Applications of Design For Value to Distributed Solar Generation in Indian Food Processing and Irrigation

by

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B.S., Franklin W. Olin College of Engineering (2012)

Submitted to the Engineering Systems Division
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Abstract

Solar panels are not installed on an off-grid farm to save on home energy bills. Those systems are installed to enable communities to do activities that they could not do before. This thesis studies the application of design for value to distributed solar energy systems by considering how the energy system will enable new income generating activities. The work here couples business and energy models to optimize with value as an objective function. The interaction between energy production and value creation is complex, so multi-objective optimization is used as a tool to explore the design space and analyze the feasibility of such projects. This methodology is practiced in two case studies. One case study considers the design of a solar irrigation pump that is specifically designed for marginal-holding farmers in east India. The other case study analyzes the feasibility of small-scale concentrated solar powered (μ-CSP) food processing with an organic Rankine cycle (ORC). In both cases, preliminary economic feasibility is established with the use of analysis by optimization and design for value. It was found that a solar pump could be produced which costs less than 500 USD cap-ex and meets 99% of a marginal-holding farmer's water demand. The solar food processing analysis showed that a system could be produced which costs 29,000 USD with a 15-year NPV of 33,400 USD at a discount rate of 18%. The programmatic tools that are used to explore this design space include genetic algorithms, pattern search, adaptive weighted sums, and Pareto fronts.

Thesis Supervisor: Olivier L. de Weck
Title: Professor of Aeronautics and Astronautics and Engineering Systems

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My family has been my earliest and most important teammates. Mom, Dad, and Julia - thank you for everything that you have taught me, and everything that you have done over the last 25 years to help get me to where I am now.

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A few dozen development practitioners and companies took the time to help me understand how technology and design can be useful in development. Thank you for believing that spending your valuable time with me might one day be helpful to the world. This thesis is my first (and definitely not the last) attempt to make good on your belief. Most notably, thank you PRADAN and STGi for taking the time to share knowledge and make this work possible.

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Nomenclature

Δh_{HTF}	Change in specific enthalpy of the HTF	$\left[\frac{\text{kJ}}{\text{kg}}\right]$
$\dot{V}_{ORC}$	Volumetric flow rate of the ORC working fluid	$\left[\frac{\text{m}^3}{\text{s}}\right]$
Δh_{tank}	Change in specific enthalpy of the HTF storage tank	$\left[\frac{\text{kJ}}{\text{kg}}\right]$
ΔP	Pressure drop	[Pa]
ΔP_p	Pressure change across the ORC pump	[Pa]
ΔT_1	Temperature difference between flows on one side of the vaporizer	[C]
ΔT_2	Temperature difference between flows on the other side of the vaporizer	[C]
ΔT_{HTF}	Temperature change in the HTF through the vaporizer	[C]
ΔT_{ORC}	Temperature change in the ORC fluid through the vaporizer	[C]
$\Delta T_{tank\ wall}$	Temperaure difference across the tank wall	[C]
$\dot{m}_{\text{air}}$	Mass flow rate of air across the condenser	$\left[\frac{\text{kg}}{\text{s}}\right]$
$\dot{m}_{\text{HTF}}$	Flow rate of the HTF	$\left[\frac{\text{kg}}{\text{s}}\right]$
$\dot{Q}_v$	Heat flow in vaporizer	[kW]
$\dot{Q}_{\text{cond}}$	Heat flux across the condenser	[kW]
$\dot{Q}_{chiller}$	Heat taken from the HTF to run the chiller	[kW]
$\dot{Q}_{cool}$	Heat pumped out of the chilled storage	[kW]
$\dot{Q}_{in}$	Heat flow into the collector	[kW]
$\dot{Q}_{out}$	Heat loss from the collector	[kW]
$\dot{Q}_{walls}$	Heat loss through the tank walls	[kW]

$\dot{V}$	Volumetric flow rate	$\left[\frac{\mathrm{m}^3}{\mathrm{s}}\right]$
$\dot{V}_{\mathrm{air}}$	Volumetric flow rate of air over the condenser	$\left[\frac{\mathrm{m}^3}{\mathrm{s}}\right]$
$\dot{V}_{daily}$	Daily volume of water lifted	$[\mathrm{m}^3]$
$\dot{V}_{HTF}$	Volumetric flow rate of the HTF	$\left[\frac{\mathrm{m}^3}{\mathrm{s}}\right]$
$\dot{W}_{\mathrm{el,fans}}$	Parasitic power draw of the condenser fan	[kW]
$\dot{W}_{elp\ HTF}$	Parasitic power draw of of the HT	[kW]
η_m	Motor efficiency	[%]
$\eta_{collector}$	Collector efficiency	[%]
$\eta_{ORCpump}$	Efficiency of the ORC pump	[%]
η_p	Pump efficiency	[%]
Cp_{HTF}	Specific heat capacity of the HTF	$\left[\frac{\mathrm{kJ}}{\mathrm{kgC}}\right]$
GHI_{daily}	Daily global horizontal irradiance	[kWh]
μ	Dynamic viscosity	[Pa s]
μ-CSP	Micro Concentrated Solar Power	
ω	Rotational velocity	$\left[\frac{rad}{\mathrm{s}}\right]$
ϕ	Angular position within the volute	$[rad]$
ρ	Density	$\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$
τ	Torque	[Nm]
θ	Zenith angle	rad
A	Heat exchanger surface area	$[\mathrm{m}^2]$
A_{cx}	Volute cross-sectional area	$[\mathrm{m}^2]$
b	Battery life constant (y-intercept)	[-]
D_{pipe}	Pipe diameter	[m]
dt	Time-step	[s]
E_{panel}	Daily panel energy production	[J]

E_{pump}	Daily pump energy consumption	[J]
f	Friction factor	$[-]$
I	Electrical current	[A]
I_{normal}	Normal irradiance	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
k	Tank wall thermal conductivity	$\left[\frac{\mathrm{W}}{\mathrm{mK}}\right]$
K_t	Motor torque constant	$\left[\frac{\mathrm{Nm}}{\mathrm{A}}\right]$
K_v	Motor speed constant	$\left[\frac{rad}{\mathrm{Vs}}\right]$
L_{pipe}	Pipe length	[m]
$L_{segment}$	Length of the collector segment	[m]
$life_{system}$	Functional life of the solar pump system	$\left[\frac{years}{system}\right]$
m	Battery life constant (logarithmic slope)	[-]
$N_{cycle\ life}$	Number of cycles in a battery	$\left[\frac{cycles}{battery}\right]$
N_{cycles}	Number of battery cycles in a year	$\left[\frac{cycles}{year}\right]$
$N_{replacements}$	Number of battery replacements	$\left[\frac{batteries}{system}\right]$
P	Pump outlet pressure	[Pa]
$P_{turb-in}$	Pressure at the turbine inlet	[Pa]
$P_{turb-out}$	Pressure at the turbine outlet	[Pa]
R	Resistance	[Ohm]
r	Radius of the center of the volute cross-section	[m]
r_d	Discount rate	[%]
r_P	Expander pressure ratio	$[-]$
$r_{SA_{min}}$	The tank radius which minimizes surface area	[m]
Re	Reynold's number	$[-]$
rpm	Revolutions per minute	$\left[\frac{rev}{min}\right]$
$s_{turb-in}$	Entropy at the turbine inlet	$\left[\frac{\mathrm{J}}{\mathrm{K}}\right]$

$s_{turb-out}$	Entropy at the turbine outlet	$[\frac{\mathrm{J}}{\mathrm{K}}]$
SA	Surface area of the tank	[m^2]
t	Tank wall thickness	[m]
T_{amb}	Ambient temperature	[C]
T_{HTF}	Temperature of the HTF	[C]
T_{WF}	Working Fluid temperature	[C]
t_{end}	Duration of the project	[$years$]
$T_{HTF\ in}$	Temperature of the HTF inlet of the vaporizer	[C]
$T_{HTF\ out}$	Temperature of the HTF outlet of the vaporizer	[C]
$T_{ORC\ in}$	Temperature of the ORC fluid inlet of the vaporizer	[C]
$T_{ORC\ out}$	Temperature of the ORC fluid outlet of the vaporizer	[C]
T_{rec}	The recommended operating temperature for the chilled storage	[C]
T_{spoil}	The temperature which causes the chilled storage to spoil	[C]
$T_{tank\ in}$	Temperature at the tank inlet	[C]
$T_{tank\ out}$	Temperature at the tank outlet	[C]
T_{warm}	The warmest acceptable temperature for the chilled storage	[C]
U	Heat transfer coefficient	$[\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}]$
V	Voltage	[V]
v	Flow velocity	$[\frac{\mathrm{m}}{\mathrm{s}}]$
v_w	Wind velocity	$[\frac{\mathrm{m}}{\mathrm{s}}]$
V_{tank}	Volume of the HTF storage tank	[m^3]
$W_{collector}$	Width of the collector	[m]
$W_{pump-in}$	Parasitic power draw of the ORC pump	[kW]
$W_{pump-out}$	ORC pump output power	[kW]
AC	Alternating Current	

AWS	Adaptive Weighted Sum method	
B2B	Business to Business	
BEP	Best Efficiency Point	
BMC	Bulk Milk Chiller	
COP	Coefficient Of Performance	[−]
DC	Direct Current	
DHI	Diffuse Horizontal Irradiance	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
DNI	Direct Normal Irradiance	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
DoD	Depth of Discharge	[%]
E	Energy captured by the battery over its life	$\left[\frac{energy}{battery\ life}\right]$
EES	Engineering Equations Solver	
GA	Genetic Algorithm	
GHI	Global Horizontal Irradiance	$\left[\frac{\mathrm{W}}{\mathrm{m}^2}\right]$
hp	Horse power	
HTF	Heat Transfer Fluid	
INR	Indian National Rupee[1]	
KASAM	Kandhamal Apex Spice Association for Marketing	
LCOE	Levelized Cost of Enectricity	
LED	Light Emitting Diode	
LMTD	Logarithmic Mean Temperature Difference	[C]
MIT	Massachusetts Institute of Technology	
NGO	Non-Governmental Organization	
NPV	Net Present Value	[USD]
NREL	National Renewable Energy Laboratory	

[1] An exchange rate of 60 INR to USD is used in this thesis.

ORC Organic Rankine Cycle

PRADAN Professional Assistance for Development Action

PV Photovoltaic

QA/QC Quality Assurance and Quality Control

SLA Sealed Lead Acid

STGi Solar Thermal Generation international

USD United States Dollars

w_{panel} Rated panel wattage $\left[\frac{W}{kW}\right]$

WS Weighted Sum method

Chapter 1

Introduction

1.1 Philosophical Motivation

"The question is not 'does it work?', but 'what does it make possible?'" Written by Brian Massumi in the translator's forward of Deleuze and Guattari's *A Thousand Plateaus* [8], this take on philosophy describes the approach to engineering systems design presented here.

The study of systems is about turning exogenous factors into endogenous factors with the goal of better designing systems and their subsystems. A natural facet of this work is also in understanding *what* exogenous variables are worth converting into endogenous ones. We do not ask if the machine works, but what the machine makes possible.

This work uses that understanding to better design distributed power systems in the context of their application. The motivation for turning end-use from an exogenous variable into an endogenous one is simple: no one installs a solar panel on an off-grid farm to save on home energy bills. Those systems are installed to enable communities to do activities that they could not do before. In this context, designs that optimize dollars-per-watt or efficiency are still relevant, but they do not capture the entire picture. If an 'efficient' or 'low-cost' set of panels does not provide enough power to turn a motor, they might as well have not been purchased at all.

By making the application of a distributed power system endogenous to the optimization problem, we expand the design space to include the design of that application. This reformulation of the problem both increases its complexity and enables more optimal designs. For example, by considering the constraints placed on a system by distributed energy, it may be more optimal to select a smaller motor for the example in the previous paragraph.

This approach relies on detailed technical and business models. Although this approach requires collecting a wider variety of data and dealing with more complexity, the goal of finding a true global optimum is not necessary. Each iteration of the model only requires the optimization process to find an acceptable design - one that justifies moving to the next stage of refinement. This analysis by optimization does not treat optimization as a means to an end – 'does it work?' Instead, the designer can use optimization to ask 'what can be made possible?' by exploring the relationship between the design and solution spaces.

This thesis is made of two case studies on design for value and analysis by optimization using the above philosophy. The first project is on the design of a solar pump that is specifically optimized for marginal-holding farmers in east India. Current solar pumps used in east India are oversized for individual farmers because they were designed for larger farms with deeper wells. By redesigning the pump alongside the power system, we show that it is possible to create a commercial product that has much fewer capital costs than existing systems.

The second project examines the techno-economic feasibility of micro concentrated solar power (μ-CSP) tri-generation in the context of food processing. It is shown that by optimizing the design of the power generation unit with the goal of profitability, a potentially profitable solar-powered business can be produced. This framework underpins a tool which can be easily modified to analyze similar projects in different locations and sectors.

Of course, there are many factors that affect the viability of both cases which are hard or impossible to quantify. In this spirit, each section includes a discussion of some remaining qualitative and unaccounted for challenges.

1.2 Overview

The rest of this chapter is an overview of the key stakeholders for this work in India. Chapter 2 presents an overview of multi-objective optimization and design for value for solar tri-generation systems. Chapter 3 provides background on both small-scale and solar irrigation before going into the theoretical design of a new solar pumping system. The design process begins with first-order estimates and becomes more refined to the point of including testing a real prototype pump in the design loop. Chapter 4 discusses the design, testing, and field trials of the prototype pump that was specified by the analysis in Chapter 3.

Chapter 5 introduces the CSP tri-generation for food processing case study. It provides a short contextual background on food processing in India, with a recommendation for the use of grinding machines and cold-storage in the final system. Chapter 6 presents the in-depth model of Solar Thermal Generation international's (STGi) μ-CSP system and the business operations that use that power system to operate. Chapter 6 concludes with the single-objective and multi-objective optimization of this integrated system for value. Both case studies demonstrate the value of considering the end use of a solar-power system from the beginning. Both results support this thesis's recommendation to pursue each opportunity on the grounds of economic feasibility and potential for social impact.

1.3 Stakeholder Analysis

1.3.1 Farmers

There are few marginal-holding (<1 hectare) farmers in east India who care about the academic field of optimization. However, every conversation with these farmers and all literature on the subject comes back to the same objective function - cost effectiveness. No matter how well designed or efficient something may be, marginal-holding farmers will not adopt a new system if it does not fit into their finances.

Marginal-holding farmers often rely on agriculture as a source of food. Many land-holding families must work locally, typically as manual labor, for their income. The Mahatma Gandhi National Rural Employment Guarantee Act ensures 100 days of manual labor with wages of 150 INR/day for one member of each household. Other local labor has wages varying between 50 INR/day to 150 INR/day, but is not guaranteed. For those who can travel, migrant labor is another source of income, but the associated overhead costs can consume that extra income.

Farmers that are able to cultivate beyond the needs of subsistence can financially support their families with the profit. Pulses and legumes can be sold for between 20,000 INR and 30,000 INR per acre of production. Vegetables and other high-value crops can be sold for 40,000 INR per acre of production or more. In regions with good market linkages, the amount can be 100,000 INR per acre of crop. There is significant variation in the actual numbers because of market conditions such as seasonal surpluses and market linkages. However, these provide a rough idea of the revenues that this type of farmer would have.

All farmers in India cultivate during the monsoon. In east India, few marginal farmers cultivate outside of the monsoon, but most can harvest for at least two more seasons with the help of irrigation. Transitioning from occasional manual labor and monsoon cultivation to year-round cultivation can significantly increase the well being of marginal farmers. Unfortunately, there are many barriers to year-round cultivation, such as free-grazing cattle, the availability and cost of lift irrigation, delayed capital, uncertainty in the weather, and lack of knowledge. The work done in this thesis on efficient solar irrigation is an attempt to reduce the lift irrigation barrier to year-round irrigation that these farmers face.

1.3.2 Non-Government Organizations

There are many non-government organizations (NGOs) in India. This thesis focuses on the NGOs that work with marginal-holding farmers, either as individuals or communities. NGOs of this type can vary in structure and approach. For example Kandhamal Apex Spices Association for Marketing (KASAM) uses a cooperative model as a member-owned company trying to maximize the profits of marginal-holding farmers in Kandhamal district, within the state of Orissa, through marketing and processing. PRADAN (Professional Assistance for Development Action) works with communities of marginal-holding farmers, often tribal or schedule caste, to help them build market linkages, creating community organizations such as Self Help Groups (SHGs), and increase income through better farming practices. They have been a key partner for this project in understanding marginal-holding farmers and implementing the solar-irrigation pilot. The Vigyan Ashram in Pabal, Maharashtra is focused on developing and piloting different methods for increasing agricultural productivity and then teaching local youth agriculture and animal husbandry practices. There are many variations on these, and other, models.

Although different, all NGOs that are stakeholders of this research aim to improve rural livelihoods with a strong focus on increasing income. They are committed to remaining connected to the communities they work with. These NGOs emphasize the importance of building community structures that will sustain the communities after the livelihood improvement project has finished.

For NGOs like PRADAN, the solar pump work in this thesis appeals to this focus on livelihood because the technology will help the farmers save money and encourage them to cultivate more land. While the NGOs can provide diesel pumps to farmers with poor grid access, paying for the diesel is outside the scope of their work. Therefore the recurring diesel costs cuts into farmers' profits during the rabi (winter) season and discourages cultivation during the dry season, a time when the farmers can make considerable income using proper field management. Diesel suffers from high recurring costs, and current commercially available solar irrigation systems have prohibitively high capital costs. A smaller solar pump will make solar irrigation available to more farmers, and create new ownership models built around greater portability and smaller up-front costs compared to other solar pumping systems. Furthermore, the pump sizing and weather analysis tool that was used to design this pump can be used to analyze other pumps that may be more appropriate in other situations. Both the pump and the solar irrigation system-sizing tool in this thesis are relevant to agriculture-centric NGOs.

NGOs like KASAM and the Vigyan Ashram are both interested in widespread food processing, even in regions where there is a weak electrical grid. The relevance of solar food processing to their goals will be dependent on the operation's ability to enable profitable operations in places where the grid would not otherwise support this business operation.

1.3.3 Solar Thermal Generation international

Solar Thermal Generation international (STGi) is a 501(c)(3) non-profit organization with a lead technical team in Cambridge, Massachusetts. Their mission is "to provide technical, financial, and intellectual support, assistance, and training to projects and organizations focused on bringing sustainable energy technologies to communities across the developing world" [9]. STGi is a 'technology-agnostic' organization which has identified gaps in existing distributed generation technologies. Diesel is costly and polluting. Solar, while cheaper than ever, struggles with the costs of expensive batteries and other balance of systems. To address these challenges, STGi has developed a small-scale concentrated solar power organic Rankine cycle power plant (μ-CSP ORC) with a scroll expander and thermal storage tank, which is inexpensive and relatively efficient at sub 30 kW scales.

STGi has been deploying μ-CSP systems in Lesotho to electrify health clinics since 2006. They are currently developing micro-grids with health-clinics and schools in Lesotho and are considering expanding into other markets, such as India. The μ-CSP ORC modeling, optimization, and framework for techno-economic analysis in this work is intended to help them explore what sectors to enter within the Lesothan, Indian, or other markets.

Chapter 2

Literature Review and Methodology

2.1 ORC Trigeneration Review

The organic Ranking cycle (ORC) is a Rankine cycle operated with an organic working fluid that boils at a relatively love temperature (30°C to 60°C). These low boiling temperatures allow for power to be generated with a relatively low-grade heat (120°C-200°C) source such as low-concentration solar power (CSP) systems and waste heat. The first ORC was prototyped in 1961 by Harry Tabor as a system for converting sunlight into electricity. In the 50 years since its invention, the design of ORCs has grown into a mature field.

While ORCs are well suited for low-heat applications, their efficiency can be limited by the poor performance of turbines at very low power production (< 20kW). Positive displacement machines are better suited to the low flow rate but can be costly. Lemort, Orosz, and others have worked to advance the use of a scroll expander as a low-cost positive displacement expander for sub 20 kW power generation [10, 11]. This thesis builds upon the small scale concentrated solar power ($\mu-$CSP) scroll expander ORC system designed and created by Orosz for generating electricity, heat, and cooling in his doctoral dissertation [6]. Ireland built upon the modeling work done by Orosz in her masters thesis [7].

Al-Sulaiman has also worked on ORC tri-generation. His work analyzes the flows of exergy throughout an ORC with trigeneration. His work presents detailed models and approximations for analyzing tri-generation systems [12, 13]. Al-Sulaiman's analytical approach is similar to the approach presented in this research but stops short of examining energy demand profiles and solar availability profiles. This work builds on his by implementing a full numerical optimization for a given expected load profile with intermittent solar availability.

2.2 Multi-objective Optimization of Distributed Tri-generation Systems Review

The optimization of small-scale solar power generation technologies in the context of a complex system with technical, environmental, and economic factors has been addressed in depth by Nixon et al. The papers presented by Nixon focus on decision-making frameworks such as the Analytical Hierarchy process [14] and Quality Function Deployment [15]. While both methodologies presented in Nixon's two papers are not quantitative, the flexibility of Nixon's frameworks enable the inclusion of qualitative factors in a well-documented and rigorous way. This is important for applications such as rural electrification, where it is primarily the qualitative factors that determine the success or failure of a technological intervention. Nixon's analysis of CSP goes beyond qualitative frameworks. In his 2012 article for *E*nergy, Nixon discussed the feasibility of concentrated solar tri-generation systems based on high-level technical factors [16]. The analysis from Nixon's 2012 article appears to provide a foundation for his other analyses [15].

Thermal systems like ORC's have been optimized extensively. Wang performs a genetic-algorithm multiple objective optimization for an ORC cycle. He generates a Pareto front for both cost and efficiency [17]. While his analysis is highly detailed for the ORC system, it does not include a discussion of intermittency or the nature of a typical demand load. Since Wang is optimizing his system for fossil fuel applica-

Figure 2-1: A hybrid CSP/biomass ORC plant near Pune, India.

tions, he addresses efficiency instead of LCOE (levelized cost of electricity), a critical performance metric when selecting a solar-powered electricity generating asset. M. Ahmadi performs a similar multi-objective Pareto front optimization for the design of a solar stirling dish engine. M. Ahmadi's work digs deeper into economic issues associated with solar power by optimizing across cost per unit energy and the overall efficiency of the system [18]. P. Ahmadi presents a hybrid exergetic-economic driven multi-objective optimization of a fossil-fuelled trigeneration plant. By focusing on the economic value associated with the destruction of exergy, P. Ahmadi's optimization is able to track down the points in the system that can be optimized the most easily by spending more money to reduce entropy production [19].

Clemente has modeled $\mu-$ORC cogeneration systems [20]. He has also worked with Bracco to experimentally validate the $\mu-$ORC model [21]. Technical-economic analysis of solar plants, ORCs, and trigeneration system have been performed at length, but it does not appear that a system containing all of these elements has been examined in this detail outside of Orosz's, Quiolin's, and Ireland's work, one of the projects that this research builds on.

Both types of analysis above provide valuable decision-making and design information. They serve as the foundation upon which the optimization aspect of this research is based. However, none of these papers account for an intermittent power source and load demand. Additionally, with the exception of Nixon's work, none of the analyses above fully integrate macroscopic qualitative issues with detailed technical analysis. One hypothesis of this research is that by building upon Nixon's work and further merging technical and socio-economic factors into the same analysis, a more optimal solution for solar powered trigeneration can be reached.

2.3 Existing Rural Energy/Agri-processing Implementations and Socioeconomic Factors

Many dairy processing cooperatives are very well established in India. The most well known example of a successful dairy processing cooperative is Amul. According to Datamonitor, there are over 100,000 dairy cooperatives clustered in over 170 producer organizations that feed into 15 milk marketing federations [22]. The economics of existing dairy processing facilities in India has been written about. Chauhan et al. examine the economics of milk processing in Haryana, providing a valuable baseline for thinking about the economics of a complete system [23]. The energy requirements for processing milk are analyzed in large facilities. Brush et al. have performed an in-depth analysis of the sub-processes for creating different dairy products and their associated energy consumption [24]. Unfortunately, no similar analysis can be found for a smaller scale rural or peri-rural operation. The most comprehensive energy analysis of a small, Indian dairy processing facility that can be found was performed by Mane out of IIT Bombay [25].

Promethean Power Systems (PPS) has created a milk-chiller which can store energy in the form of a cool thermal mass and access it with a heat exchanger in order to address grid intermittency [26]. The company started out with the goal of creating a solar milk-chilling system for locations in India that need reliable sources of milk-chilling in order to avoid milk spoilage. However, the expense of their product, 12,000 USD, was deemed too great, forcing PPS to pivot, reducing the complexity of their technology by removing the solar unit, and bringing the cost of their system down to 3,000 USD per unit [26].

This raises concerns about the applicability of a solar-powered rural food processing facility. If a system which process about 1-ton of milk/day were to cost 60,000

USD for power generation, the capital expenses could make the operation unfeasible. The proposed system will directly create value for the operating organization, and it is the goal of this research to determine if the value generated by the solar facility is great enough to justify its cost.

Other researchers have looked into the energy requirements of different 'useful' rural processing applications. Weingart et al. provides a well organized overview of how much energy useful rural applications require, and what temperature cogeneration is required for useful processing applications [27]. Solar drying is well suited for low-technology applications because, while it can be a very sophisticated operation, drying is a fundamentally simple process. Eswara et al. presents a detailed discussion of solar-thermal drying applications for which cogeneration systems are well suited [28].

2.4 General Framework for Stakeholder-Centered Engineering System Design

Chapter 1 introduced the philosophy for this thesis by asking "what can be made possible?" This chapter covered how context has been brought into energy system design. Design objectives in the current literature focus on economics, performance, and other life-cycle properties of the energy system. These life-cycle properties are referred to as ilities in engineering systems literature. de Weck defines *ilities* as "desired properties of systems, such as flexibility or maintainability" [29].

The first task in engineering system design is to formulate the problem to encompass the ilities that are relevant to the key stakeholders. This problem formulation is the system boundary. Overly narrow or broad system boundaries make problem formulations intractable or not useful. The key stakeholders, and the critical ilities to those stakeholders, make up the system boundary. Creating a valuable problem formulation is difficult, often taking time and iteration. Each independent stakeholer-ility pair needs to affect the problem formulation as a constraint, objective function, or qualitative consideration.

It took over a year to finish the problem formulation for both projects in this thesis. The topic began with a very broad formulation: make energy more affordable in rural India. Where affordable energy was the objective function, and rural India was the stakeholder. This problem statement was refined through literature review, qualitative conversations, and engineering analysis. Each level of refinement of the problem statement and design revolved around the question "is this *acceptable*?" or "does this system make the designer's goals possible?"

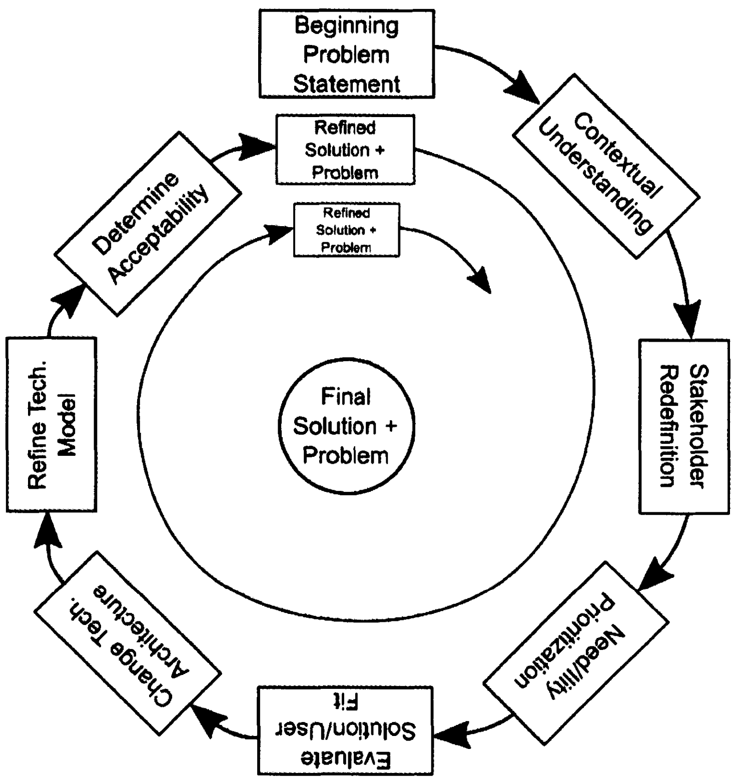

Figure 2-2: An overview of the methodological framework used in this thesis to iterate on problem statements and designed solutions.

The spiraling iterations for this workflow are shown in Figure 2-2. This converging spiral is different from Boehm's diverging design spiral for software development [30]. The divergent spiral frames user acceptance as risk to be managed and reacted to, spiraling to new designs. The spiral in in Figure 2-2 is convergent because this design process treats the context and stakeholders as the focusing motivation for the work.

Each iteration contains a more specific design as the key stakeholders are better understood and system architecture is determined.

If the system boundary was too broad, the objective functions of the key stakeholders were narrowed by engaging more in the context. Alternatively if the design was not acceptable, the system architecture and model were revisited. The problem statements and system designs evolved into the final problem formulations presented in this thesis. For example, the theoretical model of pump performance was necessary for determining if it was acceptable to manufacture a prototype pump. However, once that prototype pump was manufactured, that theoretical pump model was no longer acceptable. The theoretical model was then replaced with an empirical pump curve to re-evaluate the system.

This process of hierarchically refining both the design and problem formulation in parallel is helpful when working with a large amount of uncertainty in the end-use of the system. Small farms across east India have unique challenges. Additionally, there are limited data on the financials or conditions of these stakeholders. Therefore, the design process for this problem is not deterministic. Instead of designing one system to a specific set of functional requirements, the designer explores the design space for solutions that are acceptable to the stakeholder as the stakeholder is understood. In this work, optimization is used to help explore of a complex design space. These rounds of refinement let the designer engage with the stakeholder to learn more about how to formulate the problem.

Chapter 3

Photovoltaic Powered Irrigation for the 1-acre Farmer

3.1 Motivation

There are over 31 million marginal farms (<1 ha) in east India and eastern Uttar Pradesh (UP) [31]. Many have access to shallow groundwater but insufficient access to energy for lifting it with AC pumps. For example, 80% of villages in West Bengal have groundwater within 10 meters of the surface, but, as of 2012, only 15% of the region's pumps were electric [32]. Figure 3-1 and Figure 3-2 show that other east Indian states have similar groundwater and electrification rates to West Bengal. Making cost-effective irrigation possible in east India will bring significantly increased yields to a poverty-stricken part of the country along with other positive externalities, such as reductions in seasonal flooding [32, 33].

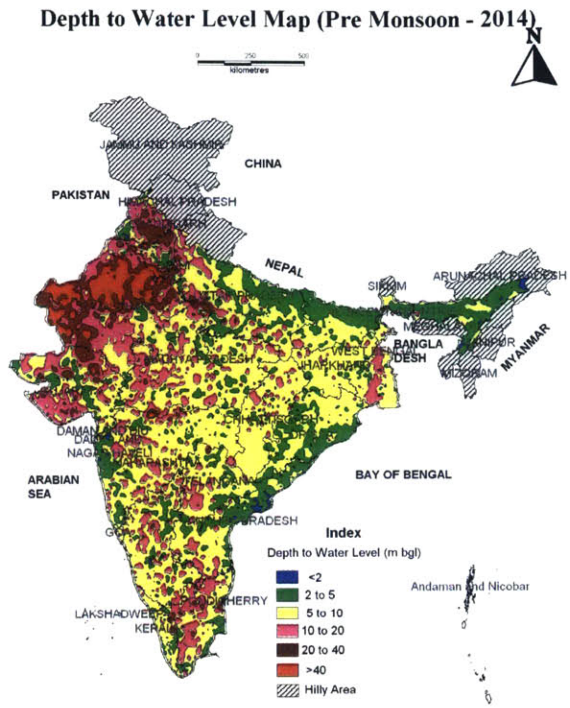

Figure 3-1: Pre-monsoon groundwater depths across India for 2014 [1].

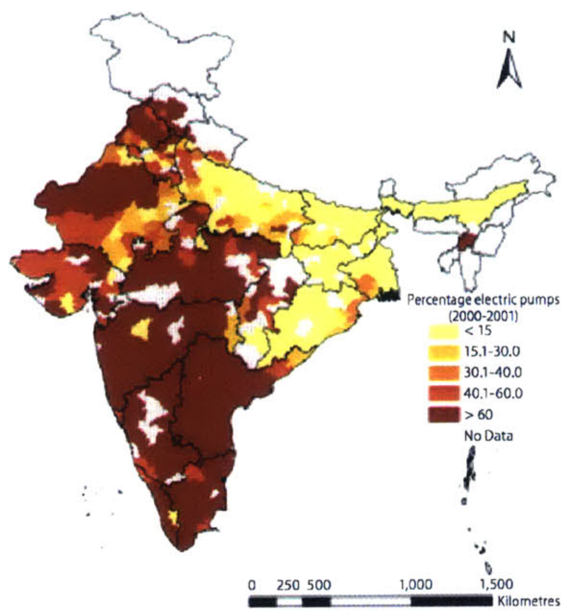

Figure 3-2: Penetration rate of electric pump sets [2]. Electrical irrigation is not common in east India, where the fields are either barren or irrigated with diesel outside of the monsoons.

To date, there is no commercially available solar pump that is sized for the individual irrigation of the millions of 1-acre plots with shallow groundwater in east India. There are pumps suited for larger farms, community management, and deeper wells, but no options that a 1-acre farmer could purchase for him or herself. Without grid connections these farmers must use diesel or labor-intensive treadle pumps for cultivation outside of the kharif (monsoon season). The expense and volatility of diesel prices cut into farmer profits and discourage both rabi (post-monson season winter) and dry-season cropping which can be major sources of income for marginal-holding farmers [34]. In fact, the price of diesel has risen at 10 times greater a rate than the price of agricultural outputs since 1990 [33]. This thesis presents the ground-up design of a direct current (DC) solar pump and accompanying photovoltaic (PV) system to address this need.

Small-scale irrigation also has benefits for the national food and energy development strategy. Small farms consume 4 to 15 times less energy than a large to produce an equivalent amount of food [35]. For India, where there is insufficient energy to serve the large population, small-scale agriculture will continue to be a big part of the national food-water-energy nexus. Smaller farms also lead to a more even distribution of wealth, which is beneficial for countries, like India, where agriculture is a major part of the economy and poverty is common.

3.1.1 Diesel Costs

Diesel is commonly used in India for transportation, as a power source for off-grid power generation, supplementing an intermittent electricity supply, and directly powering pumps. Diesel has a volumetric energy density of 35.86 MJ/liter and commonly costs 55 INR/liter[1] at the fueling station in East Singhbum, Jharkhand, where this project takes place. Since 1 liter of diesel contains about 10 kWh of energy, costs a little under 60 INR, about 1 USD[2], and is often put into a 30% efficient generator, the energy cost of diesel is approximately 0.30 USD/kWh. It should be noted here that oil prices are volatile and expected to increase [34].

[1]Personal correspondence, February 2014

[2]The exchange rate used in this paper is 60 INR to 1 USD

Remote locations with irregular electricity also face challenges acquiring diesel. One pilot site for the solar pump developed in this work is 9 km from the nearest diesel fuel station and the farmers bicycle to get their diesel approximately every 2 weeks. At the other site, the farmers take a motorcycle 17 km to the same station. This takes 45 minutes each way. The alternative for these farmers is to pay an additional 5-10 INR/liter for the fuel to run their pumps by purchasing diesel brought back in plastic 1 liter bottles[3]. This is common in much of rural east India.

A small diesel pump costs anywhere between 6,000 INR and 40,000 INR. These pumps last between 3 and 6 years before they need replacing or serious maintenance [36]. Additionally, many pumps that are used in east India are designed for other regions, such as Maharashtra and Punjab. These pumps are not appropriately sized for farms in east India, and are therefore inefficient and likely unnecessarily expensive. The delivery pressure of the best efficiency point (BEP) for most available pumps in east India is much higher than 10 meters of head, the typical well depth in this region.

Purohit estimates the cost of water from a diesel engine to be 1.13 INR/m^3 at 10 meters of total head [37]. While this is a reasonable estimate, it should be noted that this analysis is for a 5 horsepower (hp) pump, which is more efficient (40% in his analysis) than a pump that would be used on a small plot [36]. Furthermore, his analysis was performed at a time when the cost of diesel was only 32 INR/liter. For the farmers targeted in this project, the current practical price of diesel is over 60 INR/liter or about twice Purohit's value. In a comparison between the price of solar and diesel irrigation in east India, Shah claims that solar pumps can be rented to provide water at a rate of 20 INR/hour as opposed to going rate of 120 INR/hour for diesel [33].

3.1.2 Challenges with Current Non-diesel Pumps

Even in places where there is good grid access, the grid load of pumping takes up a significant portion of the available capacity. By motivating the use of efficient solar pumps, electricity can be made available for other economic and quality-of-life related

[3]Personal correspondence, March 2015

activities.

Electrical pumps are very popular in west and south India because of their low up-front and operating costs due to agricultural subsidies and extensive grid connectivity. Even in places with grid access, but no agricultural subsidies, the cost of irrigating with electricity at 6 INR/kWh is still low[4]. The low-cost of AC irrigation, along with extensive canal schemes, has turned these regions into highly productive agricultural regions [38, 34].

Unfortunately, electrical pumping in these regions also has drawbacks. The most well-known being the rapidly depleting groundwater in states like Maharashtra, Haryana, Rajasthan, and Punjab. Not only are AC pumps and this subsidy program depleting groundwater resources, they are depleting national wealth. The subsidy system enables mass power-theft, causing estimated losses of $160 million USD/year [39]. In Karnataka, each farm receiving the subsidy costs the utilities 30,000 INR/farm/year due to theft [33].

The electrical grid that brings this cheap power is also unreliable. When groundwater is the most critical to the survivability of the crop, the irrigation demands will be felt regionally, causing outages, voltage fluctuations, and variations in three-phase supply. In 2000, 1/4 of all power transformers failed in Haryana. Transformer failures take more than 10 days on average to fix, a long time for a plant to go without water during the dry-season [39]. Those outages cause regional spikes in diesel pump rentals, resulting in a shortage of backup-diesel pump availability, increasing irrigation costs or making water unavailable. The fluctuations in voltage and 3-phase supply shift pump operating points, causing wear on the hydraulic system and burnout on the coils. Repairing a damaged AC pump can cost as much as 50% of the year's irrigation costs [39]. Just as the benefits of the great canal-irrigation projects were regressively felt [38], the consequences of these system failures effect the poorest farmers most because they are the least prepared to economically absorb the expenses associated with grid-failures [39].

Fortunately, solar power has the reciprocal benefit to the challenge of high irri-

[4]Personal correspondence, July 2014

Table 3.1: Comparison of the pump designed for this thesis to other popular pump models. The most significant difference is that the system can deliver 1/3 the water of other PV systems at 1/5 the cost, making solar irrigation much more accessible to small and marginal-holding farmers. The assumed price of solar is 63 INR/watt. Fuel costs are based off of 5 hours of operation for 200 days of the year at 60 INR/liter.

Company and Model	Rotomag RS1200 Submersible [40]	Rotomag MB60 Surface [40]	Honda [41] WX10K1A	This Thesis
Type	Solar DC Centrifugal	Solar DC Centrifugal	Diesel Centrifugal	Solar DC Centrifugal
Pump Horse Power	1	2	1	1/3
Panel [Watts]	1200	1800	-	300
Max Total Head [m]	30	15	35	18
Discharge [l/hr]	12,000	24,000	8,400	3,600
Pump Price [INR]	75,000	43,000	29,000	9,000
Panel Price [INR]	76,000	114,000	-	19,000
CapEx [INR]	151,000	157,000	29,000	28,000
Fuel Costs [INR/year]	-	-	30,000	-
Lifetime [years]	10	10	7	10
Ownership [INR/Year]	15,100	15,700	36,000	2,800

gation loads during dry periods. Water demands are the greatest when the sun is out the most, providing more solar-power to lift more water. Properly sizing a PV irrigation system, i.e. by using the optimization algorithm presented in this chapter, will result in an irrigation solution that provides sufficient water year round.

Existing solar systems still have high up-front costs and are not portable. This necessitates community purchasing and makes it hard to protect the systems from theft or damage. Portability also enables secondary uses such as home lighting. However, the portability does present a moral hazard challenge - making it harder to track customers to collect payments.

3.2 Concept and First Order Analysis

It is possible to create efficient (35% or greater) solar pumps that are sized for 1-acre plots near the abundant shallow groundwater in east India. This thesis describes one pump which has been designed from the ground up for the quantitative and qualitative requirements of small-scale rural irrigation.

Solar pumps designed for 1-acre plots with east India's shallow groundwater (Figure 3-1) can be cost effective due to savings on diesel and profits from increased cultivation, in addition to enabling ownership models that were not possible before.

3.2.1 Pump Sizing

First order analysis is required before beginning the detailed design of a small-scale solar pump. This analysis serves two purposes - it evaluates feasibility quickly, and it provides a reference point for all future studies. If further simulation gives a wildly different result without providing an insight as to why, that simulation model must be revisited.

The cost of solar irrigation is often driven by the required PV panels. Therefore, the required panel wattage is a good indicator of system costs. Panel power is driven by the energy that the pump requires, which is set by the flow rate and pressure. Equation 3.1 shows the relationship between required energy inputs and output flow and pressure. Equation 3.1 can be reworked to find Equation 3.3, the minimum panel wattage that can supply the specified flow and pressure. $\dot{V}_{daily}$ is the total daily flow rate, P is the delivery pressure, η_{pump} is the efficiency of the pump, GHI_{daily} is the daily global horizontal irradiance, and w_{panel} is the rated wattage for the panel. E_{pump} and E_{panel} are the daily energy production/consumption of the pump and panel respectively.

$$
E_{pump} = \frac{\dot{V}_{daily} P}{\eta_p} \tag{3.1}
$$

$$
E_{panel} = \text{GHI}_{daily} \; \text{w}_{panel} \; 3600 \left[\frac{s}{h}\right] \tag{3.2}
$$

$$
\text{w}_{panel} = \frac{\dot{V}_{daily} P}{\text{GHI}_{daily} \; \eta_p \; 3600 \left[\frac{s}{h}\right]} \tag{3.3}
$$

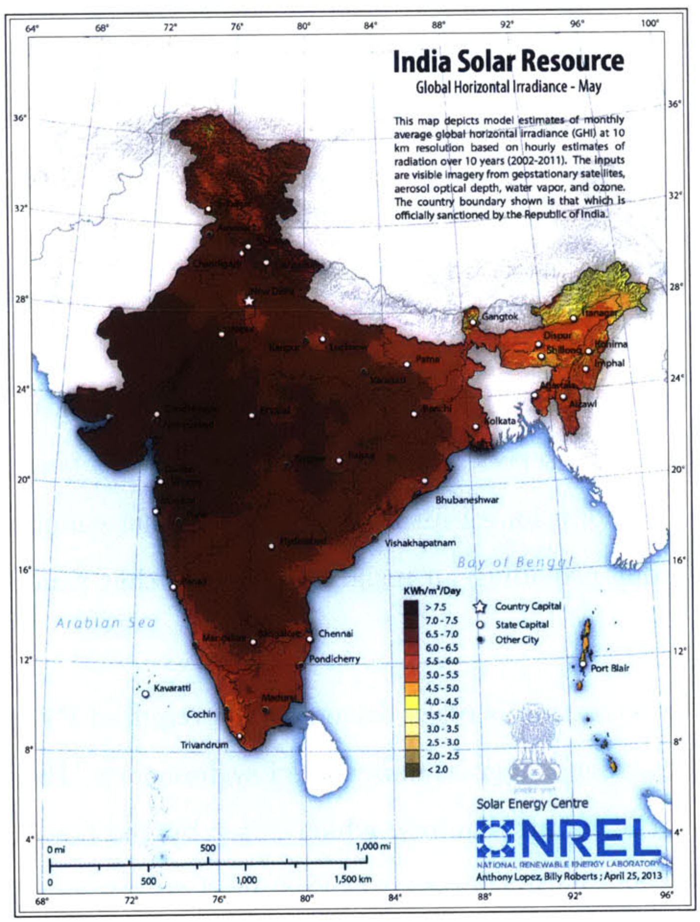

Figure 3-3: Global horizontal irradiance (GHI) for India during May, the driest month of the year in east India [3].

Discussions with farmers and practitioners from NGOs such as PRADAN indicated that anywhere between 8 and 20 m^3 of water are required in one day. This depends on the weather, soil, crop type, and what stage of growth the crop is in. Those discussions, analysis, and groundwater data show that a pump capable of delivering water efficiently at between 7 m and 12 m of head will be sufficient. This is more lift than is shown in Figure 3-1 because there are small hills and other flow restrictions, or complications, throughout these regions.

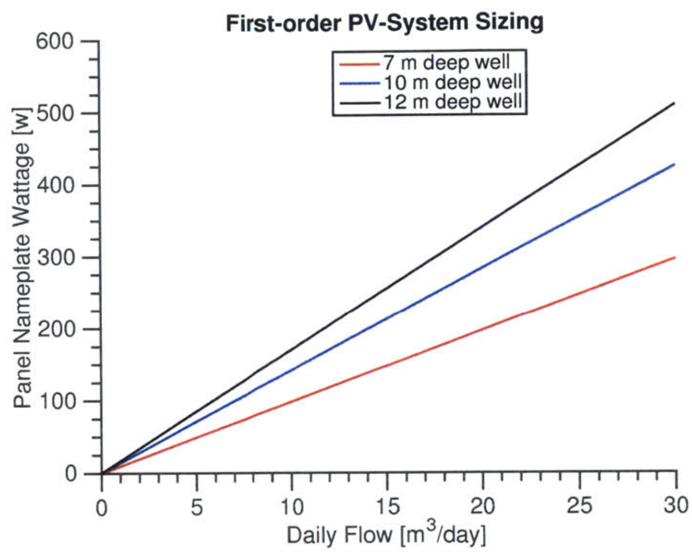

Figure 3-4: Estimate of required panel wattage to deliver adequate water at a given well depth for a 35 % efficient pump assuming 5.5 kWh of global horizontal irradiance (GHI) in the driest month, as can be seen in Figure 3-3.

Figure 3-4 shows the effect of daily flow requirements on panel wattage for different well depths with a 35 % efficient pump. The 35 % efficient target was chosen after surveying the academic and commercial literature for pumps. Prototype testing has since shown that it will be possible to exceed this efficiency. The chosen preliminary design point is 10 m of head and 20 m^3 liters of water per day, and Figure 3-4 shows that this could be possible with 300 W of solar panels.

3.2.2 Pump Type Selection

The two main types of pumps are centrifugal and positive displacement. Centrifugal pumps provide rotational acceleration to water in order to create a pressure head. This pressure can be intuited as the force that is felt by spinning a full water bucket around in a circle.

Positive displacement pumps force water through a system at whatever pressure is required to move that water. Positive displacement pumps have very high efficiencies (up to 95%) but typically suffer from two challenges that make them unattractive for irrigation - high manufacturing costs due to precision manufacturing and low efficiencies/cavitation at high flows due to pulsations [4, 42].

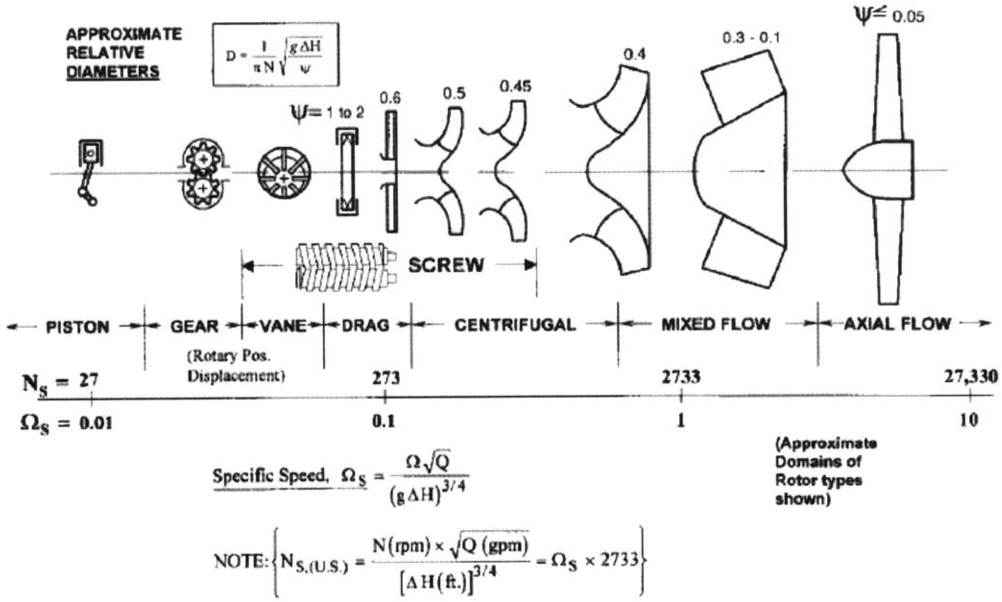

Figure 3-5: Representations of the ideal geometries at different specific speeds. Positive displacement pumps are included for illustrative purposes [4].

Centrifugal pumps are broken down into 3 categories - axial, radial, and mixed flow. Axial flow pumps are best suited to high flow rates and low pressures. Radial flow pumps are suited for high pressures and low flow rates. Between axial and radial flow is a continuum of designs which contains mixed flow pumps which both impart linear and rotational momentum to the water. This continuum is described by a pump's specific speed, which is best conveyed by Figure 3-5. The details for the performance of a pump at the design point in this thesis is plotted in Figure 3-6.

3.2.3 Qualitative Design Inputs

Theft-prevention and secondary uses have come up as two major qualitative requirements for the design of this system. Theft is a concern for all stakeholders in India.

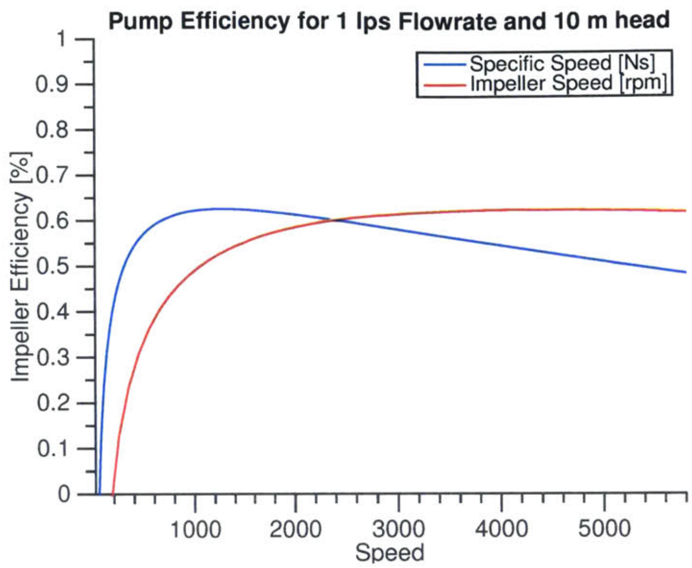

Figure 3-6: The calculated impeller efficiencies for different specific speeds and rotational velocities of a pump that can deliver 1 liter per second (lps) of water at 10m of head. The most efficient specific speed for this performance point is 1300, with an impeller velocity of 4,000 rpm.

There are many solutions, but the only fool-proof method to prevent theft is through portability. With silicon PV technologies, it was observed that one person can carry a 150 watt panel over agricultural terrain in rural India. However, bicycle carriers and more lightweight/foldable panels are being explored and show promise.

Secondary uses for the system that were requested by farmers and practitioners include LED lighting and cellphone charging. There are existing business models that deploy solar-home or micro-grid systems for this application. Mera Gao is one example. They have identified a willingness to pay of 100 INR/month for 2 LED lights and a cell phone charger [43]. Adding this capability to the solar pump requires batteries, a slightly increased panel size, and the inclusion of a USB outlet and LED lights. This addition could increase the utility of the system, decreasing payback time.

Solar batteries, i.e. flooded/deep-cycle, are hard for rural farmers to source, require skilled maintenance, and are relatively heavy. These shortcomings have made solar batteries unpopular for solar-irrigation installations. Every development practitioner and solar company that the author has encountered in India has discouraged the use of these batteries. While solar batteries are discouraged, there has been little investigation into the use of sealed lead-acid (SLA) batteries for solar irrigation. This thesis uses a rough model of SLA battery life and costs to show that they are potentially applicable to small-holding irrigation.

Ease of operation plays an important role in the adoption of new products, especially in rural India. Devices that are not fail-proof need to be repairable because access challenges in these regions can make a centralized repair scheme prohibitively expensive. To address these requirements, the pump controls have been automated with a micro-controller so the farmers only need to turn the system on and then leave it alone. All of the plugs are color-matched and non-reversible. The entire pump is dis-assemblable with common tools. The result of these simplifications is that the farmers participating in the pilot consider the system easier to operate than their diesel pump. Trained farmers can teach other farmers how to use the system in a less than 20 minute lesson.

3.3 Theoretical Pump System Model

The second order theoretical analysis of the PV pump system relies on a model that accounts for battery storage, panel sizing, and pump performance, as characterized by the impeller, pump, and system curves, to determine the design of an optimal system. To accelerate this model, it operates over hour long time-scales. However an hour exceeds the time that a battery may discharge. To address this, the model analytically determines the operating time of the pump within these intervals and discharges or charges the battery appropriately. The battery management model relies on a simple on/off hysteric duty cycle. The system runs each day until it meets the daily water demands shown in Figure 3-7.

3.3.1 Battery Module

The battery module models the battery's ability to capture and store excess energy from the solar panels. This has two benefits for the system. The batteries can capture

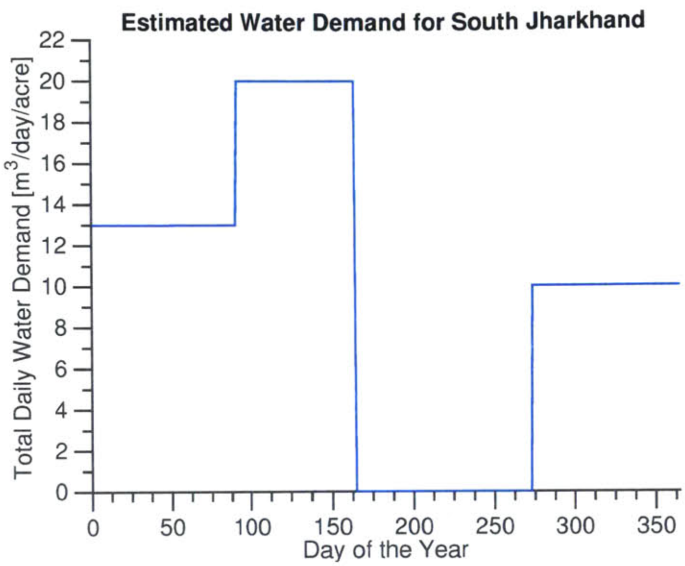

Figure 3-7: The estimated daily water demand for flood irrigated agriculture in south Jharkhand. These estimates are the result of conversations with farmers and development practitioners in the region. The season of no water demand is the kharif, or monsoon, when there is sufficient rainwater for cultivation.

excess energy when there is insufficient light to run the pump, or when there is more irradiance than is necessary to operate the pump. Furthermore, the batteries stabilize the voltage of the output, enabling the system to run when there is insufficient light, or even when the panels are entirely undersized for the system.

The battery charges with excess available solar energy at a given charging efficiency. The charging efficiency represents energy losses and waste that occurs during the battery charging process. In this model, the charging efficiency is assumed to be 85%.

The battery module also tracks the number of cycles that occur over a typical year to determine how many battery replacements will be required over the life of the system. The system model records the number of times that the batteries reach their depth of discharge (DoD) and uses an empirical relationship for number of cycles and DoD to determine how many replacements will be necessary over the 8 year life of the system in Equation 3.4.

The relationship between DoD and cycle life is typically an inverse exponential relationship. This system model uses the relationship determined by Vutetakis et al.

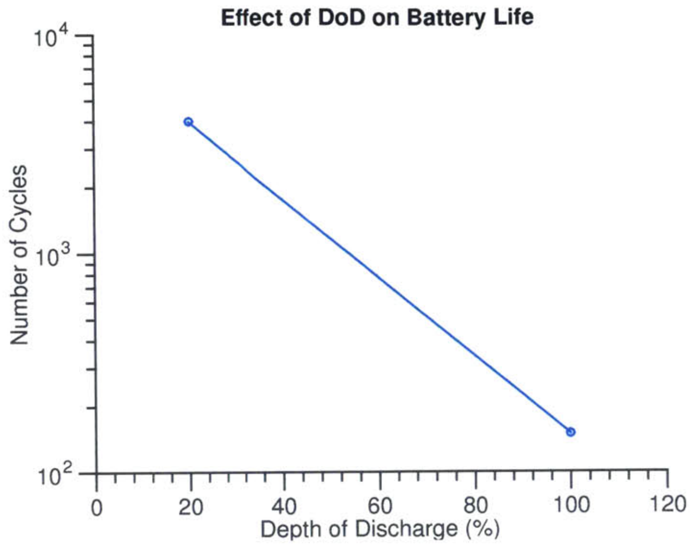

Figure 3-8: Experimentally determined battery life curve from Vutetakis et al. [5]

in Equation 3.5 where m is -4.1043 and b is 9.1149 based on their data for the life of sealed lead-acid batteries as shown in Figure 3-8 [5].

$$N_{replacements} = \frac{N_{cycles}\ \text{life}_{system}}{N_{cycle\ life}(\text{DoD})} \tag{3.4}$$

$$N_{cycle\ life}(\text{DoD}) = e^{m\text{DoD}+b} \tag{3.5}$$

This model then adds DoD as a new potential design vector. To reduce the computational intensity of the optimization, DoD is analytically optimized to yield the maximum amount of energy over its operating life. The energy captured over the life of a battery (E) is proportional to the product of its DoD and cycle life. Equation 3.7 captures this relationship, which can be analytically minimized by differentiation into Equation 3.9 to determine the optimal DoD.

$$E \propto \text{DoD} N_{cycle\ life} \tag{3.6}$$

$$E \propto \left(\frac{log(N_{cycle\ life}) - b}{m} \right) N_{cycle\ life} \tag{3.7}$$

$$\frac{dE}{dN_{cycle\ life}} \propto \frac{1 + log(N_{cycle\ life}) - b}{m} \tag{3.8}$$

$$N_{cycles\ optimal} = e^{b-1} \tag{3.9}$$

$N_{replacements}$ is then multiplied by the cost of each battery to get the total battery cost for the system.

$$\frac{cost}{battery} = 140 \frac{\text{USD}}{\text{kWh}} \frac{\text{kWh}}{battery} \tag{3.10}$$

The 140 USD/kWh for the batteries was based on SLA motorcycle batteries that could be purchased in the market at Chakradharpur, the nearest location to the pilot sites.

3.3.2 Panel and Solar Module

The solar model captures the data for hourly irradiance on the site location. It uses the global horizontal radiance (GHI). GHI is the sum of the direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) on a horizontal patch on the ground as described in

$$\text{GHI} = \text{DNI} \cos(\theta) + \text{DHI} \tag{3.11}$$

where θ is the zenith angle. The power generated from the panel is modeled as a linear function of the nameplate wattage, as is described in Equation 3.2. This model does not account for the effect of panel temperature on performance, or the mechanics of the current and voltage that the panel produces. The solar irradiation data are taken from the National Renewable Energy Laboratory's (NREL) hourly data for India at the GPS coordinate: 22.55 N, 86.25 E in the year 2011 [3]. The daily irradiance can be seen in Figure 3-9.

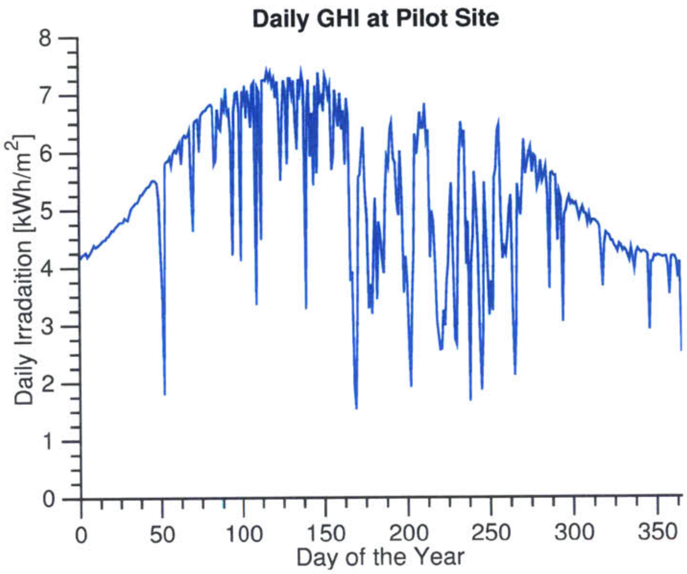

Figure 3-9: Daily solar irradiance (GHI) in south Jharkhand (22.55N, 86.25E) for 2011. The hourly breakdown of these data from NREL was used for the pump system analysis in this thesis [3].

3.3.3 Pump Module

The basis for this model comes from the 'Pump Handbook' which generalizes pump performance based on specific speed and geometric parameters [4]. That model has been implemented by Esparza [44]. The contribution of this work is to integrate that pump model with a motor module and the system curve. A cross-section of the pump design is shown in Figure 4-1.

The interaction between a pump and a hydraulic system is found by intersecting the pump and system curves. For a given input voltage or impeller speed, the flow rates at different backpressures are recorded - this is the pump curve. On the same plot, the flow resistances for different flow rates through the hydraulic system are plotted - this is the system curve. The result is a figure with two intersecting lines, such as the right side of Figure 3-11. If those lines do not intersect, then the pump is incapable of moving water through the system. Cavitation can have a strong effect on the pump curves. However, cavitation is not a concern in this model because the

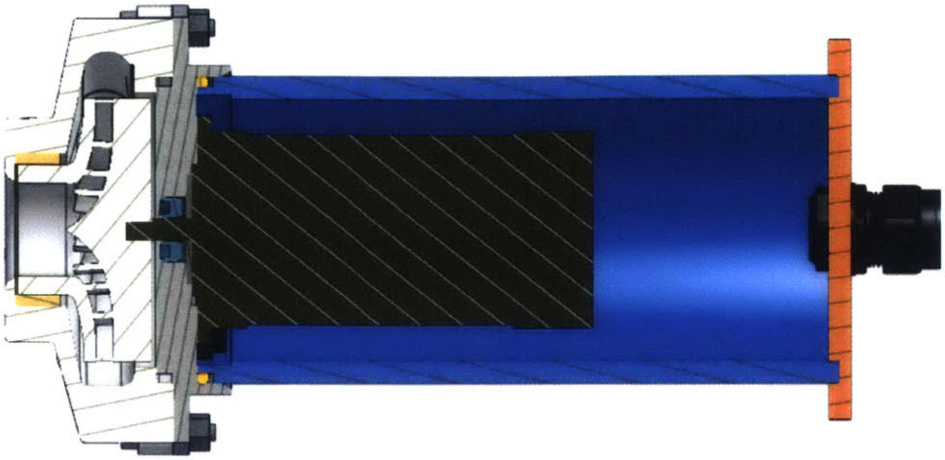

Figure 3-10: A cross-section of the final prototype.

pump is submersible and operating at low pressure heads (<15 m).

This work expands on that approach by intersecting the impeller, motor, and hydraulic system. The impeller module maps *rpm* and torque onto flow and pressure. The motor module maps *rpm* onto torque, and the system module maps flow onto pressure. The resulting coupling of those systems has two curves in two different two-dimensional spaces that are linked through the impeller module, which maps any point on one curve to a point in the other space. This mapping may or may not be unique depending on the pump's design.

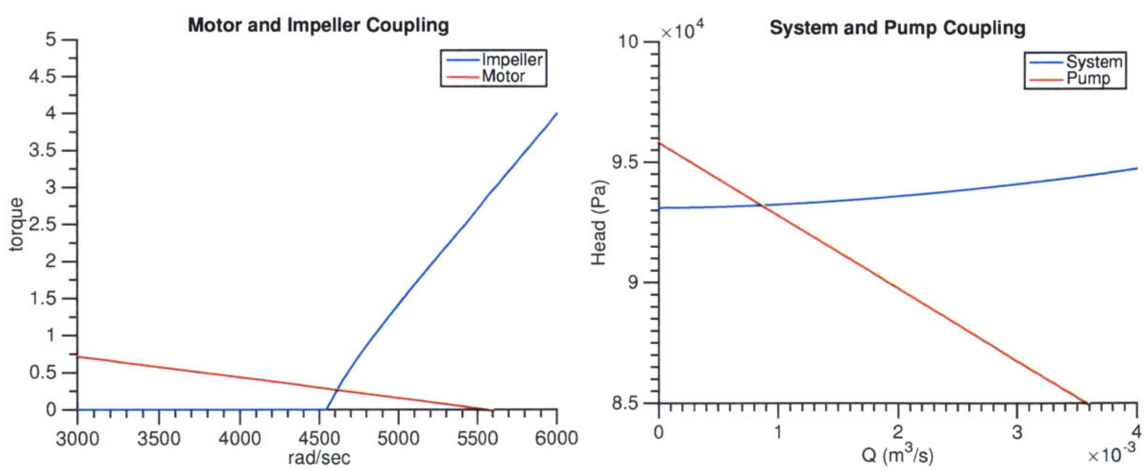

Figure 3-11: Intersecting the motor and impeller curves to find an operating speed (Right). That operating speed is used to find the intersection of the pump and system (Left).

This is implemented by first using the impeller module to convert the points on the motor curve to pressures and flows. This 2D to 2D mapping then converts the motor's $\{rpm$, torque$\}$ to $\{$flow, pressure$\}$ space. The resulting curve is intersected with the system curve to get a performance point. The two intersections can be seen in Figure 3-11.

In abstraction, the mappings are:

$$impeller\{rpm, torque\} \overset{impeller\ geometry}{\longleftrightarrow} \{flow, pressure\} \tag{3.12}$$

$$motor\{rpm\} \overset{motor\ constants}{\longleftrightarrow} \{torque\} \tag{3.13}$$

$$system\{flow\} \overset{pipe\ dimensions}{\longleftrightarrow} \{pressure\} \tag{3.14}$$

A more detailed discussion of the impeller, motor, and system functions can be found below.

Impeller

This impeller model relates the geometry and revolutions per minute (rpm) of the impeller to the flow, pressure, and shaft torque of the pump [4]. The three key geometric parameters are the designed flow rate $\dot{V}$, the designed pressure head H, and the designed rpm. From those terms, all the basic theoretical performance information for the impeller, such as specific speed, flow rates/pressures at different rotational speeds, and impeller torque can be calculated. A detailed description of the process can be found in in the work done by Karassik, or Esparza's summary and simplification of Karassik's work [4, 44]. Because this is a theoretical model, it should predict better performance than what can actually be achieved with a physical unit.

Motor

The motor behavior is characterized by the no load current (I_o), voltage constant (K_v), torque constant (K_t), and the internal resistance (R). These estimate the performance of the motor under different conditions. The motor curve is represented as the following functions of torque (τ) where ω is the rotational velocity:

$$\omega(\tau) = (V - I(\tau)R)\, K_v \tag{3.15}$$

$$I(\tau) = I_o + \frac{\tau}{K_t} \tag{3.16}$$

$$\eta_m(\tau) = \frac{\tau\omega}{VI(\tau)} \tag{3.17}$$

The result is a theoretical pump curve, such as the one shown in Figure 3-12 for the Anaheim Automation motor that was used for the pilot prototype.

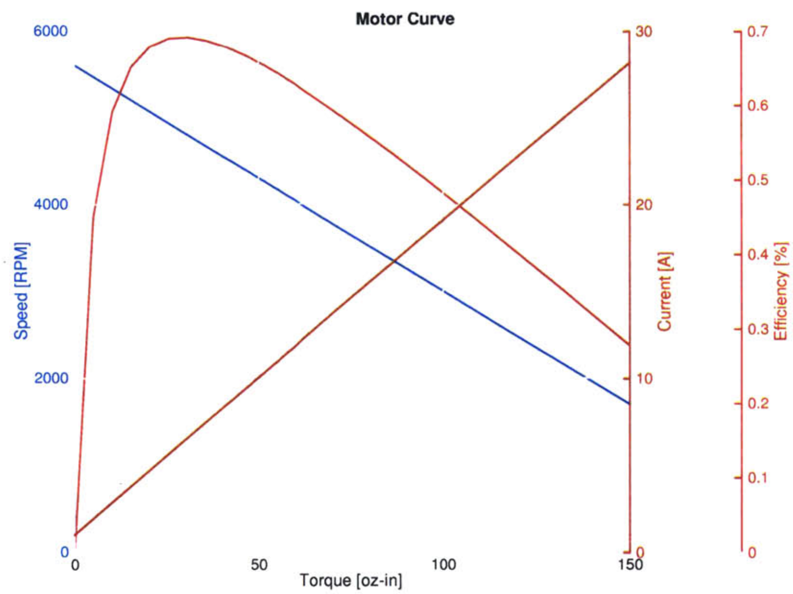

Figure 3-12: The motor curve for the Anaheim Automation motor BLWS65235S-24V-4000 that was used in our pilot. $R = 0.6$ Ohms, $K_t = 0.039\frac{Nm}{A}$, $K_v = 2285\frac{rad}{Vs}$, and $I_o = 1.0A$

System

The system is modeled as the sum of a fixed static head, which is the well depth, and the flow losses associated with bringing the water to the field. Pipe losses caused by the friction of the flow were calculated using Darcy's law, Equation 3.18. The sites for the pilot have well depths of 9.5 m.

$$\Delta P = f\frac{L_{pipe}\rho v_{flow}^2}{2D_{pipe}} \tag{3.18}$$

$$f = \begin{cases} \frac{64}{Re} & \text{if Re} < 2300 \\ \frac{0.32}{Re^{0.25}} & \text{if Re} > 2300 \end{cases} \tag{3.19}$$

$$Re = \frac{\rho v_{flow} D_{pipe}}{\mu} \tag{3.20}$$

where L_{pipe} is the length of the pipe, ρ is the density of the fluid, v_{flow} is the flow velocity, D_{pipe} is the diameter of the pipe, f is the friction factor, μ is the dynamic viscosity, and Re is the Reynold's number for that flow.

3.3.4 Results

These system components are integrated in a model that calculates how much water the irrigation pump can deliver and when. For every hour, the model tracks the energy flow between the panels, batteries, and pump and records the resulting water flow. The result of this simulation can be seen in the daily undelivered water flow (Figure 3-13) and the predicted number of daily battery cycles (Figure 3-14). Figure 3-14 demonstrates the validity of the model, a record of the movement of energy through the system on a sample day.

3.4 Multi-objective Optimality

Before the pump system is designed, it must be appropriately sized. Examining the cost-performance trade-space of the Pareto frontier is a powerful analytical tool for using quantitative modeling to make hard qualitative tradeoffs in system design when there is more than one objective function. A Pareto front is a plot that includes all non-dominated designs for a given system. For a point on the Pareto front to be non-dominated means that there is no other design that is both less expensive and higher performing than that design. Pareto fronts do not yield one obvious answer, but they

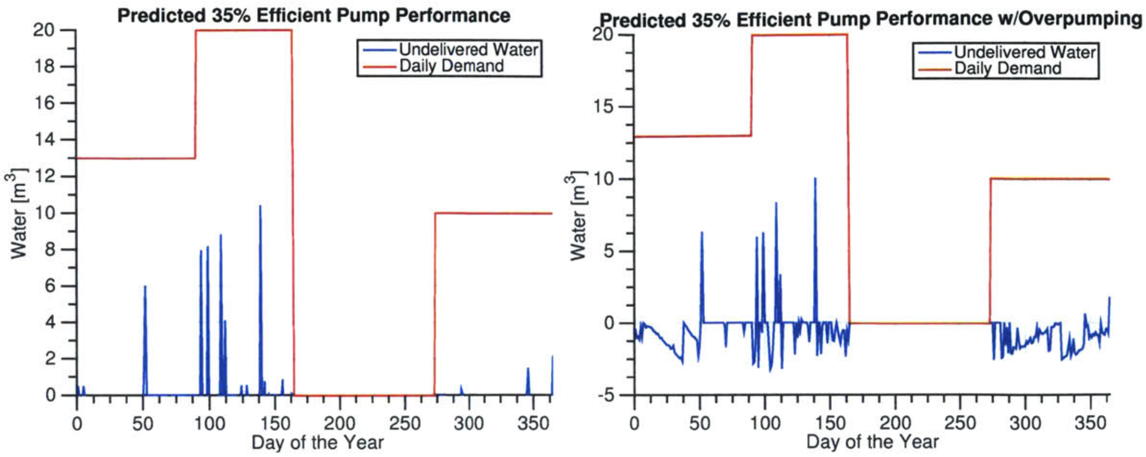

Figure 3-13: The amount of water undelivered if the pump is turned off once the desired flow has been reached (Left). If the pump is left to run for the full duration of the final hour of operation, the additional water lifted is minimal enough to limit over-irrigation but still provide extra water to cover the 'cloudy' days (Right).

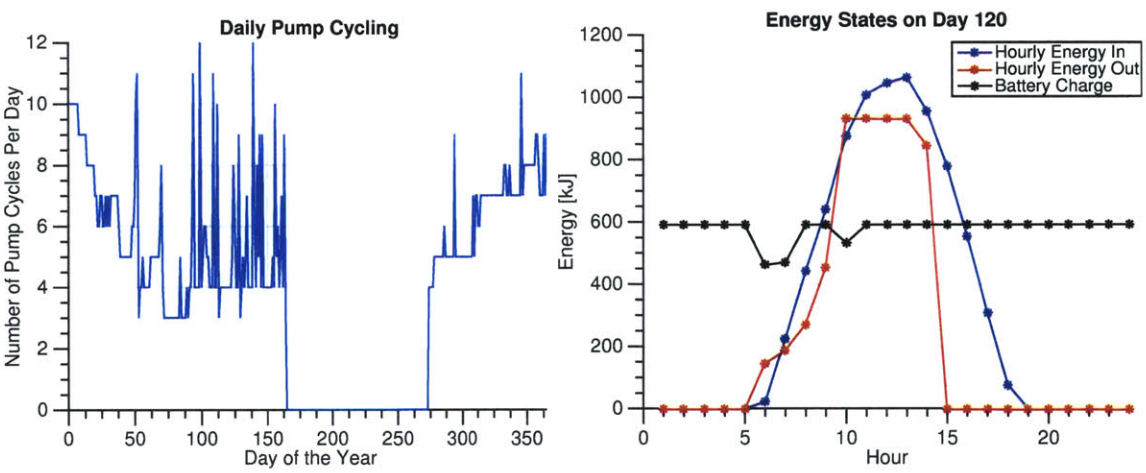

Figure 3-14: The daily number of pump cycles over the course of the simulation (Left). The movement of energy through the solar pumping system (Right). Energy comes in from the sun, and is either stored in the battery or output into pumping work.

help the system designer understand how cost and performance can be exchanged, and what design families are available in different regimes. Design families are clusters of similar designs.

Pareto fronts can be challenging to produce because they require constraints that exist within the objective function space. Of the different algorithms, this thesis uses an adaptive weighted sum (AWS) algorithm to generate the Pareto front [45]. The AWS method is an iterative variation on the weighted sum (WS) method. It begins with an objective function that is the weighted sum of two objective functions, as shown in Equation 3.21.

$$\tilde{J}(x) = \lambda J_1(x) + (1-\lambda) J_2(x) \tag{3.21}$$

$$x_0 = x_1 + U[0,1]_n (x_2 - x_1) \tag{3.22}$$

$$J_1(x) < J_{\text{ub1}} \tag{3.23}$$

$$J_2(x) < J_{\text{ub2}} \tag{3.24}$$

$$err_1 = J_1(x) - J_{\text{ub1}} \tag{3.25}$$

$$err_2 = J_2(x) - J_{\text{ub2}} \tag{3.26}$$

$$p(x) = 10^7 \sqrt{\max(err_1, 0)^2 + \max(err_2, 0)^2} \tag{3.27}$$

Where J_1 and J_2 are the two objective functions, $\tilde{J}$ is their weighted sum, x is the design vector, and λ is the weighting factor, which is swept from 0.001 to 1.001 in this case. These results are then plotted in the solution space with J_1 and J_2 as the two axes giving an initial Pareto front. This Pareto front is filled in or improved with the AWS method, which selects an interval between two points on the Pareto front and re-runs the WS optimization with constraints (Equation 3.23 and Equation 3.24) in the objective space that dictate that the new designs be non-dominated, by either of the ends of the interval.

These constraints are implemented as penalty functions show in Equation 3.27. The factor of 10^7 in the penalty function was selected by experimentation. Newly dominated designs are eliminated as the algorithm advances. This AWS method is different from the original one proposed by Kim and de Weck [45]. Their original paper offsets the objective constraints by a fraction of the distance between two constraining points on the Pareto front. The method used in this research places the constraint along the constraining points because the optimization problem is very non-linear and complex. Relaxing the constraints, and varying the weights (λ) from 0.001 to 1.001 maximizes the feasible objective space of the problem and still avoids redundant points. This algorithm is illustrated in Figure 3-15.

To further prevent the algorithm from becoming 'stuck' in a non-global optimum, the starting point for the search algorithm (either Pattern Search or Sequential Quadratic Programming) is randomly selected from the axis aligned box between the constraints as described in Equation 3.22, where $U[0,1]_n$ is a vector of random numbers between 0 and 1 that is the same length as the constraints. When the AWS constraints become more limiting, the point is randomly selected from the axis aligned box between the bounding AWS design vectors. This helps the search algorithm find a feasible design.

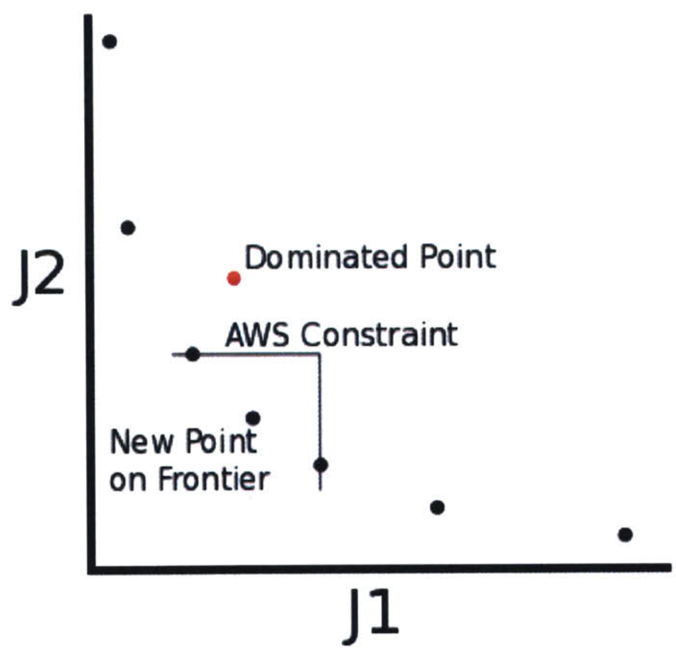

Figure 3-15: A representation of the AWS method implemented in this thesis for making Pareto fronts of the pump-design trade-space.

The result of the AWS method is shown in Figure 3-16. These Pareto fronts have the benefit of showing the trade-off between cost and performance, providing insight into the nature of different design families. Figure 3-16, Figure 3-17, and Figure 3-18 show that achieving perfect performance under a whole year of fluctuating solar conditions requires an expensive system. Relaxing the demands on performance, by as little as 2%, yields considerable cost savings (30% or more). As long as the crop is tolerant to a few cloudy days without water, everything will be fine. Alternatively, the farmer can find a spot-irrigation solution, such as renting a diesel pump. Considering the strong correlation between clouds and rain/low evaporation, and the nature the pump-rental market in India, both of these scenarios are likely. If solar pumps significantly displace diesel, there might not be enough diesel pumps to rent, which would pose a problem for long, cloudy, rainless spells.

3.4.1 Theoretical Pump Optimization Results

Optimizing across panel size, battery size, rated pressure head, rated flow rate, and rated impeller rotational velocity for the model parameters (water requirements, solar availability, motor specs, well depth) results in the Pareto front seen in Figure 3-16. This curve describes all of the pump designs that could be found which are non-dominated (no design could be found that is both cheaper and better performing). It required many iterations of the AWS algorithm with pattern search to generate this full plot. This optimization problem is non-convex because there are many local minima that the optimizer becomes 'stuck' in. Fortunately, this ideal curve (because real efficiency will never match the theoretical efficiency) shows that it is possible to produce a system that can support at least 1 acre of agriculture for as little as 450 USD capital costs. This price point justifies creating a real pump and determining if its performance curve can also enable a cost-effective system. One interesting design point from this theoretical model is listed in Table 3.2.

Table 3.2: A promising design point from the theoretical Pareto front. It is the red dot on the Pareto front in Figure 3-16

Panel [W]	Battery [Wh]	ω	Q	H	Undelivered Water [%]	Cost [USD]
283	153	568	0.0036	4.37	1.4	447

3.5 Empirical Pump Optimization

After the model identifies the specifications of an ideal pump, an actual pump can be designed and manufactured to be as close to those specifications as possible. However, the fabricated pump is not identical to the theoretical pump. To address this

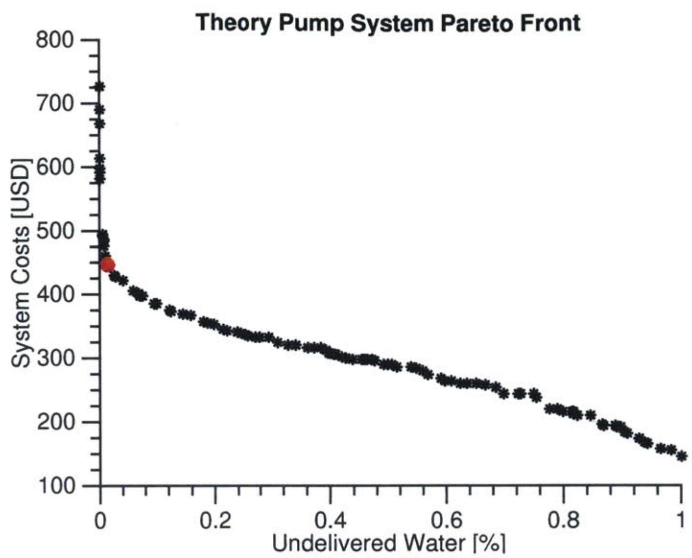

Figure 3-16: Pareto front for the theoretical pump models. The red circle is the location of the point described in Table 3.2.

difference between theory and implementation, the optimization model, with the new pump curve, re-calculates the size of the other system components using the measured performance of this new pump.

The model takes one of the pump curves measured in Figure 4-8 and intersects it with the pressure curve for the site depth. This pump curve already has pump power calculated, so the pump power draw is directly computed. Since the system curve/pump curve intersection is quickly executed with this model (a simple interpolation call), the model can use well depths that are variable over the course of the year. This could use the groundwater depth data that the Central Ground Water Board (CGWB) collects. However, both sites source their water from perennial streams (or a well that is recharged from a perennial stream), so the model still draws from a static height between the stream to the field (about 9.5 m in both cases).

3.5.1 Results

The multi-staged design approach eliminates the 'chicken and egg' challenge of system architecture and subsystem design. The initial optimization selected an ideal pump design. Now that a real, non-ideal, pump has been created, the optimal system architecture is different. To address this shift of optimality, a new system component sizing is identified with a second optimization run. This validates the feasibility of the new physical component.

The optimization identified optimal designs for the pilot based on the prototype that was produced in lab. These results can be seen in Figure 3-17 and their implications for the design of the pilot system will be discussed in section 4.5.

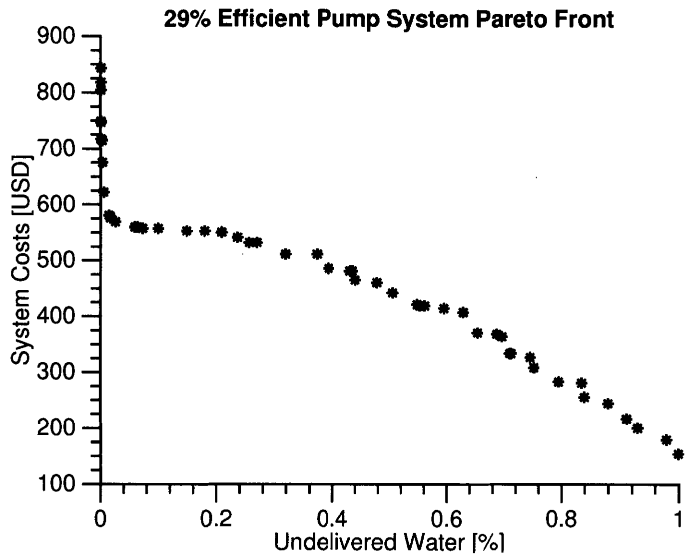

Figure 3-17: The empirical system optimization for the 29% efficient pump that was produced in lab for bench-top and field testing.

Now that a pump has been made, the feasibility of the system is re-evaluated. Rough economic analysis, and interviews with farmers and NGOs, have shown that a system priced at 30,000 INR (500 USD) or less would be affordable to many marginal-holding farmers, especially if a financing option were available. Figure 3-17 shows that the new prototype does not enable a system that meets those specifications. However, the motor used in the prototype was also sub-optimal. A new, specifically designed motor, would increase the efficiency of the entire pump past 35% efficiency. To estimate how this change would affect the final system cost and performance, the power draw of the pump can be reduced by 29/35 for another run of the optimization simulation. The results in Figure 3-18 show that a 35% efficient pump with the new motor enables a system that meets 99% of water demands for the marginal farmer in this part of Jharkhand and only costs a little more than 500 USD.

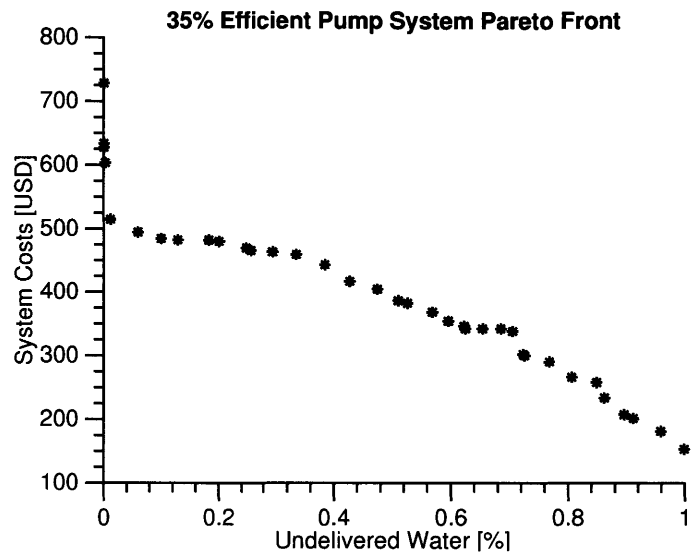

Figure 3-18: The empirical system optimization for the 35% version of our pump. The selected design for the 35% efficient pump is a panel size of 305 watts, and a battery capacity of 590 kJ. That design costs 503 USD and only misses 54.5 m^3 (1.5%) of water demand each year.

3.6 Groundwater Resources

No discussion on solar pumping in India is complete without a discussion of groundwater resources. Shah and other prominent academics have expressed their concern for the damage that unchecked solar pumping could do to groundwater tables, particularly in south and west India [33]. Simplistic solar subsidies incentivize farmers to use their systems during all hours of the day. Current solar subsidy programs limit the wattage of subsidized solar pumps to reduce aquifer over-draw, but this will only remain relevant until the solar-pump market becomes developed and grows unchecked, without subsidies [33].

While solar-irrigation does have the potential to damage groundwater resources, development of this sector in east India will be beneficial to the nation's water, food, and energy resources. East India only uses 40% of its renewable groundwater resources [2]. This statistic excludes the large amount of rainwater that is not captured by hilly land or over-full aquifers and flows directly into the ocean. For this reason, the groundwater resources of east India are better situated to be exploited than any other region in the country. In fact, promoting irrigation in east India will reduce the pressure to meet India's growing food demand on farmers in more water constrained regions like Punjab and Haryana [2].

One method for reducing groundwater overdraw is to incentivize farmers to use their excess electricity for other purposes. The Surya Raitha Scheme in Karnataka is a new subsidy scheme which incentivizes solar pump owners to conserve water. It provides subsidized pump-sets to farmers, and purchases the electricity back from them at a favorable rate (5 INR/kWh in this case) [46]. This creates a market for the extra energy produced by those solar pumps, which provides some extra energy to the grid and reduces groundwater overdraw [33].

However, the benefits of a feed-in-tariff do not exist in places where there is no grid access. There is a limited electrical grid in east India, although it has very intermittent service. This network will benefit from energy feed-in by the solar-pumps. There also are alternative local distribution models, such as Mera Gao's or OMC power's for distributing solar-generated electricity in places without a developed grid. Creating local markets for excess electricity may encourage farmers to manage their water more responsibly. This case might even be stronger than the feed-in-tariff because these off-grid programs are able to sell energy for as much as 60 INR/kWh [43]. While there is promise in creating systems like these to profit farmers and encourage groundwater conservation, there are many technical challenges (such as tamper-proofing meters) and socio-economic challenges to successful implementation.

Further technical contributions that can be made to groundwater resource management include the monitoring of groundwater resources. There are several facets to such a strategy. There needs to be the ability to measure total dynamic head and use analytics to extract the static head from the total head data. This will enable the widespread use of information on aquifer health in regional water resource planning. Near-realtime data on well depth could be overlaid with rainfall data to better understand aquifer capacity and recharge mechanisms. An even more blue-sky extension of tracking groundwater depth would be to map out the water structures in confined-aquifers by tracking the connections between different well depths.

3.7 Future Work

There is still work to be done on the tehcno-economic analysis of a solar pumping system such as this one:

- The capital cost and operational impact of including a LED lighting and cell-phone charging system with the unit should be included in the model. This could increase the value of the system, but the interactions between capital costs, operations, and value in this case need to be better understood before a final judgement is made.
- More physics-based models of the panels and batteries should be implemented to understand the effect of things such as DoD, temperature, panel voltage, etc.
- Discrete components, such as the batteries and the panels, that are currently represented as continuous could be optimized as discrete components. i.e. one cannot purchase 3/4ths of a solar panel. This will likely have an effect on the optimal configuration.
- The motor, currently a fixed component, is modeled on a physical basis as described in subsection 3.3.3. This means that the design vector can be expanded into a discrete set of motors to be chosen from for optimizing the system. Alternatively, physical parameters, such as number of windings and poles, could be used to identify the design of an ideal motor in addition to designing an ideal impeller.
- Current water demand data are based on estimations from conversations in the field. Refining the water-demand model will enable the design of a pump that is even more appropriately sized to the changes in water demand and solar availability over the course of the year. One next step is to build this more sophisticated agricultural model which will decrease the amount that the system is oversized and increase the designer's confidence in its performance.

Chapter 4

Pilot System Deployment in Jharkhand

4.1 Site Selection and Community Engagement

The goal of piloting the system is to evaluate how much dry-season cultivation the solar pump can support. There are other business hypotheses to test (financing models, transitioning from monsoon to year-round cultivation, etc.), but enabling dry-season cultivation is core to the value-proposition of the solar pump, so it is the focus of this pilot. To best isolate other variables, the selected pilot site already needs to be practicing irrigated agriculture.

The community also needs to have a strong connection with PRADAN, the project's local partner, since the MIT team was remote for most of the pilot. There are two sites for this pilot, both are located near the PRADAN office in Chakradharpur, Jharkhand, and are current project locations for other work that PRADAN is doing. Each site also has a self-help group (SHG) to manage the ownership of each pump system, ensuring that the system is used appropriately while PRADAN staff is not present.

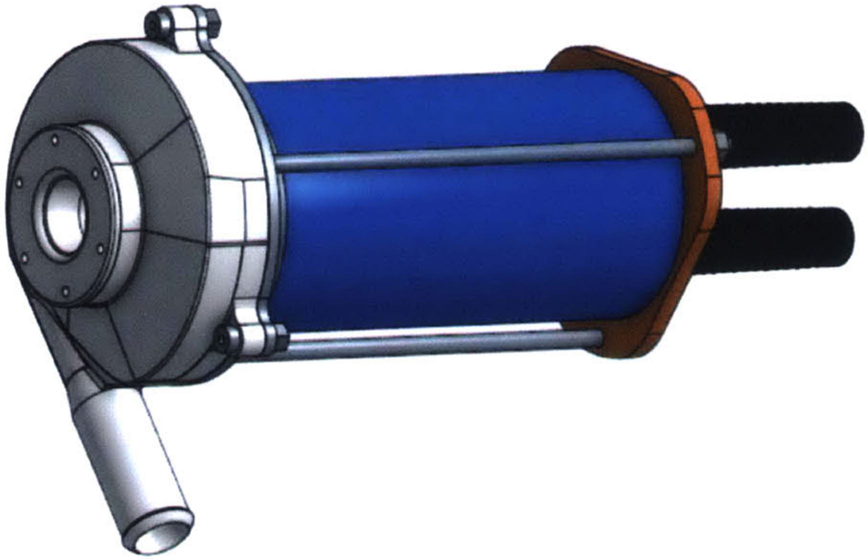

Figure 4-1: A full CAD model of the final prototype design.

4.2 Prototype Design

4.2.1 Impeller Design

The impeller was designed by Esparza for his undergraduate thesis [44]. The geometry for the impeller is derived from the specified performance point (1 lps flow rate at 10m of head). Unfortunately, the design points produced by the theoretical model (3.7 lps designed flow rate at 4.19 m of head) in subsection 3.4.1 do not match the specified performance point. The performance-point impeller (1 lps at 10m head) has been selected for the empirical optimization and field testing.

4.2.2 Volute Design

The volute is designed to convert the rotational velocity of the fluid exiting the impeller into a pressure head. Volutes are designed for a specific performance point. At other performance points, there is recirculation or progressive acceleration of the fluid within the impeller. It is assumed that the fluid exits the impeller at all points (ϕ) along its edge, contributing to the flow rate at that point, $\dot{V}(\phi)$. For an even pressure head to remain inside the volute, the dynamic head of the fluid $v(\phi)r(\phi)$ must remain constant. This will balance pressure loads on the structure and ensure high efficiency. At the BEP, the cross-section of the accumulator $A_{cx}(\phi)$ should proportionally increase as the volute accumulates water and decelerates with the increasing radius (Equation 4.1).

$$A_{cx}(\phi) = \frac{\dot{V}(\phi)}{v(\phi)} \tag{4.1}$$

$$\dot{V}(\phi) = \dot{V}(2\pi)\frac{\phi}{2\pi} \tag{4.2}$$

$$v(\phi) = \frac{v(2\pi)r(2\pi)}{r(\phi)} \tag{4.3}$$

$r(\phi)$ is the middle of the cross-section at the position ϕ.

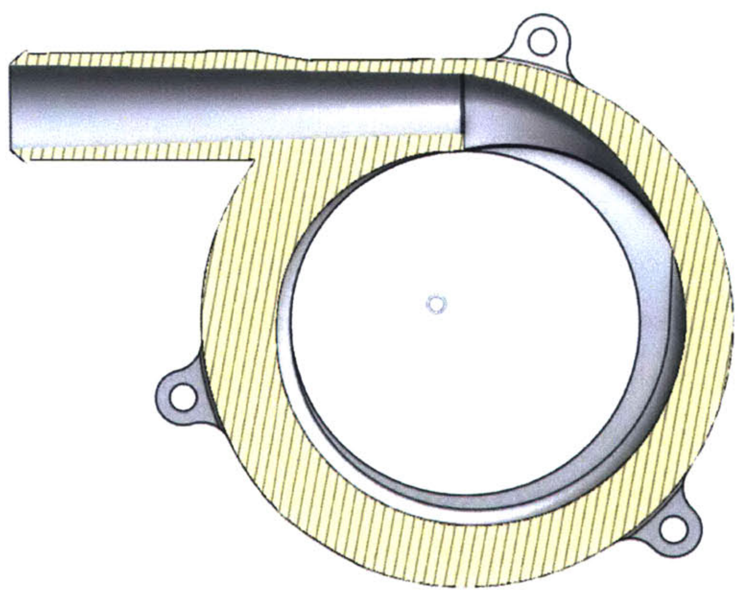

Figure 4-2: A cross section of the volute.

4.2.3 Sealing

Reliable sealing is essential to the longevity of the pump. For this system, there are 3 critical sealing junctions: the motor housing opening, the shaft seal, and the power cable junction. Each one has different functional requirements.

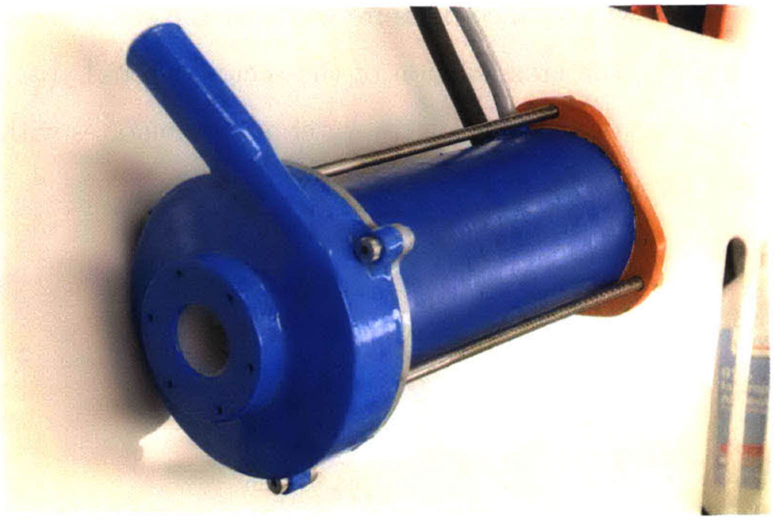

Figure 4-3: The one of the 5 final manufactured pumps for the pilot in Jharkhand.

The junction between the top plate and the rest of the motor housing is required to install and service the motor inside the housing. This interface needs to be watertight up to 0.1 MPa (10 meters of submersion) and be easily serviceable. This is accomplished with a Buna-N O-ring. Due to the low pressure requirements, the groove is sized with the 15% compression and 70% cross-sectional fill heuristics. To ensure that the same compression is applied to the O-ring each time, a bore-seal is used instead of a face seal. A drawback to bore-seals is that they often require undercuts which complicate the machining process for prototypes and increase mold-tooling costs in the long-term. To solve this challenge, over-lapping lips are used to contain the O-ring, which can be seen in Figure 4-4.

The shaft seal needs to handle up to 0.3 MPa of pressure from submersion and the pump's stall pressure. This seal needs to be accessible in a non-destructive way but must remain well protected from the elements. U-cup seals are good solutions for 4,000 rpm on a 0.25" shaft with only 0.3 MPa of sealing pressure because as lip seals, they provide a pre-load on the seal, have low friction, and retain their own grease for sealing and lubrication. They are some of the simplest lip-seals which makes them affordable, while still being rated for the pressures that the shaft seal will encounter. To simplify machining and installation, there is a pocket for the U-cup, which is then

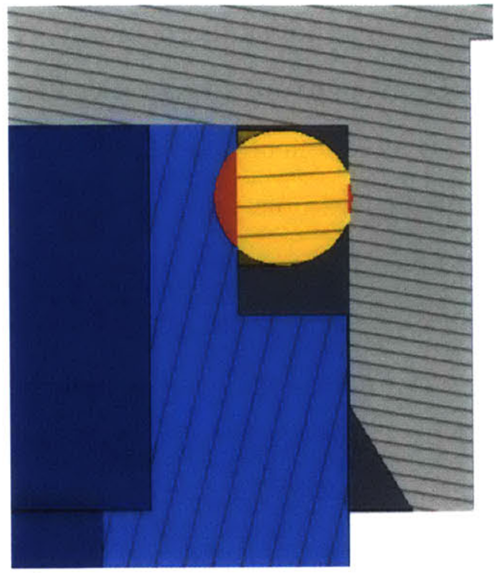

Figure 4-4: A cross-section of the O-ring groove for sealing the motor housing. The O-ring is in yellow, the motor housing in blue, and the front plate in grey.

held in place with a retaining ring that rests between the motor face and the top plate as shown in Figure 4-5. The retaining ring does increase the part count, but it can be eliminated if the motor has a sufficiently flat and smooth faceplate.

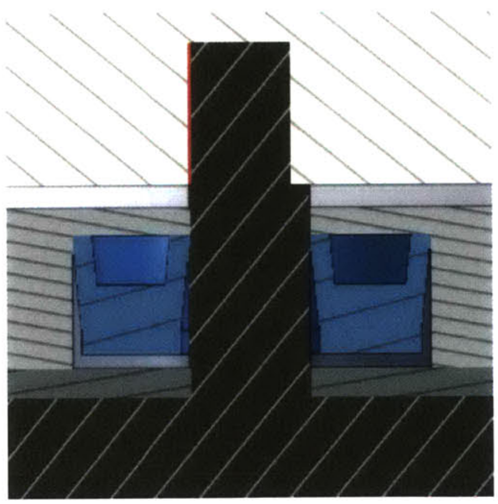

Figure 4-5: A cross-section of the u-cup, groove, and retaining ring for the shaft seal. The U-cup is shown in blue.

Cable-housing connections, while static, are complicated by the bending moment that is generated at the interface between the housing and the connection. Adhesive solutions can be strong, but matching the adhesive to the cable sheath and the housing material is challenging and may fail catastrophically. Thus the cable-connection seal is mechanical and uses St. Venant's Principle. St. Venant's principle provides a heuristic for coupling different components, typically shafts, within mechanical systems [47]. St. Venant's Principle is simple - firmly coupling two components requires stabilizing forces applied 3-5 diameters, or characteristic lengths, apart. Decoupling two components requires isolating the point of application from the force by 3-5 characteristic lengths. In the case of housing-cable connectors, this means that there must be 3-5 diameters of wire between the sealing structure and the other end of the connector to isolate the O-ring from the cable's bending moment. The selected connectors for the prototype are shown in Figure 4-6.

Figure 4-6: Waterproof connectors with cable strain relief that have been used in different iterations of prototype design.

During the pilot, field modifications and repairs were made at the plot. This is a dry, dusty environment which will likely lead to O-ring contamination and eventual failure. Whatever maintenance and repair program is implemented, there will need to be a strong system for quality assurance in the O-ring removal, cleaning, and installation. These are robust components, but they can destroy the motor, or other sub-systems, if they fail.

4.3 Pump Testing and Performance

4.3.1 Experimental Setup

The pump curve was created by running the pump within a flow-loop inside a small pool of water as shown in Figure 4-7. The flow loop began at the outlet of the pump, and includes a pressure gauge, ball-valve, and flow meter. The pressure gauge was upstream of the ball-valve, so the ball valve can be used as a variable flow restriction to test the flow rate at different pressures. The flow loop feeds back into the pool, so as long as the pressure gauge is at the same elevation as the pump, it can be read as the outlet pressure of the pump.

Pressure measurements were taken with the 'high-accuracy test gauge', part number 4007K2 available at McMaster-Carr. Flow measurements were taken with the Omega FTB792 for 2 to 20 gallons per minute flow. Current measurements were made with the Fluke 373 True-RMS Clamp-On meter.

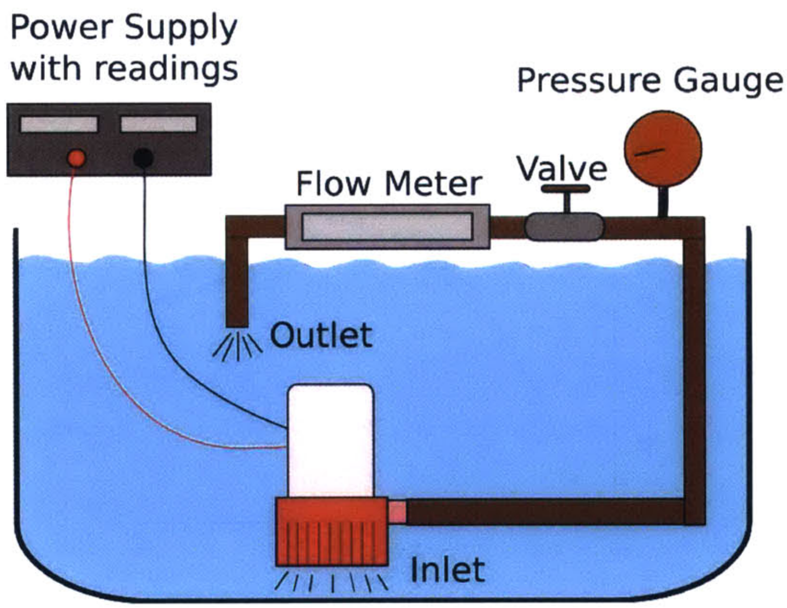

Figure 4-7: The experimental setup for measuring the pressure-flow curves of prototype pumps.

Error in the pump curve measurements can come from pressure losses in the 1" diameter tube between the flow-meter and the pump. Those have been calculated and are negligible. Error also comes from the pressure and flow-meters. The flow meter has an error of +/- 1.5% of the reading. The pressure-sensor has an error of +/- 0.5% of the maximum reading pressure (30 psi). The amp-meter has an error of +/- 1% of the reading. The voltage of the output was measured to deviate from 24 V by as much as 0.1 V.

4.4 Performance

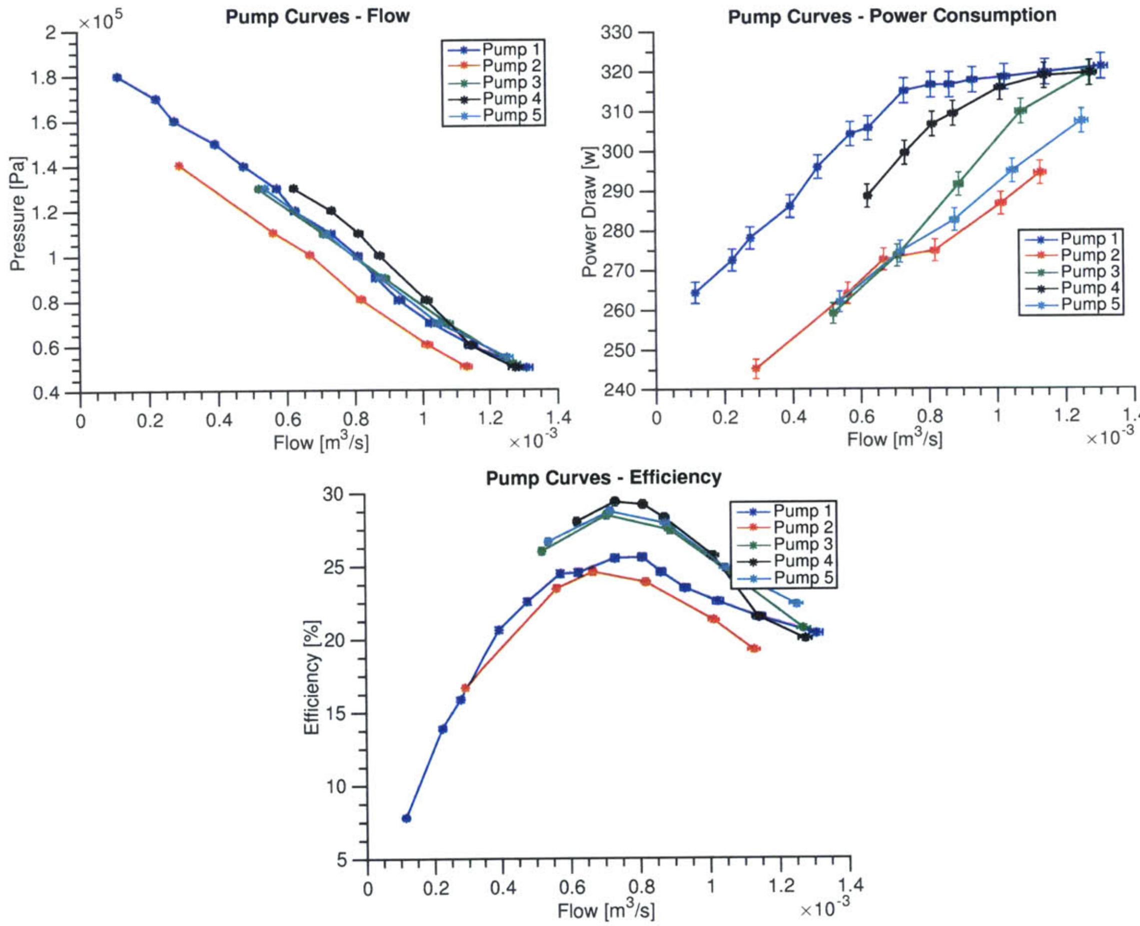

Figure 4-8: The pump curves for pressure, power draw, and efficiency for the 5 pumps that were produced at MIT for the pilot in Chakradharpur, Jharkhand.

8 m^3/s flow is clearly the BEP point for this geometry. That is the flow rate for which recirculation is minimized. While there is considerable variation with pumps 1 and 2, pumps 3, 4, and 5 have shown considerable consistency, even without a quality control (QC) process for the manufacture of these pumps at MIT. This pilot manufacturing run has shown that, for a real product, better fixtures and more QC will be necessary to ensure the production of efficient pumps.

4.5 System Sizing

The panels and the batteries have discrete sizes, something unaccounted for in the system model. Additionally, the system must be portable for the pilot. After sampling the local selection of solar panels, it was concluded that panels larger than 150 watts are too cumbersome to carry between homes and farms and that carrying more that 2 panels would be too much trouble. The design points on the Pareto front in Figure 3-17 includes systems with 300W of panels and 2x 9Ah, 12V batteries which still deliver a good amount of water, as shown in Figure 4-9.

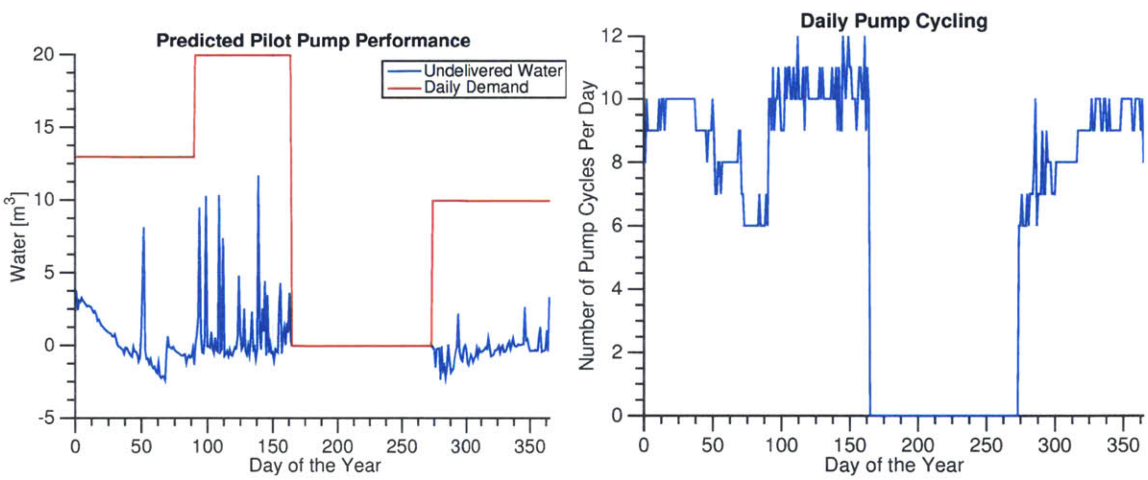

Figure 4-9: The performance of the pilot pump with a 300 watt panel and 2x 9Ah 12V batteries over a sample year in the West Singhbum district of Jharkhand. The pump may not be able to deliver enough water to support an entire acre of cultivation, and the cycling frequency will limit the battery life to approximately 1 year. However, the cumulative missed flow in the dry season is 66 m^3, or just 3 days of flow.

The optimization work was acceptable for getting the project to the field. The system model confirmed that the final design, selected with the Pareto front and inputs form the field, is sufficient. Those constraints could have been considered from the beginning, but the constraints on portability and discrete module sizes can vary from site to site. To this effect, the Pareto front does not specify the optimal design point, but informs the designer of the nature of the design space so he or she can make the final decision by taking all of the auxiliary factors into account.

4.6 Results

To date, the pilot has been delivering water for 2 acres of land at each pilot site near Chakradharpur, Jharkhand. The farmers at these locations use spot irrigation with watering cans and jalkunds (water structures). This type of spot irrigation is much more water efficient than flood irrigation, which is the irrigation type that this system is sized for. Three operators were trained in each community. At the time of publishing this thesis, farmers at both sites were growing crops during the dry season, some of them for the first time. The site locations and trainings are shown in Figure 4-10.

Figure 4-10: An image of the water source below the fields (Top Left). The pump secured to a bamboo structure in a river at the second site (Top Right). Training for operation and maintenance of the electrical system (Bottom Left). Training for proper installation of the pump (Bottom Right).

Chapter 5

Solar-powered Food processing

This thesis addresses the adoption of distributed energy systems on two levels. The system optimization presented in chapter 6 has the ability to aid in evaluating site selection and system design of a μ-CSP ORC. Issues surrounding electrification are complex, and technical feasibility is not sufficient to justify the development of a system. To be sustainable, the system must be coupled to a productive business that has appropriate inputs, good market linkages, trained labor, and is sized appropriately to the generation capacity of the distributed generation source. This chapter provides a brief background on some value-added processes that could be powered by a μ-CSP ORC. Due to the limited data on small-scale food processing, this chapter is mainly anecdotal but still introduces the context of these applications.

5.1 Motivation

There is a wide variety of operations possible in rural India, and almost all of them rely on electricity to operate. Some of these operations are decentralized - chaat stands, food processing, brick-and-mortar shops, tailors, and others. Others are parts of the rural network for major Indian companies - cell towers and banks for example. Some of these business operations require high quality service. Cell towers have a >99.99% service level agreement, while many other applications simply close shop or run a diesel generator when the power is not on and absorb the associated costs. There are many locations in India that do not have a reliable enough grid connection to operate a value-creating business. Grid reliability was cited as a concern by almost every rural business owner that was interviewed over the course of this research.

Food processing is the focus of this feasibility study because it is of the correct scale (3-30 kW), often requires a thermal load, and has social benefit. Food processing covers a wide range of activities, and for the purpose of the discussion here will be, defined as the 'process of adding value to a food product.' Cold-storage is included within this definition because it increases the value of food that would otherwise perish. Food processing operations in India can be as simple as a 1.5 kW motor grinding spices, or as sophisticated as a full dairy operation spanning chilling, pasteurization, and packaging, which consumes hundreds of kW at peak.

One thermodynamic advantage of μ-CSP systems is the ability to inexpensively generate and store heat. This makes such systems well suited to facilities with additional thermal and/or cooling loads. In those cases, the competition is thermal energy created from fuel, biomass, or electricity, which are recurring costs. While biomass can be inexpensive in some regions, the use of forests for heat is contributing to the rapid deforestation of India, a practice which is not sustainable.

Food processing can be a major source of social value, even if the business unit might be owned by a small number of people in the community. Every farmer who sells to the processing center is able to make more money and travel a shorter distance. Food processing will also incentivize farmers to invest in cultivating higher-valued crops due to the better access to value-added processes and risk-reducing cold-storage [34].

5.2 Types of Food Processing

There are many different types of food processing operations. This section is not intended to be exhaustive, but to provide perspective on different operational scales and context behind some examples of food processing operations.

5.2.1 Dairy

Liquid milk is a major part of Indian health, culture, and religion. Traditionally, milk is consumed twice per day, once in the morning, and once in the evening. Estimated milk consumption in Punjab is approximately 600 ml/day/person[1]. Haryana and Rajasthan are also major consumers of milk. The pervasiveness of liquid milk makes it a good choice for chilling but a poor choice for processing. Almost every family in India drinks milk, but many of them do not drink processed milk. Instead, they boil the milk before drinking it. It will be challenging to come up with a business model in rural India which can compete with the price of raw milk purchased directly from dairy farmers.

Historically, dairy processing has played a major role in strengthening India's rural economy. The 'White Revolution', centered around 'Operation Flood' by the National Dairy Development Board, has famously revolutionized the dairy industry in India. Dairy is, in many ways, a good candidate for solar food processing of some form. Regions with lots of dairy are also often rich in sunlight. Additionally, milk is available from cows at all times of the year. This means that there will be abundant energy for food processing and that the facility can be operated year-round.

Cold Storage

Cold storage plays an important role in the dairy supply chain in India. Because milk spoils quickly in India's hot climate, milk is aggregated and chilled at bulk milk chillers (BMCs) before going to a central processing facility.

This discussion is based off of a BMC that was visited in central Maharashtra. In India's hot climate, raw milk spoils in less than 4 hours. To prevent spoilage, milk is collected from farmers for transport to BMCs at each milking point of the day - around 7 am and 6 pm. At the BMC, 30°C milk is chilled to 4°C in 4 hours where it can be stored until the central processing facility collects the milk for processing. The BMC that was visited collects 5,000 liters of milk/day from more than 200 farmers

[1] Personal correspondence, July 2014

in labeled canisters which are weighed and tested for quality and fat content. Every fifteen days, farmers are paid at their doorstep for the milk. The center takes 2 INR/liter as their commission. It employs 10 laborers part-time (2 shifts, 6 am to 10 am and 6 pm to 10 pm) and 1 manager, who are all paid about 3,000 INR/month. The facility cost 1,500,000 INR for construction and all of the equipment. The chiller consumes 10 hp between the compressor and the agitator. There is a 15 hp diesel backup generator for when the grid goes down. These small BMCs were not selected for the analysis because they have low profit margins, are dependent on a central processing operation to operate, and have high, time sensitive, loads at times of the day when there is little sunlight.

Full Processing Operation

Discussions with managers of dairy processing plants raised a major concern about quality assurance and quality control (QA/QC). Having a high-quality and consistent product is essential to getting the margins necessary to profitably operate a processing facility. The high fixed cost of dairy processing units is often prohibitive to the growth of new dairy operations, even though only 7% of milk produced in India is processed [23]. Because there are few options to decrease the scale of the operation, and the QA/QC challenges associated with dairy processing, full dairy processing was not selected for this analysis. One interesting research project could be on the design of machinery for processing milk that are cost and energy effective at small scales.

5.2.2 Homestead Operation

Homestead-scale food processing is a low-risk operation. Those operations can be so small that, instead of adopting the risk of purchasing the raw-materials from farmers, the operation charges the farmers a fee for processing the produce. The farmer can then consume, process by hand, or sell the product. The processing operation changes its risk profile by providing services instead of managing products. The small operation focuses on simple activities that do not require retention in the facility (grinding, extruding, etc.), so local farmers can arrive and have the produce handled immediately. Labor charges are 150 IN/day, or about 30 INR/hr.

Table 5.1: The economics and energy consumption of one homestead-scale food processing operation in central Maharashtra.

Activity	Profit [INR/kg]	Throughput [kg/hr]	Power [kW]
Coconut and Date Grinding	20	25	1.5
Flour Mill	5	15	1.5
Papadum	40	50	1.5
Semolina Noodles	20	20	1.5
Spice Grinding	30	10	1.5

5.2.3 Vegetable Cold-storage

Cold storage is considered by Indian agribusiness as a form of food processing. This technology enables preservation of products to limit the farmers' exposure to risk of fluctuations in market price for produce. By reducing spoilage risk, farmers are able to sell the same produce for a higher price on average and are able to invest in riskier, higher-value crops. These fluctuations can be very extreme. In just outside of Patna, in Bihar, there is currently a shortage of potatoes. However, in 2012 it was reported that there was such an abundance of potatoes that they were being discarded on the side of the road[2]. It was the local and seasonal surplus that caused the sudden drop in potato price.

Now, there are several cold-storage facilities in the region to address this storage issue. This section discusses one of those cold-storage facilities which is powered by 200kW of PV, purchased at approximately 77 INR/watt installed. The chillers are sized to consume approximately 170kW at capacity. Batteries smooth out the supply curve to ensure continuous operation. The unit uses 240 batteries with 1000Ah capacity at 2V each, amounting to 480kWh of storage, enough to run the facility without power for around 2.5 hours.

This plant exists in a region of Bihar that is physically connected to the grid.

[2]Personal correspondence, July 2014

However, the supply of electricity is so intermittent that it is impossible to run a cold-storage facility without backup power of some form. Three other diesel-powered, cold-storage facilities exist in the immediate area, but, due to high fuel-costs, none of the other facilities are profitable. Cold-storage requires a narrow-enough temperature and atmospheric range that highly irregular energy access is not adequate for proper plant operation. The only profitable cold-storage operation in the region is this PV powered system. It is important to note that, although there is a 30% capital subsidy for installed PV capacity, due to the slow movement of Bihar's government, the PV cold-storage facility has yet to receive the subsidy. Thus far, the facility has remained profitable, even without the subsidy.

The system cost approximately 25,000,000 INR to construct, including the PV system costs. Their yearly interest rate is 15%. Common rates for India are between 12 and 18% due to the approximately 10% inflation rate. The yearly payment on the debt is 20%, 5,000,000 INR per year, to pay down their principle on the loan. The facility has a storage capacity of 30,000 quintals (100kg) of potato per year. They charge a yearly fee of 240 INR/quintal to store the potatoes for 9 months. If the actual stored material is between 20,000 and 30,000 quintals, the facility makes between 4,800,000 and 7,200,000 INR per year in revenue. Compared to the 5,000,000 INR yearly payments, the facility is profitable under most conditions. Sometimes, farmers are charged 300 INR per quintal to make sure that the facility is profitable.

Not only is the facility profitable, it benefits 3,000 to 4,000 farms located within a 50 km radius of the unit. Potatoes are harvested in February and stored in March. From June through January, farmers withdraw from the cold-storage facility to feed their families and sell at market to pay for their expenses.

It remains a question what will happen when full electrification comes and the PV system will need to compete with low-cost grid power. It is likely that by the time that full-energy access reaches the region, the PV panels will be paid off, and the operation will remain profitable.

5.3 Market Linkages

No discussion on food processing in rural India is complete without mentioning market linkages, the ability to access paying customers. Market linkages are critical to the success of any agricultural operation, and are often a barrier to growth for remote farmers.

Profit from the value-added products can only be captured if they are delivered to a market that can afford the product. High margin products, such as sweets, cold-drinks, ice-cream, etc., are dominated by major multi-national players, such as Coke or Frito-Lay. Small operations face tough competition for shelf space in urban markets. Fortunately, there are solutions to the challenges of urban and peri-urban market linkages.

5.3.1 Target Rural Markets

While urban markets are saturated with products trying to get shelf space, rural (and remote peri-urban) markets also consume value-added products. Flour, sweets, milk, ghee, and other traditional consumables are purchased in rural markets. Often these are markets that major corporations struggle to reach because their distribution channels in rural India are under-developed. The challenge with making adequate profit in rural markets is the low margins associated with these less formal markets. Rural people have smaller discretionary incomes than their urban counterparts.

5.3.2 Co-operative Marketing and Sales

Aggregating into larger marketing structures is another way to improve market linkages. By selling as a larger entity, risk is reduced by guaranteeing more revenue, and it is possible to negotiate better prices. Some of the value of aggregation is captured by the rural producers instead of by the distributors and re-sellers.

In particular, there are many dairy cooperatives operating under this model. Many of them use a hub-and-spoke chiller milk collection system. Amul is a very well-known dairy cooperative which has good penetration into urban markets as well.

Other cooperatives, such as KASAM, a processor and seller of spices, has limited penetration in retail sales and primarily has a B2B sales network.

5.4 Selected Operation for Case Study

The business unit that will be analyzed for the operational case study is a homestead processing and cold-storage facility. The homestead operation described above has the advantage of good profit margins, modular operations, minimal inventory risk, and a focus on serving rural markets by producing goods that are consumed locally. The cold-storage facility, powered by a thermal absorption chiller, described below, provides considerable social benefit to the community by reducing post-harvest waste and spoilage. Using a system that is directly driven by thermal energy will also take advantage of the system's ability to produce heat at low costs.

5.5 Future Work

Although large-scale food processing is well understood, there is little detailed literature on the economics of small-scale food processing. Without an understanding of how the financials of these small operations change with size, it will be impossible to quickly scale these systems. Below is a list of future research that can be done to make small-scale food processing:

- A formalized model of the economics of small-scale food processing should be developed. This model should be modular such that different machinery, activities, and timing can be pieced together and analyzed.

- The dynamics of informal rural markets for processed foods needs to be better understood. Flour, sweets, and other consumables are commonly purchased in rural markets across India. The dynamics of how these consumables are priced need to be better understood.

- The physical mechanics of small-scale food processing need to be better understood. Motors rated for 1 hp do not always consume 750 watts of power. The power draw depends on how much the machine is loaded, and how efficient the implement is. There is more technical work to be done on understanding and improving the speed and energy efficiency of small-scale food processing.

Chapter 6

Organic Rankine Cycle and Business System

6.1 Organic Rankine Cycle Basics

The Rankine cycle is an idealized model of a thermodynamic cycle that converts heat to mechanical work with turbo-machinery. It is typically used to model steam turbines and is characterized by isentropic compression, isobaric heating, expansion, and condensation. The organic modifier to the Rankine Cycle refers to the use of an organic fluid, such as R245fa used in this system. The subject of this system model is a small-scale concentrated solar power organic Rankine cycle power plant (μ-CSP ORC) produced by Solar Thermal Generation international (STGi) for rural micro-grids, schools, and health clinics.

6.2 Steady State Model

Steady state modeling was first done in EES (Engineering Equation Solver) by Orosz [6]. Ireland expands on this μ-CSP ORC EES model by creating polynomial approximations of the behavior of components in the system and implementing those models in a dynamic simulation [7]. For simplicity, the polynomial-fit models presented by Ireland are mainly used here. The analysis and optimization work is all done in

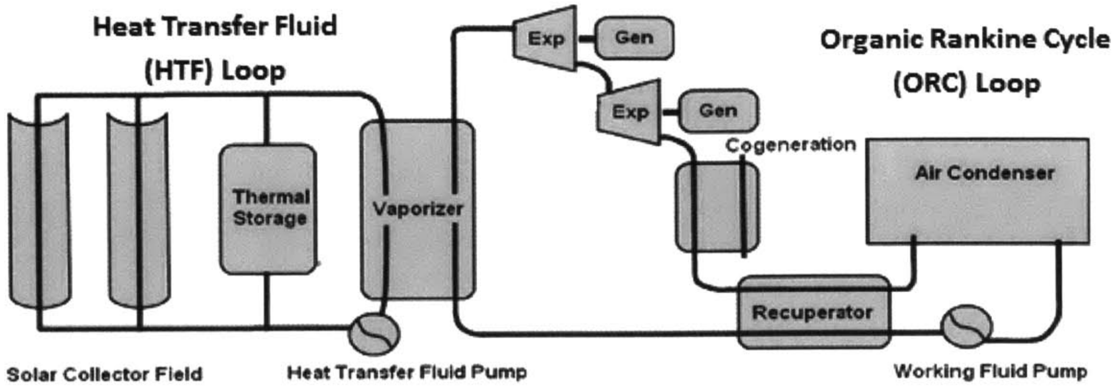

Figure 6-1: A diagram of STGi's μ-CSP system [6]. The heat transfer fluid (HTF) loop is on the left, and the ORC loop is on the right.

MATLAB.

The EES model has been translated over to MATLAB for two reasons. MATLAB code executes more quickly than EES, or even Dimola, making it better suited for computationally intensive optimizations. MATLAB's structure also supports a modular code-base built around different, interchangeable modules linked by fluid flows throughout the system. Because the code is modular, it is easy to explore the performance of new system architectures, submodules, and business models.

FluidProp, a free thermodynamic property library made by Asimptote, models the behavior of the thermal properties of the fluids as they move through the system. It is easily integrated with MATLAB through a documented API.

6.2.1 Solar Model

Collectors can only concentrate normal irradiance. The normal irradiance (I_{normal}) is computed from NREL data by subtracting the direct horizontal irradiance (DHI) from the global horizontal irradiance (GHI) as shown in Equation 6.1 [3]. The data here are from (23.05N, 72.55E), in western Gujarat. It is used as representative data for a site with high DNI in India.

$$I_{normal} = \text{GHI} - \text{DHI} \tag{6.1}$$

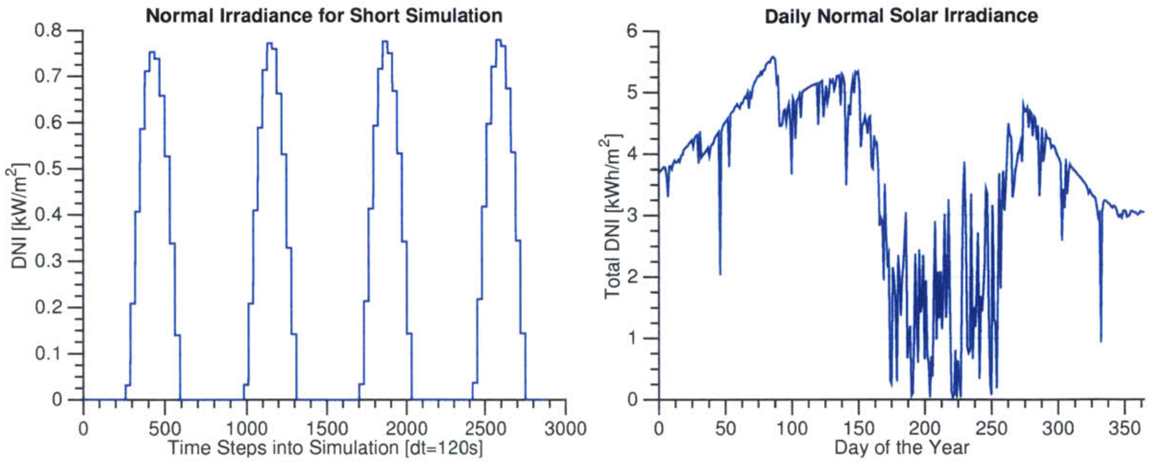

Figure 6-2: Hourly (Left) and daily (Right) irradiance for this food processing case study at 23.05N, 72.55E [3].

6.2.2 Scroll Expander Model

The expanders are modeled as two isentropic expanders with fixed efficiencies and fixed pressure ratios. From those relationships, the states of the fluids throughout the expanders can be calculated using FluidProp. In Equation 6.2, r_P is the pressure ratio of the expander, P is the pressure at the inlet/outlet, and s is the specific entropy at the inlet/outlet.

$$P_{turb-out} = \frac{P_{turb-in}}{r_P} \tag{6.2}$$

$$s_{turb-out} = s_{turb-in} \tag{6.3}$$

$$\tag{6.4}$$

6.2.3 Collector

The collector for STGi's μ-CSP system is a low-cost parabolic trough focusing onto a linear non-evacuated collector. The collector warms the heat transfer fluid (HTF) with concentrated sunlight before it returns to the tank. In this model, mono-ethylene glycol is used as the HTF, but glycerine also has promise because of its higher boiling point.

The collector model is broken down into discrete control volumes to capture the change in the temperature of the working fluid as it travels through the collector tube. The discrete control volumes capture heat from the sun and lose heat to convection and radiation in each segment as described in Equation 6.5. The empirical relationship for the collector used in STGi's pilot system is calculated by Ireland [7].

$$\dot{m}_{\text{HTF}}\Delta h_{\text{HTF}} = \dot{Q}_{in} - \dot{Q}_{out} \tag{6.5}$$

$$\dot{Q}_{in} = I_{normal}L_{segment}W_{collector}\eta_{collector} \tag{6.6}$$

$$\dot{Q}_{out} = L_{segment}(d_0 + d_1(T_{\text{HTF}} - T_{\text{amb}}) + d_2T_{\text{HTF}}^2 + d_3T_{\text{HTF}}^3 + d_4(\text{GHI} - \text{DHI})T_{\text{HTF}}^2 + \sqrt{v_w}\,(d_5 + d_6(T_{\text{HTF}} - T_{\text{amb}}))) \tag{6.7}$$

Where $\dot{m}_{HTF}$ is the mass flow rate of the HTF, Δh_{HTF} is the change in specific enthalpy of the HTF going through the collector, $\dot{Q}_{in}$ is the heat flux into the collector from the sum, $\dot{Q}_{out}$ is the heat lost through the walls of the collector tube, $L_{segment}$ is the length of each segment in the collector, $W_{collector}$ is the width of the collector, $\eta_{collector}$ is the efficiency of the collector.

Table 6.1: Constants for heat loss from the collector taken from Ireland [7].

Coefficient	Value
d_0	5.34E-01
d_1	2.18E-01
d_2	-2.64E-04
d_3	4.93E-06
d_4	7.38E-08
d_5	1.06E-02
d_6	1.15E-02

6.2.4 Heat Exchangers

There are three heat exchangers in the CSP system. One transfers heat from the HTF to the ORC fluid through the vaporizer. The second heat-exchanger acts as a recuperator within the ORC. The last heat exchanger is a condenser which returns the ORC fluid to a pure liquid for recirculation.

The vaporizer is modeled using the logarithmic mean temperature difference (LMTD) between the flows on each side of the heat exchanger (ΔT_1 and ΔT_2) as shown in Equation 6.8 where U is the overall heat-transfer coefficient, A is the heat-transfer surface area, $\dot{Q}_v$ is the heat flux across the vaporizer, and LMTD is calculated in Equation 6.9

$$\dot{Q}_v = UA \text{ LMTD} \tag{6.8}$$

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{6.9}$$

Equation 6.9 can be reformulated as Equation 6.10, a closed form relationship between ΔT_1 and ΔT_2, using the Lambert W function [48]. Since the inlet temperature to the vaporizer on the ORC side is known, the inlet temperature on the HTF side is known, and the outlet of the vaporizer on the ORC side is pseudo-fixed, the necessary outlet temperature for the HTF side of the vaporizer is calculated using Equation 6.10. Once the desired ΔT_{HTF} is calculated, the required mass-flow rate for the HTF loop is determined with Equation 6.11.

$$\Delta T_2 = -W\left(\frac{-\dot{Q}_v}{UA}\Delta T_1 e^{-\Delta T_1}\right) \tag{6.10}$$

$$\dot{Q}_v = \dot{m} \text{ cp } \Delta T_{ORC/HTF} \tag{6.11}$$

$$\Delta T_1 = T_{HTF\ in} - T_{ORC\ out} \tag{6.12}$$

$$\Delta T_2 = T_{HTF\ out} - T_{ORC\ in} \tag{6.13}$$

$$\Delta T_{HTF} = T_{HTF\ in} - T_{HTF\ out} \tag{6.14}$$

$$\Delta T_{ORC} = T_{ORC\ in} - T_{ORC\ out} \tag{6.15}$$

The recuperator brings the temperature of the fluid exiting the second expander down to a temperature where it is ready to enter the condenser. That change in enthalpy is captured in the heat-exchanger and returned to the cooled fluid exiting

Figure 6-3: A diagram of flows through the vaporizer and the temperature differences used in the LMTD calculations.

the condenser before it enters the vaporizer. Unfortunately, the LMTD model relies on the assumption of single phase flow, which is, by definition, not the case in a vaporizer. A more accurate model would involve a moving-boundary that treats the single-phase section differently from the mixed-phase heat transfer [6].

The condenser involves three stages of convective cooling - pure vapor, mixed flow, and liquid. This is modeled in three different regimes with heat transfer calculated separately for different cells in the condenser [6, 7]. That model was not implemented, and the polynomial fit determined by Ireland was used instead [7]. The equations that characterize the condenser for this model are found below.

$$\dot{Q}_{\text{cond}} = 7.48094441 * 10^3 + 1.25976724 * 10^2 T_{\text{WF}} - 1.51787477 * 10^2 T_{\text{amb}} + 6.34710507 * 10^3 \dot{m}_{\text{air}} \quad (6.16)$$

$$\dot{W}_{\text{el,fans}} = 5.70339029 * 10^2 + 5.03148392 * 10^2 \log \dot{V}_{\text{air}} \quad (6.17)$$

Where $\dot{Q}_{\text{cond}}$ is the heat dissipation of the condenser, T_{WF} is the temperature of the working fluid, T_{amb} is the ambient temperature, and $\dot{m}_{\text{air}}$ is the mass flow rate of the air over the condenser. In Equation 6.17, $\dot{W}_{\text{el,fans}}$ is the parasitic power draw of the fans, and $\dot{V}_{\text{air}}$ is the volumetric flow rate of air over the condenser. The air flow rate through the condenser is fixed to ensure that $\dot{Q}_{\text{cond}}$ is sufficient to condense the working fluid.

6.2.5 Thermal Storage

STGi uses two different types of tanks for thermal energy storage: a mixed tank that is filled entirely with glycol and a packed bed tank filled with quartz. The quartz tank has the benefit of being less expensive, but it also has more thermal inertia. The model used in this simulation is a mixed tank. The mixed tank is modeled as a control volume with equal mass flows entering and exiting the tank and a steady heat loss to the environment. The governing equations for the temperature of the tank over time are:

$$\frac{\Delta h_{tank}}{\mathrm{d}t} = \frac{\dot{Q}_{walls} + \dot{m}_{\mathrm{HTF}}\mathrm{Cp}_{\mathrm{HTF}}\left(T_{tank\ in} - T_{tank\ out}\right)}{m_{tank}} \tag{6.18}$$

$$\Delta T_{tank} = \frac{\Delta h_{tank}}{\mathrm{Cp}_{HTF}} \tag{6.19}$$

where Δh_{tank} is the change in specific enthalpy of the tank, dt is the time-step, $\dot{Q}_{walls}$ is the heat flux through the tank walls, $\dot{m}_{HTF}$ is the mass flow rate of the HTF, Cp_{HTF} is the specific heat capacity of the HTF, $T_{tank\ in}$ is the temperature of the HTF entering the tank, $T_{tank\ out}$ is the temperature of the tank, and m_{tank} is the mass of the tank. For a specified volume, the dimensions for the tank are selected with Equation 6.20 to yield the minimal surface area. Heat loss through the walls is calculated with simple Fickian diffusion, Equation 6.21.

$$r_{SA_{min}}(V) = \sqrt[3]{\frac{V_{tank}}{2\pi}} \tag{6.20}$$

$$\dot{Q}_{walls} = \frac{\mathrm{SA} * k\Delta T_{tank\ wall}}{t} \tag{6.21}$$

where SA is the surface area, V is the tank volume, r is the tank radius, h is the height of the tank, t is the thickness of the tank, k is the thermal conductivity of the tank walls, and $\Delta T_{tank\ wall}$ is the temperature difference across the tank walls.

6.2.6 Chiller

In this ORC system, the chiller is used for the cold storage of vegetables, potatoes in this case. Vegetables are stored in an insulated cold-house which is cooled by an absorption chiller. Absorption chillers are well-suited to this application because they can be directly powered by heat, as little as 80°C in the case of the single effect chiller used for this system. Single, double, and even triple effect chillers are commercially available; each one has progressively greater coefficients of performance (COP) and requires higher grade heat to drive their respective cycles. The parasitic power draw of the chiller is not modeled here.

In this system, the chiller pulls heat out of the HTF after exiting the vaporizer. It converts that heat ($\dot{Q}_{chiller}$) into cooling capacity ($\dot{Q}_{cool}$) by a factor of the COP as calculated with Equation 6.23 [49].

$$\dot{Q}_{cool} = \dot{Q}_{chiller}\text{COP} \tag{6.22}$$

$$\text{COP}_{A-1} = 0.7(-0.05046 * (T_{\text{amb}} + 4) + 2.472) \tag{6.23}$$

To minimize surface area, the potato storage unit is modeled as a cube. The volume is fixed by a design variable for storage capacity by weight and the density of the contents, potatoes (641 kg/m^3) in this case [50]. Heat enters and exits the cube by Fickian diffusion (Equation 6.21) through the walls and the heat from incident solar irradiation is not modeled in this module. The chiller's operation is set by 3 temperatures: T_{rec}, T_{warm}, and T_{spoil}. They respectively specify: the recommended cold temperature, when it is too warm and the chiller needs to be run, and the temperature at which the vegetables will spoil.

Variable	Value
T_{rec}	1 [C]
T_{warm}	7 [C]
T_{spoil}	10 [C]

6.2.7 Pump Modules

The models for the pumps are based on Ireland's polynomial simplification of pump behavior [7]. The parasitic power draw of the HTF pump ($\dot{W}_{elp\ HTF}$) can be calculated with Equation 6.24 where T_{su} is the temperature of the HTF, and $\dot{V}_{su}$ is the volumetric flow rate of the HTF.

$$\dot{W}_{elp\ HTF} = c_o + c_1 * T_{HTF} + c_2 * T_{su}^2 + c_3 * \dot{V}_{su} + c_5 * T_{su} * \dot{V}_{HTF} \tag{6.24}$$

Table 6.2: HTF pump power coefficients

Coefficient	Value
c_0	1.86411220E+01
c_1	-8.91044338E-01
c_2	9.53566173E-03
c_3	5.03864468E+00
c_4	3.87583484E-01
c_5	-8.50046125E-02

The power draw of ORC pump is calculated from the energy that is imparted to the working fluid and a fixed isentropic efficiency (η_{pump}) of 75%, approximately the average efficiency of the pump used in STG's pilot systems [7].

$$W_{pump-out} = \dot{V}_{ORC} \Delta P_p \tag{6.25}$$

$$W_{pump-in} = \frac{W_{pump-out}}{\eta_{ORCpump}} \tag{6.26}$$

6.2.8 Validation

Due to the long run-time for a year-long simulation of power plant operations, it is not realistic to optimize over such a long period of time. Since the demand profile is assumed to be constant from day to day, the simulator models 4 days of operations, three of which are used to reach steady-state and the last one is analyzed as realistic. The cost module then extrapolates this final day for 15 years, which is the assumed system life time. It should be noted that this day is not necessarily representative of a true 15 year period. This simplification was necessary to make the optimization process tractable within the limited available computational resources.

Because the operation and energy output of the system depend heavily on the weather, there are no direct experimental results to use for model validation. The modules are built on empirical relationships, experimentally validated physical models, or a combination of the two approaches. One of the main purposes of this study is to capture the interactions between system components for the design of similar systems.

Given this lack of experimental data, the validation of the simplified model was conducted by benchmarking it with the detailed EES model developed and validated by STG international. The baseline configuration for the system was also based on their current design, which has an insulating wall thickness 20mm, and the minimum temperature to turn on the ORC is 150^oC. These two variables were fixed for model validation purposes. In contrast, all the other design variables were varied as a percentage of the base level. The result of this process is detailed in table 6.3 where 13 benchmark levels are specified.

The criterion for model comparison is the total energy output over 15 years, and the result is shown in table 6.4, where a positive % error indicates larger energy output from the base EES model. From table 6.4, it is observed that in general, the simplified model consistently has an energy output lower than that from high fidelity model. The percent error is between 34% and -17%, but is most commonly around 20%. This consistent error suggests that the main source of modeling error is not related to the

Table 6.3: Benchmarking base case and levels

	Tank volume $[m^3]$	No. collectors [#]	HTF flow rate [kg/s]	Turbine input temp [°C]	Pinch point [°C]	ORC flow rate [kg/s]
Base	2.26	7	0.4679	132	6	0.155
Level 2	1.70	7	0.4679	132	6	0.155
Level 3	3.01	7	0.4679	132	6	0.155
Level 4	2.26	6	0.4679	132	6	0.155
Level 5	2.26	8	0.4679	132	6	0.155
Level 6	2.26	7	0.4229	132	6	0.155
Level 7	2.26	7	0.5129	132	6	0.155
Level 8	2.26	7	0.4679	126	6	0.155
Level 9	2.26	7	0.4679	138	6	0.155
Level 10	2.26	7	0.4679	132	3.6	0.155
Level 11	2.26	7	0.4679	132	8.4	0.155
Level 12	2.26	7	0.4679	132	6	0.205
Level 13	2.26	7	0.4679	132	6	0.105

power plant itself but to the amount of solar resource available. Another significant source of error is aliasing in the energy buffer. Because the simulation window is short, the energy stored in the buffer at the end of each simulation is relatively large. That variation is best seen in levels 2 and 3. In particular, the EES model estimates the solar input based on the latitude, longitude and average meteorological conditions of the power plant location. In contrast, the MATLAB model uses meteorological data from the National Renewable Energy Laboratory [3].

6.3 Structure of the Model

The model is constructed around the flow of the fluids within the system. Each component module takes the state of the fluids, uses them as inputs for the operation of the module, and returns the exit state of the fluids for the next modules to use. There are also logical modules that use the states of other modules to set the oper-

Table 6.4: Benchmarking results. Comparison of 15 year energy outputs [kJ] at the same lat/long for the EES and MATLAB models.

	EES	MATLAB	% error		EES	MATLAB	% error
Level 2	1.34e5	9.78e4	27	Level 8	1.20e5	8.71e4	27
Base Level	1.17e5	8.77e4	25	Base Level	1.17e5	8.77e4	25
Level 3	8.75e4	1.03e4	-17	Level 9	1.13e5	1.01e5	11
Level 4	8.87e4	8.91e4	-1	Level 10	1.16e5	8.96e4	23
Base Level	1.17e5	8.77e4	25	Base Level	1.17e5	8.77e4	25
Level 5	1.38e5	1.12e5	19	Level 11	1.17e5	8.69e4	26
Level 6	1.17e5	8.77e4	25	Level 12	1.04e5	1.10e5	6
Base Level	1.17e5	8.77e4	25	Base Level	1.17e5	8.77e4	25
Level 7	1.32e5	8.77e4	34	Level 13	8.62e4	8.93e4	-4

ational logic of the system. This method is not the most computationally efficient option (structures within MATLAB are generally slower than other variables), but the benefit of interchangeability is worth the slow-down because modularity of this model will enable more analysis in the future.

6.4 Business Module Integration

This model captures the flows of energy and capital between the technological and operational systems. Businesses require energy to run and generate capital. Distributed energy systems, such as the μ-CSP, require startup capital but can produce the energy required to run a business. This interaction is modeled by a business submodule that can only operate when the ORC is running. Right now the ORC is configured to run during pre-determined windows of time, but the demand curve can be made more sophisticated or dynamic in the future.

6.5 NPV and Risk

Net present value (NPV) is a tool for determining the value of a project which accounts for the risk and time-dependence associated with the value of money. NPV is calculated by discounting all cash flows in the future at a 'discount rate'. Discount rates can be used to account for inflation, opportunity costs, or uncertainty associated with revenue. The further away from the beginning of the project, the less the cash-flow is valued.

$$\text{NPV} = -C_0 + \sum_{t=1}^{t_{end}} \frac{C_t}{(1 + r_d)^t} \tag{6.27}$$

Equation 6.27 is the formal definition of NPV, where C_0 is the up-front capital expenditure on the project, C_t is the net cash flow in year t, and r_d is the discount rate. This simulation uses an 18% discount rate because it was the highest interest rate on loans mentioned in interviews with small-business owners and NGOs in India [1].

NPV alone as an objective function can bias the results of the optimization toward larger projects with greater capital costs. Large capital costs increase risk for entrepreneurs in rural India, making some designs unacceptable. Therefore, the advantage of high NPV projects are balanced by the risk of high capital costs with an objective function, Equation 6.28, that normalizes expected NPV by capital expenditures.

$$J(x) = \frac{\text{NPV}(x)}{\text{capEx}(x)} \tag{6.28}$$

Where x is the design vector, $J(x)$ is the objective function, $\text{NPV}(x)$ is the net present value as calculated in Equation 6.27, and $\text{capEx}(x)$ is the sum of capital expenditures for the project. This was minimized with a hybrid genetic algorithm and pattern search minimization.

6.5.1 Optimization and Acceptability

With a very ill tempered objective function, such as this one, gradient and pattern optimizers can struggle to go from an un-acceptable design to something that resembles an acceptable design. Genetic Algorithms (GAs), on the other hand, take a long

[1] Personal correspondences, 2013 - 2015

time to find a global optimum, with no formal guarantee, but can quickly find families of acceptable solutions. The use of GAs here is not to find a true global optimum but to identify acceptable designs. Acceptable designs make the goals of the designer possible. The notion of acceptability comes back to the beginning of this thesis - asking 'what does it make possible?' [8]. Acceptable designs are often more than feasible but are not necessarily optimal.

Acceptability, as it relates to this process is focused on design-by-optimization. The designer's goal is to understand whether it makes sense to delve deeper into the opportunity of CSP-food processing. Optimization can be a tool for analysis, identifying if it is possible to find an acceptable solution with the current model. Once that criterion is satisfied, the designer moves on to the next level of model refinement. The result from the GA will be improved below with a pattern search (PS) algorithm to find better solutions, which can give more insight into the design space and constructs a stronger argument for moving forward with the project.

6.5.2 Optimization Results

Single Objective

The results from the GA optimization and the subsequent pattern search (PS) are in Table 6.5. PS is an optimization algorithm that evaluates surrounding points, as a pseudo-gradient, and steadily climbs uphill. It is capable of exploring a design space without using gradients, which can give it an advantage when solving non-smooth or non-convex problems like μ-CSP ORC food processing.

The GA did find an acceptable result with a NPV/capEx ratio of 2.15 for the simplified simulation and 0.7 for the extended simulation. This is a relevant result because of the 18% discount rate used for calculating the NPV. Even though the design might be acceptable, it is sub-optimal because the PS could improve the result to a NPV/capEx ratio of 2.39 in the simplified simulation and 0.9 in the extended run. The sub-optimality of the GA for finding even a true-local optimum requires the use of a hybrid search after executing the GA. The results from the multi-objective GA below may have room for improvement with a weighted PS or gradient-based-method.

Chillers do not appear to be a part of the optimal solution space. This could be because the current formulation of the cold-storage system is not profitable with the 18% discount rate used for this analysis. Because of the high social value of cold-storage for reducing post-harvest losses, the economics of cold-storage should be revisited to see if a higher-value application than potatoes can be characterized and modeled. The cost and performance of the chiller and cold-storage structure are also worth revisiting.

Table 6.5: The best design vector found by optimization after the genetic algorithm (GA) and subsequent pattern search (PS).

Variable	GA	PS
Tank Volume [m3]	1.67	1.23
Wall Thick [mm]	96	10
Col. N Units	14	14
T_{ORC} [C]	172.12	156.12
HTF $\dot{m}$ $[\frac{kg}{s}]$	0.58	0.58
T_{in} turbine [C]	146.9	149.9
Pinch Point [C]	3.42	3.0
ORC $\dot{m}$ $[\frac{kg}{s}]$	0.178	0.182
Chiller Power [kW]	5.8	0
Chiller Capacity [kg]	61446	0
No. of Machines	5	3
$\frac{NPV}{capEx}$ Short	2.15	2.39
$\frac{NPV}{capEx}$ Long	0.7	0.9

Multi-objective

The solar food processing problem is about understanding the tradeoff between risk (capital expenditures) and benefit (NPV). The single-objective normalization presented above is one way of making that tradeoff. The Pareto front, discussed in section 3.4 is another powerful tool for examining that trade-off in detail.

$$J_{1,2}(x) = [\text{CapEx},\ \text{NPV}] \tag{6.29}$$

Due to the computational intensity of enforcing objective-space constraints for

AWS, the Pareto front is created with a multi-objective genetic algorithm which has a fitness function based on whether the designs are on the non-dominated such that no other design is both cheaper and better (Figure 3-15).

Table 6.6: Interesting designs identified by the multi-GA Pareto front and their performances. The chiller power and capacity are relatively small, indicating that the chiller system is not optimal on this front. This is validated by checking the boolean for whether the produce has spoiled is true.

Variable	1 Machine	Improved 1 Machine	Transition	Big System
Tank Volume [m3]	1.13	1.13	1.66	12.5
Wall Thick [mm]	21	21	31	99
Col. N Units	5	4	7	15
T_{ORC} [C]	172.3	172.3	172.3	163.5
HTF $\dot{m}$ $\left[\frac{kg}{s}\right]$	0.93	0.93	0.69	0.49
Turbine T_{in} [C]	150.0	150.0	139.4	150.0
Pinch Point [C]	5.3	5.3	4.0	3.3
ORC $\dot{m}$ $\left[\frac{kg}{s}\right]$	0.054	0.054	0.129	0.203
Chiller Power [kW]	0.225 (0)	0.225 (0)	0.225 (0)	0.225 (0)
Chiller Capacity [kg]	4,471 (0)	4,471 (0)	4,471 (0)	4.471(0)
No. of Machines	1	1	2	4
$\frac{NPV}{capEx}$ Short	2.88	3.02	1.5	2.21
NPV Short	9.0E4	8.7E4	9.2E4	2.43E5
NPV Long	4.2E4	3.34E4	1.2E4	9.77E4
capEx	3.1E4	2.9E4	6.1E4	1.1E5

The resulting Pareto front in Figure 6-4 has some interesting properties. There are three clear design families: zero machines (blue triangle), 1-machine (red square), and multiple-machine (black circle) moving from left to right. The bottom left design point is not capable of doing any work. The near-vertical cluster to the right of that is a collection of systems which run on one processing machine. That one machine needs at least 1.5 kW of power to operate (hence a minimum capital expenditure requirement) and can operate for longer or shorter amounts of time depending on the total generation and storage capacity of the energy system. The final cluster on the far-right is a continuum of more than one machine running for different amounts of time over the course of the day.

The design variables and their objective functions form interesting points on the curve. Some examples are shown in detail in Table 6.6. None of the designs in-

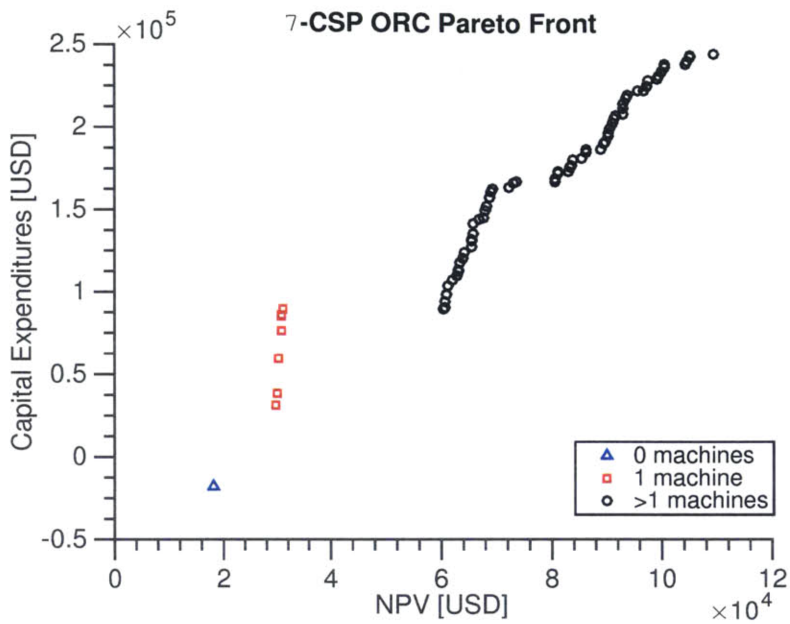

Figure 6-4: The Pareto front for a μ-CSP food processing and cold-storage project.

clude cold-storage, which indicates that the formulation of that system in the model is not profitable. A subject of further investigation will be to get better data and produce better models on the economics and physics of cold-storage. '1 machine' and 'improved 1 machine' refer to the point in the one machine cluster with the highest NPV. That point is sub-optimal because it increases the temperature of the tank beyond the boiling point of the HTF as shown in Figure 6-5. Fortunately, that point is improved by removing one collector, with the resulting performance shown in Figure 6-6. Interestingly, the 'improved 1 machine' design point has a better NPV/capEx ratio than the design that is explicitly optimized with pattern search. However, the '1 machine' design vector outperforms that 'improved 1 machine' in the year-long simulation. This does speak to the sub-optimality of the Pareto front, but those designs are sufficient to justify further investigation into the economic performance of these systems. This nature of local optimality speaks to the importance of using multi-objective optimality to explore the design space of complex problems that have more than one measure of quality.

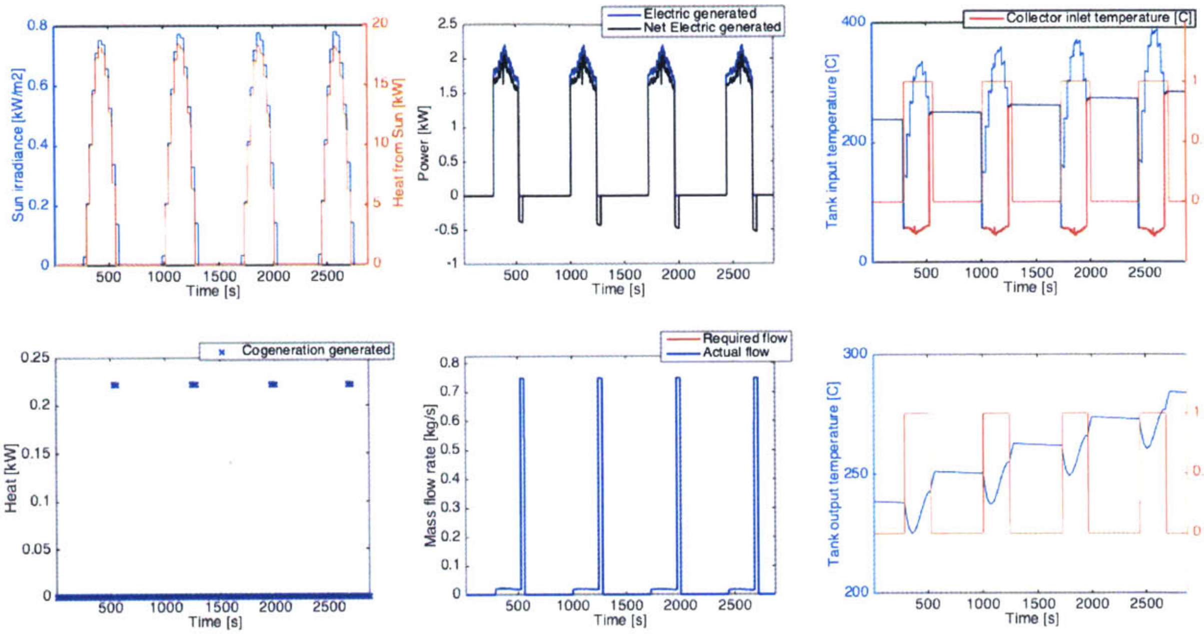

Figure 6-5: The performance of the unimproved 1-machine system over the course of the short simulation.

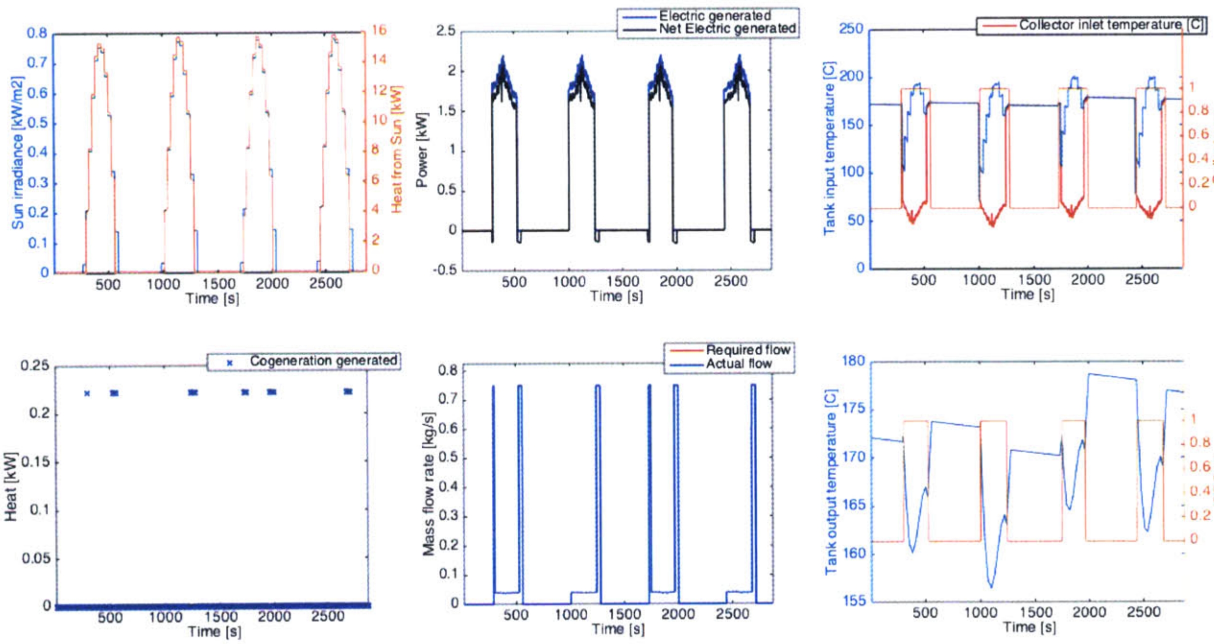

Figure 6-6: The performance of the improved 1-machine system over the course of the short simulation.

6.6 Future Work

There is a lot of work which remains to be done on the modeling of the business and $\mu-$CSP systems. Below is a list of ways to improve the model and optimization problem formulation:

- The vaporizer and the condenser are modeled using Logarithmic Mean Temperature Differences. This only works for single-phase flow on each side, which is not the case. New models for both heat exchangers should account for this change in phase with moving boundaries between different heat transfer regimes.

- Currently the size and material of the condenser is fixed because the model is empirical. A more physically-based model should be implemented to see how the size of the condenser changes with system sizes. The effect of vaporizer size on performance should be investigated as well.

- The logic module that determines the flow rate of the HTF fixes the flow of the HTF to what is required at the vaporizer. The behavior of this module should be modeled more intelligently.

- A physics-based collector module should be implemented. This model will provide more reliable results over a wider range of operating conditions.

- A packed-bed storage tank module should be implemented. The packed bed storage tank is generally less expensive than a mixed tank, and adds more thermal inertia to the system.

- The year-long simulation provides different results than the short run simulation. The optimization algorithm should be run using the year-long simulation for its objective function. In order for this to execute in a timely manner, the execution speed of the year-long simulation will need to be increased.

- Currently, the cost of the chiller is proportional to its cooling capacity. However, absorption chillers come in discrete sizes, and have a minimum size. The minimum size or the discrete component size should be implemented in the optimization to ensure that the resulting chiller size is feasible.

- Resource allocation for multiple business operations is an important consideration for running this $\mu-$CSP system. For example, the chiller needs enough backup power to maintain homeostasis, but the machinery generates more income than the chiller for each kWh. Balancing those two requirements is non-trivial, and an improved operational model would improve the quality of the results from the simulation.

- It is assumed that the homestead processing machinery can operate year-round. This is not the case because there is seasonal variation in supply of raw materials and demand for the product. Correctly estimating this seasonal variation will improve the quality of the optimization results.

- Once a satisfactory energy and business system model has been constructed, that model should be directly validated against the existing experimental systems.

Chapter 7

Conclusion

The goal of rural electrification projects is to enable livelihood-improving activities that could not be done before. The high capital costs of solar, or any distributed energy system, require that the system produces capital to pay for the system and still benefit its owner. These systems have functional requirements to create value. Therefore, the traditional objective functions of cost/watt, or efficiency, do not provide a complete picture. This thesis argues that new systems can be better designed and evaluated by considering value-generation from the very beginning of the process.

The argument is made in two case studies where design for value is at the center of the technology development process. In the case of irrigating marginal-holding farms in east India, this work has designed an appropriately sized solar pump which can deliver enough water to support a full year of cultivation and could pay for itself in less than two years. With food processing, this work has begun to explore the design space for μ-CSP ORC powered value-added and storage facilities. Using optimization to identify the existence of acceptable designs, it was shown that there is economic potential for a solar food processing operation and that it should be explored in greater depth. Both design case studies are built on a framework and code-base that can be adapted to other regions and variations on the application or power system.

The main limitations of this analysis are in the quality of the model and the data. The battery, panel, and motor models are not configured to model how the actual operating voltage of the system changes under different operating conditions. The water demand model is based off of simple estimates. The simplifications in the μ-CSP ORC system are numerous, although some operating points have been compared with the STGi EES model and were found to match closely enough. The business models are derived from interviews and not detailed observation of the actual business operation. Additionally, the CSP system was only optimized against a few days of sunlight, not a full year of operation due to the time constraints on the optimization process. This means that the design points are sub-optimal for a full-year of operation.

There are also limitations in the optimization methods. Because the problem has many local optima, there is no way to guarantee that the identified points are globally optimal. However, finding a globally optimal point is not the goal of this work.

In the case of the irrigation pump, the optimization tool identified a performance point for the new pump. After testing the new pump, system component sizing with the optimization tool showed that an affordable and portable system could be produced with that pump. Now, a pilot system is deployed near Chakradharpur, Jharkhand, India to test the assumptions on water demand and field performance. At each stage in the design process, system optimization was able to identify acceptable solutions that justified moving to the next stage of the process. In the case of the μ-CSP system, the optimization tool has identified acceptable designs which show that a food processing and cold storage operation could be profitable, even with a discount rate of 18%. The existence of these solutions, even though they may be sub-optimal, show that the proposed systems should be explored in greater depth.

Appendix A

Couhes Forms

मैं ने उपरोक्त वर्णित प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन मे भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

अध्ययन-प्रतिभागी का नाम प्रीखा नागराई

कानूनी प्रतिनिधि का नाम (यदि लागू है)

अध्ययन-प्रतिभागी अथवा कानूनी प्रतिनिधि के हस्ताक्षर प्रीखा नागराई

28/3/15
दिनांक

अनुसंधाता के हस्ताक्षर

मेरे विचार से अध्ययन-प्रतिभागी ने स्वेच्छापूर्वक और सोच-समझकर सूचित सहमति प्रदान की है तथा वह इस अनुसंधान अध्ययन में भाग लेने के लिए सोच-समझ कर सहमति प्रदान करने की कानूनी क्षमता रखता है।

अनुसंधाता के हस्ताक्षर

28/3/15
दिनांक

28/3/15
Translator

साक्षात्कार में भाग लेने हेतु सहमति

सौर-शक्तिचालित पम्प अध्ययन

आपसे मैसाचुसेट्स इंस्टिट्यूट ऑफ टेक्नोलॉजी (एम.आई.टी.) के मेकैनिकल इंजीनियरिंग के विद्यार्थियों कैथरीन टेलर (Katherine Taylor), केविन साइमन (Kevin Simon) तथा मार्कोस एस्पारज़ा (Marcos Esparza) द्वारा संचालित अनुसंधान अध्ययन में भाग लेने के बारे में पूछा गया है। इस अध्ययन का उद्देश्य भारत के झारखंड राज्य में छोटी जोत वाले किसानों की सिंचाई संबंधी जरूरतों, इच्छाओं और दैनिक व्यवहारों को बेहतर ढंग से समझना है। इस अध्ययन के परिणाम कैथरीन टेलर, केविन साइमन के स्नातकोत्तर शोध-प्रबंध तथा मार्कोस एस्पारज़ा के अंडरग्रेजुएट शोध-प्रबंध में सम्मिलित किए जाएंगे। आपको इस अध्ययन में संभावित प्रतिभागी के रूप में चुना गया है क्योंकि आप एक छोटी जोत वाले किसान हैं तथा अपनी जमीन की सिंचाई के लिए डीजल पम्प का उपयोग करते हैं। आप नीचे दी गई जानकारी पढ़ें और जो आपको समझ नहीं आए उसके बारे में प्रश्न पूछें और उसके बाद इसमें भाग लेने या नहीं लेने का निर्णय करें।

- यह साक्षात्कार स्वैच्छिक है। आपको कोई भी प्रश्न पूछने तथा किसी भी समय या किसी भी कारण से साक्षात्कार रोकने का अधिकार है। हम आशा करते हैं कि साक्षात्कार में 30 मिनट से 1 घंटे तक का समय लगेगा।
- आपको इस साक्षात्कार के लिए कोई क्षतिपूर्ति नहीं दी जाएगी।
- जबतक कि आप अपनी जानकारी का उपयोग इस अनुसंधान के परिणामस्वरूप भावी प्रकाशनों में करने की अनुमति नहीं देते हैं, आपके द्वारा प्रदान की गई जानकारी गोपनीय रखी जाएगी।
- यह साक्षात्कार रिकार्ड नहीं किया जाएगा।

यह परियोजना 1 मई, 2015 तक पूर्ण कर ली जाएगी।

मैंने उपरोक्त प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(कृपया उस सब पर निशान लगाएं जो लागू है)

[] मैं यह साक्षात्कार रिकार्ड करने की अनुमति प्रदान करता/करती हूं।

[] मैं निम्नलिखित जानकारी इस अध्ययन के परिणामस्वरूप प्रकाशनों में सम्मिलित करने की अनुमति प्रदान करता/करती हूं:

[] मेरा नाम [] मेरी उपाधि [] इस साक्षात्कार के प्रत्यक्ष उद्धरण

अध्ययन-प्रतिभागी का नाम श्री जो. नागराई

अध्ययन-प्रतिभागी के हस्ताक्षर ________________ दिनांक 28/3/15

अनुसंधाता के हस्ताक्षर ________________ दिनांक ________

28/3/15

मैं ने उपरोक्त वर्णित प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(बालूका) सुरेवसई

अध्ययन-प्रतिभागी का नाम

No.

कानूनी प्रतिनिधि का नाम (यदि लागू है)

(बालूका) सुरेवसई

अध्ययन-प्रतिभागी अथवा कानूनी प्रतिनिधि के हस्ताक्षर

27/3/15

दिनांक

अनुसंधाता के हस्ताक्षर

मेरे विचार से अध्ययन-प्रतिभागी ने स्वेच्छापूर्वक और सोच-समझकर सूचित सहमति प्रदान की है तथा वह इस अनुसंधान अध्ययन में भाग लेने के लिए सोच-समझ कर सहमति प्रदान करने की कानूनी क्षमता रखता है।

अनुसंधाता के हस्ताक्षर

27/3/15

दिनांक

27/3/15

translator

साक्षात्कार में भाग लेने हेतु सहमति

सौर-शक्तिचालित पम्प अध्ययन

आपसे मैसाचुसेट्स इंस्टिट्यूट ऑफ टेक्नोलॉजी (एम.आई.टी.) के मेकैनिकल इंजीनियरिंग के विद्यार्थियों कैथरीन टेलर (Katherine Taylor), केविन साइमन (Kevin Simon) तथा मार्कोस एस्पारज़ा (Marcos Esparza) द्वारा संचालित अनुसंधान अध्ययन में भाग लेने के बारे में पूछा गया है। इस अध्ययन का उद्देश्य भारत के झारखंड राज्य में छोटी जोत वाले किसानों की सिंचाई संबंधी जरूरतों, इच्छाओं और दैनिक व्यवहारों को बेहतर ढंग से समझना है। इस अध्ययन के परिणाम कैथरीन टेलर, केविन साइमन के स्नातकोत्तर शोध-प्रबंध तथा मार्कोस एस्पारज़ा के अंडरग्रेजुएट शोध-प्रबंध में सम्मिलित किए जाएंगे। आपको इस अध्ययन में संभावित प्रतिभागी के रूप में चुना गया है क्योंकि आप एक छोटी जोत वाले किसान हैं तथा अपनी जमीन की सिंचाई के लिए डीजल पम्प का उपयोग करते हैं। आप नीचे दी गई जानकारी पढ़ें और जो आपको समझ नहीं आए उसके बारे में प्रश्न पूछें और उसके बाद इसमें भाग लेने या नहीं लेने का निर्णय करें।

- यह साक्षात्कार स्वैच्छिक है। आपको कोई भी प्रश्न पूछने तथा किसी भी समय या किसी भी कारण से साक्षात्कार रोकने का अधिकार है। हम आशा करते हैं कि साक्षात्कार में 30 मिनट से 1 घंटे तक का समय लगेगा।
- आपको इस साक्षात्कार के लिए कोई क्षतिपूर्ति नहीं दी जाएगी।
- जबतक कि आप अपनी जानकारी का उपयोग इस अनुसंधान के परिणामस्वरूप भावी प्रकाशनों में करने की अनुमति नहीं देते हैं, आपके द्वारा प्रदान की गई जानकारी गोपनीय रखी जाएगी।
- यह साक्षात्कार रिकार्ड नहीं किया जाएगा।

यह परियोजना 1 मई, 2015 तक पूर्ण कर ली जाएगी।

मैंने उपरोक्त प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(कृपया उस सब पर निशान लगाएं जो लागू है)

[] मैं यह साक्षात्कार रिकार्ड करने की अनुमति प्रदान करता/करती हूं।

[] मैं निम्नलिखित जानकारी इस अध्ययन के परिणामस्वरूप प्रकाशनों में सम्मिलित करने की अनुमति प्रदान करता/करती हूं:

[] मेरा नाम [] मेरी उपाधि [] इस साक्षात्कार के प्रत्यक्ष उद्धरण

अध्ययन-प्रतिभागी का नाम

अध्ययन-प्रतिभागी के हस्ताक्षर ______________ दिनांक 27/3/15

अनुसंधाता के हस्ताक्षर ______________ दिनांक 27/3/15

27/3/15

साक्षात्कार में भाग लेने हेतु सहमति

सौर-शक्तिचालित पम्प अध्ययन

आपसे मैसाचुसेट्स इंस्टिट्यूट ऑफ टेक्नोलॉजी (एम.आई.टी.) के मेकैनिकल इंजीनियरिंग के विद्यार्थियों कैथरीन टेलर (Katherine Taylor), केविन साइमन (Kevin Simon) तथा मार्कोस एस्पारज़ा (Marcos Esparza) द्वारा संचालित अनुसंधान अध्ययन में भाग लेने के बारे में पूछा गया है। इस अध्ययन का उद्देश्य भारत के झारखंड राज्य में छोटी जोत वाले किसानों की सिंचाई संबंधी जरूरतों, इच्छाओं और दैनिक व्यवहारों को बेहतर ढंग से समझना है। इस अध्ययन के परिणाम कैथरीन टेलर, केविन साइमन के स्नातकोत्तर शोध-प्रबंध तथा मार्कोस एस्पारज़ा के अंडरग्रेजुएट शोध-प्रबंध में सम्मिलित किए जाएंगे। आपको इस अध्ययन में संभावित प्रतिभागी के रूप में चुना गया हैं क्योंकि आप एक छोटी जोत वाले किसान हैं तथा अपनी जमीन की सिंचाई के लिए डीजल पम्प का उपयोग करते हैं। आप नीचे दी गई जानकारी पढ़ें और जो आपको समझ नहीं आए उसके बारे में प्रश्न पूछें और उसके बाद इसमें भाग लेने या नहीं लेने का निर्णय करें।

- यह साक्षात्कार स्वैच्छिक है। आपको कोई भी प्रश्न पूछने तथा किसी भी समय या किसी भी कारण से साक्षात्कार रोकने का अधिकार है। हम आशा करते हैं कि साक्षात्कार में 30 मिनट से 1 घंटे तक का समय लगेगा।
- आपको इस साक्षात्कार के लिए कोई क्षतिपूर्ति नहीं दी जाएगी।
- जबतक कि आप अपनी जानकारी का उपयोग इस अनुसंधान के परिणामस्वरूप भावी प्रकाशनों में करने की अनुमति नहीं देते हैं, आपके द्वारा प्रदान की गई जानकारी गोपनीय रखी जाएगी।
- यह साक्षात्कार रिकार्ड नहीं किया जाएगा।

यह परियोजना 1 मई, 2015 तक पूर्ण कर ली जाएगी।

मैंने उपरोक्त प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(कृपया उस सब पर निशान लगाएं जो लागू है)

[] मैं यह साक्षात्कार रिकार्ड करने की अनुमति प्रदान करता/करती हूं।

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[] मेरा नाम [] मेरी उपाधि [] इस साक्षात्कार के प्रत्यक्ष उद्धरण

अध्ययन-प्रतिभागी का नाम

अध्ययन-प्रतिभागी के हस्ताक्षर ________ दिनांक 27/3/15

अनुसंधाता के हस्ताक्षर ________ दिनांक 27/3/15

27/3/15

translator

मैं ने उपरोक्त वर्णित प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

पुरी सुमाकरई

अध्ययन-प्रतिभागी का नाम

NO

कानूनी प्रतिनिधि का नाम (यदि लागू है)

पुरी सुमाकरई

अध्ययन-प्रतिभागी अथवा कानूनी प्रतिनिधि के हस्ताक्षर

27/3/15

दिनांक

अनुसंधाता के हस्ताक्षर

मेरे विचार से अध्ययन-प्रतिभागी ने स्वेच्छापूर्वक और सोच-समझकर सूचित सहमति प्रदान की है तथा वह इस अनुसंधान अध्ययन में भाग लेने के लिए सोच-समझ कर सहमति प्रदान करने की कानूनी क्षमता रखता है।

अनुसंधाता के हस्ताक्षर

27/3/15

दिनांक

27/3/15

translator

मैं ने उपरोक्त वर्णित प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

कुलविंदर सिंह सोहल

अध्ययन-प्रतिभागी का नाम

कानूनी प्रतिनिधि का नाम (यदि लागू है)

कुलविंदर सिंह सोहल

अध्ययन-प्रतिभागी अथवा कानूनी प्रतिनिधि के हस्ताक्षर

27/3/15

दिनांक

अनुसंधाता के हस्ताक्षर

मेरे विचार से अध्ययन-प्रतिभागी ने स्वेच्छापूर्वक और सोच-समझकर सूचित सहमति प्रदान की है तथा वह इस अनुसंधान अध्ययन में भाग लेने के लिए सोच-समझ कर सहमति प्रदान करने की कानूनी क्षमता रखता है।

अनुसंधाता के हस्ताक्षर

27/3/15

दिनांक

27/3/15

Translator

साक्षात्कार में भाग लेने हेतु सहमति

सौर-शक्तिचालित पम्प अध्ययन

आपसे मैसाचुसेट्स इंस्टिट्यूट ऑफ टेक्नोलॉजी (एम.आई.टी.) के मेकैनिकल इंजीनियरिंग के विद्यार्थियों कैथरीन टेलर (Katherine Taylor), केविन साइमन (Kevin Simon) तथा मार्कोस एस्पारज़ा (Marcos Esparza) द्वारा संचालित अनुसंधान अध्ययन में भाग लेने के बारे में पूछा गया है। इस अध्ययन का उद्देश्य भारत के झारखंड राज्य में छोटी जोत वाले किसानों की सिंचाई संबंधी जरूरतों, इच्छाओं और दैनिक व्यवहारों को बेहतर ढंग से समझना है। इस अध्ययन के परिणाम कैथरीन टेलर, केविन साइमन के स्नातकोत्तर शोध-प्रबंध तथा मार्कोस एस्पारज़ा के अंडरग्रेजुएट शोध-प्रबंध में सम्मिलित किए जाएंगे। आपको इस अध्ययन में संभावित प्रतिभागी के रूप में चुना गया हैं क्योंकि आप एक छोटी जोत वाले किसान हैं तथा अपनी जमीन की सिंचाई के लिए डीजल पम्प का उपयोग करते हैं। आप नीचे दी गई जानकारी पढें और जो आपको समझ नहीं आए उसके बारे में प्रश्न पूछें और उसके बाद इसमें भाग लेने या नहीं लेने का निर्णय करें।

- यह साक्षात्कार स्वैच्छिक है। आपको कोई भी प्रश्न पूछने तथा किसी भी समय या किसी भी कारण से साक्षात्कार रोकने का अधिकार है। हम आशा करते हैं कि साक्षात्कार में 30 मिनट से 1 घंटे तक का समय लगेगा।
- आपको इस साक्षात्कार के लिए कोई क्षतिपूर्ति नहीं दी जाएगी।
- जबतक कि आप अपनी जानकारी का उपयोग इस अनुसंधान के परिणामस्वरूप भावी प्रकाशनों में करने की अनुमति नहीं देते हैं, आपके द्वारा प्रदान की गई जानकारी गोपनीय रखी जाएगी।
- यह साक्षात्कार रिकार्ड नहीं किया जाएगा।

यह परियोजना 1 मई, 2015 तक पूर्ण कर ली जाएगी।

मैंने उपरोक्त प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(कृपया उस सब पर निशान लगाएं जो लागू है)

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अध्ययन-प्रतिभागी का नाम

अध्ययन-प्रतिभागी के हस्ताक्षर कुवाँर सिंह सोरेन दिनांक 27/3/15

अनुसंधाता के हस्ताक्षर ____________________ दिनांक __________

27/3/15

Translator

साक्षात्कार में भाग लेने हेतु सहमति

सौर-शक्तिचालित पम्प अध्ययन

आपसे मैसाचुसेट्स इंस्टिट्यूट ऑफ टेक्नोलॉजी (एम.आई.टी.) के मेकैनिकल इंजीनियरिंग के विद्यार्थियों कैथरीन टेलर (Katherine Taylor), केविन साइमन (Kevin Simon) तथा मार्कोस एस्पारज़ा (Marcos Esparza) द्वारा संचालित अनुसंधान अध्ययन में भाग लेने के बारे में पूछा गया है। इस अध्ययन का उद्देश्य भारत के झारखंड राज्य में छोटी जोत वाले किसानों की सिंचाई संबंधी जरूरतों, इच्छाओं और दैनिक व्यवहारों को बेहतर ढंग से समझना है। इस अध्ययन के परिणाम कैथरीन टेलर, केविन साइमन के स्नातकोत्तर शोध-प्रबंध तथा मार्कोस एस्पारज़ा के अंडरग्रेजुएट शोध-प्रबंध में सम्मिलित किए जाएंगे। आपको इस अध्ययन में संभावित प्रतिभागी के रूप में चुना गया हैं क्योंकि आप एक छोटी जोत वाले किसान हैं तथा अपनी जमीन की सिंचाई के लिए डीजल पम्प का उपयोग करते हैं। आप नीचे दी गई जानकारी पढें और जो आपको समझ नहीं आए उसके बारे में प्रश्न पूछें और उसके बाद इसमें भाग लेने या नहीं लेने का निर्णय करें।

- यह साक्षात्कार स्वैच्छिक है। आपको कोई भी प्रश्न पूछने तथा किसी भी समय या किसी भी कारण से साक्षात्कार रोकने का अधिकार है। हम आशा करते हैं कि साक्षात्कार में 30 मिनट से 1 घंटे तक का समय लगेगा।
- आपको इस साक्षात्कार के लिए कोई क्षतिपूर्ति नहीं दी जाएगी।
- जबतक कि आप अपनी जानकारी का उपयोग इस अनुसंधान के परिणामस्वरूप भावी प्रकाशनों में करने की अनुमति नहीं देते हैं, आपके द्वारा प्रदान की गई जानकारी गोपनीय रखी जाएगी।
- यह साक्षात्कार रिकार्ड नहीं किया जाएगा।

यह परियोजना 1 मई, 2015 तक पूर्ण कर ली जाएगी।

मैंने उपरोक्त प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

(कृपया उस सब पर निशान लगाएं जो लागू है)

[] मैं यह साक्षात्कार रिकार्ड करने की अनुमति प्रदान करता/करती हूं।

[] मैं निम्नलिखित जानकारी इस अध्ययन के परिणामस्वरूप प्रकाशनों में सम्मिलित करने की अनुमति प्रदान करता/करती हूं:

[] मेरा नाम [] मेरी उपाधि [] इस साक्षात्कार के प्रत्यक्ष उद्धरण

अध्ययन-प्रतिभागी का नाम

अध्ययन-प्रतिभागी के हस्ताक्षर *Puna Simbri* ______________________ दिनांक ____________

अनुसंधाता के हस्ताक्षर ______________________________ दिनांक ____________

मैं ने उपरोक्त वर्णित प्रक्रिया समझ ली है। मेरे प्रश्नों का संतोषप्रद जवाब दिया गया है और मैं इस अध्ययन में भाग लेने के लिए सहमत हूं। मुझे इस प्रपत्र की प्रति प्राप्त हो गई है।

PUSA SUMBRUI

अध्ययन-प्रतिभागी का नाम

कानूनी प्रतिनिधि का नाम (यदि लागू है)

Pusa Sumbrui

अध्ययन-प्रतिभागी अथवा कानूनी प्रतिनिधि के हस्ताक्षर

27/3/15

दिनांक

अनुसंधाता के हस्ताक्षर

मेरे विचार से अध्ययन-प्रतिभागी ने स्वेच्छापूर्वक और सोच-समझकर सूचित सहमति प्रदान की है तथा वह इस अनुसंधान अध्ययन में भाग लेने के लिए सोच-समझ कर सहमति प्रदान करने की कानूनी क्षमता रखता है।

अनुसंधाता के हस्ताक्षर

27/3/15

दिनांक

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