be very low. So what we do is, by reducing this we actually run like that. You are running water like this." [150410_013]*

“In the pipe, [it] actually needs to be kept to 2-3 meters [per second - velocity]. Two or three meters [per second - velocity]. It is not very high precision. But the bigger [diameter] pipe you use, the more advantageous it is. Your losses are reduced.” [150410_013]

“You have to select the pipe size. Then the experience shows and also the books say that the speed of water in this should not be more than three meter per second. If it is more than that, there will be losses, head losses in that. So you try to keep that, 3 meters per second.” [161228_002.28]

“We design always for the peak highest load…it is up to you to shut down some water, very easy to do that, so always think of big.” [161228_018]

“You do have to make the actual calculations and see. <> But normally these [pipelines] are oversized. Generally are oversized. And if you want to add on later, then you have the [capacity for] power available. I.. I go by this principle.. [na]. <> And plus bearing life is high. Because changing the bearings is a very big problem. Only an experienced person can change the bearings. Otherwise a lot of people you know, they hammar bearings, they ruin bearings, actually [na??] the bearing. <> And bearings are very expensive.” [150410_013]

A2.3.3 Design of the turbine and other mechanical components

EP finds it easier to control the design of a turbine than the design and costs of the civil construction.

“See, if you see the cost of the construction, if cost [conception?] is very high, then you avoid it, if you work in machine then cost are lesser actually. <> We work better on turbine and nozzle rather than [channels]” [161228_018]

The role of a turbine runner/wheel is to convert the kinetic energy of the water jet into maximum possible RPM of the turbine shaft. For EP a turbine does its role best, without wasting much energy of the jet, when its design satisfies a thumb rule about the density (number) of blades on the runner.

“.. see you have to have a minimum number of blades on the wheel.” [161228_011]

“All turbines have this. This is a standard principle, that a jet should strike three blades, not more than that.” [150410_010]

A Cross flow turbine is easier to standardize, as he can modify it by changing the width, while keeping the diameter large enough to accommodate different blade lengths. This he cannot do with a Pelton turbine, where changing a blade changes every other parameter specification.

> *"You need to change the whole design <> Pelton especially you change the blades and everything changes." [161228_004.2-4]*

> *"But cross flow you get standard things, 30 m umm 300 mm dia, 400 mm of dia.. of.. in that.. thing is that .. either you have this width or that width. So that's easier actually. Cross flow that way is easier. So it's a width change only. The umm.. your basic .. angles remain the same.. so.. you should have a good dia actually, it should be able to take all the blades.. small.. big ones." [161228_004.6]*

EP designs with more than one pulley for coupling the turbine shaft and the alternator shaft, as otherwise the strong rotational forces acting on the shafts damage the shaft bearings very fast.

> *".. your turbine should not be, you know, connected by single bearing eh single pulley.. pulley, actually. You should have one pulley in the hinter.. in in between. And the shaft should actually run the alternator by coupling. So you.. you tend to avoid, umm you know, damages to the bearings of alternator. <> Because there are such heavy forces when you are using belts, that the bearing tend to get spoiled very quickly, in the alternator. And if alternator gets damaged you have to get somebody from outside, you know, for the repair of the alternator. And that is very expensive." [150411_004]*

> *"The most important component is RPM, you should raise RPM to 1500 for alternator. Okay? Your turbine.. turbine gives you some RPM, isn't it? You have to make a match with this. Okay? You have to find out its pulley ratio." [161228_002.54-60]*

> *"You know the.. actually contact angle on the pulleys should be good. If the contact angle is not good, then there is slippage actually. So you lose lot of power in that. So that's why we prefer high RPM..." [150410_001]*

> *".. normally we prefer a ratio 1:3. If you are able to run a turbine at 500 RPM, then three times, 1500 is alright. But if you go beyond that, then there is lot of slippage in the belts." [150410_001]*

EP knows about gear box as a sophisticated coupling device to transfer the turbine shaft rotations to the alternator shaft. But he also considered the faster wear and tear of gears, and the accessibility, availability, and affordability issues in remote areas. So he preferred to use belts and pulleys in his systems.

> *"If it's a major issue.. if it's a big problem, then you need to go for a gear box.. otherwise you.. you can manage with this. Actually there are lots of losses, the more you use gears, the more are your losses. <> Belting is the best system.. belting is the best.." [161228_002.54-60]*

He reiterated this thinking while exploring the simulation interface. He checked the performance of both the gears and the pulley, and then selected pulley.

> *"I don't want to put the gear box." [161227_009]*

> *"Actually you can put both [i.e. either]. There is no problem. You can use both. <> Umm normally, don't use gear box, because of wear and tear. Normally it's a belt-driven." [161227_010]*

> *".. big wheel gives a small RPM, small wheel gives you a big RPM.." [161228_011]*

> *"...we can use umm permanent magnets... permanent magnets, alternators, which gives some voltage... alright?" [161228_002.100]*

> *"In three-phase you have the advantage that you can run a big machine, it is more efficient. Three-phase energy is more efficient than single phase. But for three-phase, you need to generate bigger power. You need a power station of at least 10 kW." [161228_015]*

In the simulation Task 3 (numeric), he set the head to 20 m, (the system limit was 15 m). He then set the discharge to 60 LPS. The system feedback indicated that he was generating 1953 W more than the required 3000 W. EP commented that the simulated system seemed to have assumed a high efficiency, while he set values assuming only 50%.

> *"it has calculated the efficiency on its own. Excess power? <> actually the power this generates.. at 100% efficiency. Okay? So.. if you want to have a good turbine, it can produce at.. what I had given.. <> So I had given it on the higher side actually. It was at 50.. 50%. This is even higher efficiency ratio used.." [161227_009]*

He understood the problem situation as: the components of this simulation system are designed with a high value of efficiency, so it generates more than 3000 W for the 15 m head and 60 LPS discharge values he set. But in real world, he explained that such efficiencies are not likely.

> *"For proper engineering designs, you can get above 80% efficiency. Okay? If your alternator is also very good, their combined efficiency can go up to 90%. Combined efficiency. But if these are non-engineering designs.. the ones we have.. you are not following all your clearances and all that and that, you can have a turbine giving you about 60% efficiency. And normally these generators are 80-85% efficient. So total you get up to 45 to 50 % efficiency. This is the difference actually. If it is a very finely designed turbine, then it will give you 85-90%. And if it is not, then it gives you anywhere between 50 to 70 %. This is the difference between the two." [161227_009]*

He also preferred to build robust systems.

> *".. the sliding portion, movement of valves. It should be easy, umm because, people tend to, here, apply a lot of force. They tend to break a lot of things, actually. So there has to be proper stoppers with warnings. Don't extend this, don't do that." [150411_004]*

A2.3.4 Design of electromagnetic and electronic components

> *".. it helps in maintaining umm you know.. the speed of turbine. It can control a lot of things actually. I'd say in controlling. If your.. there is a lot of switch On switch Off regularly, you'll be able to stabilize things. That's why flywheels are used. <> If flywheel was not there.. Then there'll be lot of fluctuations." [161227_010]*

> *"Now here we are using 10kW energy.. now what happens.. this is at 1500 rpm. Now if I switch it Off, and its running at 4kW. Now you are getting the same energy from the water. Okay? So what happens, this system will start running very fast. This system will go to 200 rpm. If it runs at this.. system.. your alternator is spoiled. <> So either you cut off water. This is one system. Number 2.. number 2 is you have electronic load controller. <> This is automated. It.. has.. It keeps on sensing the rpm. So it just works like this nozzle. .. But those are very expensive systems. <> That is called governing system actually. Mechanical governing system. <> Just as your speed increases, speed goes up, frequency goes up. Okay? So when that frequency.. frequency is easy to sense.. very easy in digital systems. .. It will switch On a coil, the power going to your load circuit, instead it will go to the coil. .. So it will balance, it will compensate." [161227_010]*

> *"Fly wheel is important, fly wheel is actually umm you know brings a steady state. <> When you are using a controller, it is an asset to a controller. <> It is not to be too much of variation. It stabilizes. It is required in every turbine, flywheel." [161228_006]*

> *"Actually, when you are running a power station, you can't be sitting there all the time. You don't want that, you want it to run automatically. So this all is designed/built to make it automatic." [161228_008.32]*

“Load controller.. earlier we did not have good load controllers. So there used to be a lot of [shunting]. There used to be a lot of up and down, fluctuation. Then slowly we.. we developed from elsewhere. Now this one is perferct. <> But the load controllers are rather expensive as well..” [161228_008.26]

“This means it should give 30 kW. But what you actually do is design for a slightly higher value. Generally. When you design for a higher value, it gives more safety. So instead of 30, you will make it for 40.”

“If you don’t want to invest, don’t want to add a controller.. many systems don’t. <> So these other kind of alternators are there.. alternators with brush, they take some times quite a lot of fluctuations. <> Normally where you don’t have a load controller, you use an alternator with brush. But then you can't connect it with grid. You cannot have grid connectivity, it is fine for the local area. <> In some aspects it is good for local systems.” [161228_008.30]

A2.3.5 Summary of observations across design considerations

This description of some of the key areas of EP's embodiment and detailed design indicates how changes to need identification trigger changes in all the stages of the design process. It would not be possible for a EP to arrive at appropriate design decisions at the component level, if the larger perspective from his need identification and problem formulation was not connected with the later design stages.

The following salient points emerge from EP's design considerations:

1. EP's detailed design considerations are not based on purely formal techno-scientific knowledge, nor are they exclusively numeric or quantitative. Despite formal training, he often uses thumb rules or trial and error methods.

2. EP's design considerations are qualitative, where the technical, material, and social are intertwined in his decision-making and thinking. His repertoire of alternatives to select from is thus diverse and largely comprehensive.

3. EP combines his formal, experiential, even heuristical knowledge. His detailed design of components indicates that even where formal knowledge is used, the design decisions are not purely based on technical criteria such as input-output efficiency or technical sophistication. Where the conceptual design is guided by formal concepts, the embodiment and detailed design are a result of the interaction (= combination = imagination) of the formal, experiential, and eco-social considerations, down to the last detail. Without this, it would not be possible for him to innovate and provide solutions that meet the real grassroots requirements.

Appendix 3: Data Collection Tools

Data were collected empirically, to trace/probe the grassroots innovators' design and thinking processes. This was done using interviews (narratives/semi-structured), and observations (of their artifacts/representations as well as the simulation interface).

A3.1 Generic interview questions for the grassroots designers

1. What did you do? What did you do first? What did you do after that?
2. What happened then?

A3.1.1 Semi-structured interview protocol for the first round

1. In what way was the problem bothering you, and when did you first notice it? (Any specific incident, or person who pointed out something causing you to notice?) What did you think at that time about it?
2. Can you draw for me what came to your mind as the idea then?
3. Do you recollect what made you think that there could be a technological solution to the problem?
4. Does any part of your routine work bring you in contact with the things you used in the innovation? How will you describe these things?
5. Did you share /discuss your solution/idea with anyone who could understand it? Why did you think they would/not understand?

6. Did anyone assist you in creating the innovation? How did you tell them exactly what you wanted to make?
7. Can you take me through the various stages of creating your innovation in detail? What were the tough parts? What did you do to get over those?
8. Can you show me drawings of the stages, or discarded models or parts? Can you tell me how and when you changed the design?
9. What did you already know about the technology you used? How?
10. What did you have to learn new? How did you learn it?
11. What steps did you initially think were involved in the innovation? Was there any change after you started? Why?
12. Did you make any other things before? Or after?
13. Did you actually want to use a material which you could not? Why?
14. Did you help NIF in finding other innovators? How do you do it?
15. Is the innovation patented? Why?
16. Has anyone licensed the patent?
17. Has anyone started commercial manufacture?
18. Have people adopted the technology?
19. Has anyone modified the innovation?
20. Do you feel comfortable with 'technology' or 'machines'? Why?
21. Do you see your innovation applicable in other situations or problems?

A3.1.2 Probing interview protocol for the simulation tasks

1. How did you find the experience of working with this simulation and tasks? (Suggestions, queries?)
2. Do you usually start designing by keeping in mind the available water or required power or something else? How do you decide about that?
3. Do you aim for getting the maximum speed of the turbine wheel from available water or for something else? Why?
4. How do you know how much electricity you can generate, and what does it depend on? Do you try to maximize it? How?
5. Do you generally prefer to modify the turbine parameters, the generator, or some other components? Why?
6. In what ways was this simulation close to/different from the actual systems you work on?

A3.1.2.1 Components - specifications

1. Were any critical components missing here? Could you elaborate on the components and

   devices that were important to your design and why?
2. Which one of belt pulley/gears do you prefer and why?
3. How do you decide on the specifications for the various components? Did it change from task

   to task?

i. Turbine type, diameter, width, number of blades, shape of blades, angle of blades

ii. Nozzle placement, angle, diameter, control mechanism

iii. Nozzle jet and number of blades hit

iv. Generator type, size

v. Load variation control mechanism

vi. RPM required for generator and pulley/gear ratio

vii. Any other/missing

4. What would you prefer to change about the components or their specifications, if you had the

   choice here?

A3.1.2.2 Efficiency - Calculations - Units

1. What will be the efficiency of your system, and the efficiencies of various individual components?
2. Are you satisfied with this efficiency, or you prefer more or less? How will you change the

   efficiency for more or less? Which components will be you focus on to do that?
3. What calculations did you need to do for these designs? Do you generally work with measuring units in meters and liters or any other?
4. What are the design considerations when there is seasonal variation in available water?

(Based on Task 2/4).

A3.1.2.3 Consumption/load

1. What was important while choosing the devices and number of houses? Are any typical

   devices missing here?

2. Did you design for peak load power or average power, and why? What were your assumptions about consumption? (Based on Task 1 /3).

3. What do you do with the surplus power, if any?

A3.1.2.4 Maintenance/repair

1. How do you take care (while designing) of the system stability/sturdiness and wear and

   tear?

2. Which of these components are usually more likely to need repair? Who will be able to repair

   them and where?

3. Were your choices of components and devices based on the availability or expense of spare

   parts, repairer etc?

A3.1.2.5 Cost

1. What is the likely cost of this kind of system when built as per your design?

A3.1.2.6 Fluid dynamics/electricity sense

1. (Whether he thinks of potential energy, transformation of energy etc, how he imagines water

   flow and its relation to the turbine design.)
2. Would you change the settings if the bucket size is different? How?
3. Would it be possible to improve performance by redesigning the angles of the buckets?
4. Is there some way to reuse the power of the water after it hits the bucket?

A3.1.2.7 About the task actions

Task 1:

1. When do you try for more height/water flow/control on water? how?
2. Could you describe your turbine/generator?
3. Why do you use/not the flywheel? heating coil?
4. Is anything missing in the components provided?

Task 2:

1. Why did you set these gadgets/this number of houses?
2. To get more power with this water, which components or specifications need to change?

Task 3:

1. Which gadgets?

Task 4:

1. Which gadgets and how many houses?

A3.2 Generic observation points for field visits to GRI, EP

1. Working methods in the workshop, with customers, trainees.
2. Time spent in various places such as home, workshop, other people's places, market, junkyards, teaching others, scouting for or sharing with like-minded people/innovators, as experts, tinkering, discussing problems, drawing.

A3.2.1 Additional observations points

1. What are the constraints and assumptions he is working with?
2. Which options did he consider, and which ones did he reject? Why?
3. Which things did he need to estimate? How did he estimate?
4. Did he need to measure anything? What methods did he use to measure things?
5. Did he make any mistakes, and did they lead to any changes to the design?
6. Can he describe each part in detail, and its role? Also what else did he try in that place earlier?
7. Why did he get an idea after a particular stage of the product/design/drawing, and not before?
8. How did he check if the design was good? Did he test? What methods did he use for testing?

9. Did anyone other than him try to use it, and did he learn anything from that?
10. How does he teach this process to an apprentice?
11. Does he seem to plan for quick, inexpensive failures to learn fast and avoid loss of time/effort?
12. Is his creativity not hindered by rote learning?
13. If (and how) is his intuition built through years of heuristics from hands-on experience?
14. What were the non-formal avenues of gaining knowledge for him?
15. How do his designs fit the situation, what does he modify to customize?
16. Did he construct any special machines/devices to build the innovation?
17. Does he have any notes, notebooks, diaries, correspondence letters?
18. How would his experiences help someone do this kind of things? (Kerala schools with farmers teaching the students)
19. When he goes to ask for info or parts, what or how does he ask about it, phrase his questions?
20. Does he keep the cost factor in mind, and how does it affect his designs?

A3.3 Demographic data

1. Date of birth or age
2. Place of birth
3. Place of education

4. Kind of school and curriculum
5. Father's occupation
6. Age of starting work
7. Chronology of jobs or occupations
8. Nature of current work
9. Innovation that was awarded
10. Year of award
11. Year of starting the innovation
12. Months taken for innovations
13. Major time gaps if any
14. Year of contact with NIF
15. Effect of contact with NIF
16. Effect of award
17. Economic background/annual income bracket
18. Family members
19. Number of dependents
20. Number of daughters
21. Assistants or colleagues
22. About the place and inhabitants

Appendix 4: GR's sample DPRs/invoices

1) 1996 June

INVOICE

No	Particulars		Amount
1	10 K.V. Turbyne (Including alternator)	:	87,000.00
2	Fitting and Service	:	6,000.00
3	Transportation charges	:	2,000.00
4	4" heavy gate valve – 1 No's	:	3,800.00
5	Panel Board	:	3,800.00
6	6mm Mains wire 10 coils	:	6,020.00
7	GI wire – 10 kg	:	750.00
8	UG Cable – 80 mts (10mm)	:	6,400.00
9	Insulators – 100 No's	:	150.00
10	Breakers – 10 No's	:	200.00
11	Change-over switch – 2 No's	:	760.00
12	Service and labour	:	1,200.00
	Total..............	:	**1,18,080.00**
	Amount received as Advance	:	85,000.00
	Balance outstanding	:	**33,080.00**

2) 1999 September

1	30 HP Capacity Turbyne	1,60,000.00
2	25 KVA Alternator (Very low RPM)	85,000.00
3	Transportation charges	9,000.00
4	Fitting and Service	20,000.00
5	Visiting and Supervising charges	10,000.00
6	Penal Board	15,000.00
	Total.........	**2,99,000.00**

1) The above amount is applied only for Turbyne. Additional charges will be separate for all kind of Civil, labour, wiring, Electrical items etc.
2) Generated current will be only for domestic purpose.
3) Work will be commenced from the date of receipt of 80% amount.
4) Project will be completed within 45 days from the date of agreement.
5) Remaining balance due should be paid only after completion of project.
6) The Power Generation Unit will have 1 year of on site warranty.
7) Your are required to provide staying facility for our team members during the period of work.

3) 2004 August

Si no	Particulars	Details
1	Name of the power generation site.	Blue mountain estate
2	Place of the power generation	Rex Khon feeld
3	Capacity of the power generation	25 KVA
4	Capacity of the turbine	35 HP
5	Power generation in volts	440 volts
6	Power generation in amps	15 to 20amps
7	Power generation in wats	10,000 wats
8	Power can be used for	15 HP pump set or 500 CFL lights
9	Power control by	AVR & Transformers
10	Power transmission by	UG cable
11	Source of the water	SB tank - Rex Khon
12	Discharge of the water for power generation	25 LPS
13	Available source in the year	365 Days
	Pipe line	
1	Quality of the pipe	PVC pipe(Phinolex)
2	Size of the pipe	8 Inches and 6 Inches
3	Number of leanthes	25 numbers
4	Gage of the pipe	10 KG
5	8 Inches butter fly value	1
6	Plange and fittings	

4) 2006 December

DETAILS OF PROJECT REPORT

1	Capacity of Power Generation	10 K.V.A
2	Height of the source. (Vertical head)	100 pt.
3	Water discharge in (L.P.S)	15 L.P.S
4	Volts	200-220 Volts
5	Amps	8-10 amps
6	Transmission line	U.G.C or Open line.
7	Power house	10 X 8 by sheet roofing

PIPELINE AND OTHER METERIALS

1	6 inches 6 kg pressure pipeline PVC Pipe 25 lengths or 6" 6 kg pressure 150 mts long pipe HDP Pipes	
2	6" Butterfly valve	
3	6 amps 2 core UG Cable 150 mts	
4	5 Bags of Cements	For Turbo structure fitting with concrete bed.
5	30 Bags Sand	
6	25 Bags Crusher	
7	10 x 6 AC Sheet – 4 No's for Power House	
8	1200 Bricks , 10 Bag Cement, Roofing materials, 1 Door and 2 Windows ; These materials are for Power House.	

5) 2010 March

Si.no	Particulars	Amount
1	5 K.V capacity turbine (customized design) Including alternator 240volts	90.000.00
2	Transportation charges	2000.00
3	Fitting and service	4000.00
4	Penal board	4500.00
5	U.G. cable 30.mtrs. 10amps	2400.00
	Grand total	1.02.900.00
	One lack two thousand rupees nine hundred rupees	

Note: The above project report excluding pipe line, civil wiring and etc….. charges. Pipe line and civil work is to be done according to our suggesting for the better prospectus and success of the proposed power plant.

6) 2011 July

10 KW Turbo		
01	Capacity of the Turbyne	10 KW
02	Capacity of Power Generation	7 KW
03	Design of the Turbyne	Giant Wheel Turbyne
04	R.P.M	500 RPM
05	Discharge	15 LPS
06	Transmission	UG Cable
	Power Generation of volts	240 volts

EXPENDITURE

01	10 KW Turbyne with alternator (Low RPM)	1,65,000.00
02	10 Inches H.D.P Pipe 300 feet – 380 Rs per Feet	1,14,000.00
03	Panel board	6,850.00
04	Fitting and service	6,000.00
05	Transportation charges	5,000.00
	Two lakshs ninety sixes thousand Eight fifty only	**2,96,850.00**

Note: 1. Above mentioned rates are applicable to mechanical work.
2. The civil work / labour work will be charged extra.

Conti.

7) 2011 October

PROJECT COST DETAILS

MECHANICAL PART			
1	10 KV Turbyne including Kirloskar make alternator .	:	1,60,000.00
2	10 KV Transformer	:	45,000.00
3	Panel Board	:	15,000.00
4	Voltage Control (AVR)	:	30,000.00
WIRING AND LIGHTS			
5	Wiring to 100 points	:	40,000.00
6	100 CFL Lights (10 watts each)	:	25,000.00
7	Street lights 10 No's	:	15,000.00
TRANSMISSION LINE			
8	10 amps 2 core UG Cable – 3500 mts (@Rs. 85/- per meter)	:	2,97,500.00
PIPE LINE			
9	4 inches 6 KG PVC Phinolex pipe 350 No's (@ Rs. 1050 per length)	:	3,67,500.00
10	6 inches 10 KG PVC Phinolex pipe 25 No's (@ Rs. 3170 per length)	:	79,250.00
11	2 inches 4 Kg PVC Phinolex pipe 400 lengths @ Rs. 385/- per length. [for drinking water supply]	:	1,54,000.00
12	Air-wall 10 No's	:	15,000.00
13	4 inches Gatewalve – 2 No's	:	7,500.00
14	6 inches Gatewalves – 2 No's	:	8,400.00
15	PVC Gum and Pipe fittings	:	8,000.00
CIVIL WORK			
16	Trench work (3/1) 3500 mtrs (@ Rs. 30/- per mtr)	:	1,05,000.00
17	Trench work (2/1) 4000 mtrs (@ Rs. 25/- per mtr)	:	1,00,000.00
18	1 / 1 Cable trench work (@ Rs. 10/- per mtr)	:	3,000.00
19	12 x 10 x 5 Tank	:	60,000.00
20	12 x 8 power house	:	75,000.00
21	Pen stock channel	:	40,000.00
COMMISSIONING AND ERECTION		:	15,000.00
METERIAL SHIFTING – By head load		:	18,000.00
TRANSPORTATION CHARGES		:	12,000.00
	NET EXPENSES..........	:	**16,95,150.00**

8) 2012 June

PROJECT COST

SI. No	Particulars	Amount
01	5 K.V Capacity Turbine (Customized design) including alternator 240 volts single phase	90,000.00
02	Transportation Charges	2,800.00
03	Fitting and Service	2,500.00
04	Penal Board	2,300.00
	Total………	**97,600.00**
	(Ninety seven thousand and six hundred only)	

The above project report excluding pipe line, civil works, wiring and etc., charges. Pipe line and civil work is to be done according to our suggestion for the better prospectus and success of the proposed power plant.