Department of Applied Physics

Reliability and sustainability analyses of frugal solar photovoltaic micro-grid systems in emerging markets

Sini Numminen

Aalto University

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Sini Numminen

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Aalto University
School of Science
Department of Applied Physics
New Energy Technologies

Supervising professor
Professor Peter D. Lund, Aalto University, Finland

Preliminary examiners
Professor Jouko Korppi-Tommola, University of Jyväskylä, Finland
Docent Jyrki Luukkanen, University of Turku, Finland

Opponent
Professor Ewa Wäckelgård, Uppsala University, Sweden

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Abstract

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Abstract

Massive over-consumption of natural resources has resulted in severe environmental and climate problems, which in turn threaten life supporting ecosystems. Moreover, despite some nations driving this over-consumption, millions of people in other parts of the world, still suffer from energy poverty: 2.7 billion people live without access to clean cooking facilities, and one billion without access to electricity mainly in the sub-Saharan Africa and the developing regions of Asia. The main motivation of this dissertation is to better understand the relevance of frugal energy innovations in providing affordable energy services to impoverished people in emerging economies in a sustainable manner.

The dissertation contains a novel five-criteria method for the identification of frugal energy innovations, which underlines local appropriateness, affordability, sustainability and technical durability. A frugal technology, a solar micro-grid system with locally manufactured pre-paid energy meters was investigated in rural Northern India through a set of field measurement trials. The micro-grids included an advanced pricing method that could potentially decrease system cost, which is of the utmost importance in low-income communities. However, the dynamic pricing function was not found beneficial in the field trial, because the impoverished customers minimized their power consumption, so demand response benefits could not be demonstrated. Therefore it is recommended to design technology and business models with an essential user-centered approach without overlooking the potential necessity of educating end-users in areas where people may have not had access to power grid services before. Moreover, the frugal electronic component quality requires attention.

A particular focus in this dissertation is on the reliability of solar micro-grid systems. In the field trial, power was measured to be available for the households 87% of the time. The number of days without blackouts was 200 out of 356 days measured. The reasons for a lack of reliability were related to a lack of solar energy in the winter season, component failures, and unexpected user activities such as power theft. This study also presents a new reliability assessment method for renewable off-grid power systems, based on an interview study with solar micro-grid operators in India. The method is descriptive, which has an advantage of better highlighting localized problems, such as long maintenance outages in remote regions or a lack of sufficient protective measures of some critical system units. The use of the framework may encourage reliability thinking and assist in designing more reliable power systems.

Keywords Solar photovoltaic, micro-grids, reliability assessment, frugal innovation, energy frugality, emerging markets, energy for sustainable development, India

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Tiivistelmä

Luonnonvarojen ylikulutus on johtanut vakaviin ympäristö- ja ilmasto-ongelmiin, jotka puolestaan uhkaavat elämää ylläpitäviä ekosysteemejä maapallolla. Samaan aikaan miljoonat ihmiset kärsivät energiaköyhyydestä: 2,7 miljardia ihmistä elää ilman puhtaita ruoanlaittovälineitä ja -tiloja ja miljardilla ihmisellä ei ole pääsyä sähköverkkojen palveluihin, lähinnä Saharan eteläpuolisessa Afrikassa ja Aasian kehittyvillä alueilla. Tämän väitöskirjan päätavoitteena oli ymmärtää niukkojen energiainnovaatioiden merkitystä tarjota kestäviä ja kohtuuhintaisia energiapalveluita köyhille väestöryhmille kehittyvillä markkinoilla.

Tämä väitöskirja sisältää uuden viiden kohdan määritelmän niukkojen energiainnovaatioiden tunnistamiseksi. Määritelmä korostaa teknologioiden paikallista sopivuutta, edullisuutta, kestävyyttä ja teknistä laatua. Tutkimuksen keskiössä oli aurinkosähköinen pieni mikroverkko Pohjois-Intian maaseudulla. Intiassa paikallisesti valmistettujen energiamittareiden avulla sähkön hinta muuttui dynaamisesti. Ratkaisu voisi pienentää järjestelmän kokonaiskustannuksia, mikä olisi keskeistä matalan tulotason yhteisöissä. Dynaamisen sähkön hinnoittelun hyödyllisyyttä ei kuitenkaan voitu tässä kokeessa osoittaa, sillä köyhdytetyt asiakkaat käyttivät sähköverkkojen energiaa vain hyvin pieniä määriä. Tällaisissa toimintaympäristöissä on ensiarvoista, että liiketoimintamallit ja teknologiat suunnitellaan käyttäjälähtöisesti. Joskus on syytä arvioida, olisiko uusien käyttäjien kouluttamiselle tarvetta, etenkin jos asiakkaat eivät aikaisemmin ole voineet käyttää sähköverkkojen palveluita. Lisäksi niukkojen elektronisten laitteiden laatuun on kiinnitettävä huomiota.

Väitöskirjassa keskityttiin erityisesti mikroverkkojärjestelmien luotettavuuteen. Tuotanto- ja kulutusmittausten avulla havaittiin, että mikroverkkojen tarjoama sähkö oli kotitalouksien saatavilla 87% ajasta. Kun mittauspäiviä oli 356, sähkökatkottomien päivien lukumäärä oli 200. Luotettavuuspuutteet liittyivät aurinkoenergian saatavuuteen, komponenttien rikkoontumiseen sekä käyttäjien ei-odotettuun toimintaan, kuten sähkön pihistämiseen. Lisäksi tässä työssä esitellään uusi arviointimenetelmä mikroverkkojen luotettavuudelle, joka pohjautuu Intian maaseudulla toimivien aurinkosähkömikroverkko-operaattoreiden haastattelututkimukseen. Arviointimenetelmä on kuvaileva, jolloin ongelmien paikallinen luonne voidaan huomioida paremmin. Pitkiä sähkökatkoja aiheuttivat esimerkiksi varaosien saatavuusongelmat, tai puute jonkin järjestelmän osan suojauksessa. Menetelmän käyttö voi kannustaa luotettavuusajatteluun ja sen avulla voidaan suunnitella kestävämpiä sähköjärjestelmiä.

Avainsanat Aurinkosähkö, mikroverkot, luotettavuuden arviointi, niukka innovaatio, energianiukkuus, kehittyvät markkinat, energia ja kestävä kehitys, Intia

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Preface

This dissertation is based on work carried out in the New Energy Technologies Group of the Department of Applied Physics, Aalto University School of Science, under the supervision of Professor Peter D. Lund. The work was funded by the Tiina and Antti Herlin Foundation, Finland, with a personal doctoral research grant for the author (30 months) and by the Finnish Technology and Innovation Agency (TEKES) through the New Global project of Aalto University (first 20 months). The funding for field trips to India were covered by New Global and by the Finnish University Partnership for International Development (UniPID). The financial support is greatly appreciated as I was able to focus fully on my research.

I wish to thank my supervising professor Peter D. Lund for offering this opportunity, as well as for the valuable feedback, guidance and lots of encouragement throughout the PhD process. I also wish to express my gratitude to Professor Johannes Urpelainen from the Johns Hopkins School of Advanced International Studies (USA) for being an inspiring project leader in the pico-grid experiment, and Professor Semee Yoon from Yonsei University in South Korea for the fruitful research collaboration. I also profoundly thank Mr Rustam Sengupta, Mr Simran Grover and all other staff members of Boond Engineering & Development Pvt Ltd and Mr Gopi Krishna from Emsys Electronics Pvt Ltd for their efforts in the outstanding pico-grid experiment, and for patiently answering my thousands of questions, as well as my other Indian interviewees for their time and contributions.

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I am deeply grateful also for my other co-workers and friends. Dr. Panu Hiekkataipale was a continuous help with everything. He helped me to understand the joy of conducting laboratory measurements and also gave valuable comments on the final draft of the dissertation. Laura Euro, Juhani Paasonen, Harri Häivälä, Lindsay Simmonds, Dr. Kati Miettunen and my mentor Eeva-Liisa Mauno were indispensable in their technical, methodological and emotional support as well as Laura Euro, Taina Numminen, and Elisa Hauhia in helping with graphic materials. I also wish to acknowledge Bill Hellberg and Tommi Kakko for elevating my English writing skills through the Writing Clinic of Aalto University. Finally, I want to express my heartfelt gratitude to my father, my mother, my sisters and all my dear friends for always being there.

Helsinki, April 4, 2019,

Sini Numminen

Contents

Nomenclature

Abbreviations

AC Alternating current

CEEW Council on Energy, Environment and Water

CEO Chief executive officer

CLEAN The Clean Energy Access Network

CTO Chief technology officer

DC Direct current

DSM Demand side management

ESCO Energy service company

ESMAP Energy Sector Management Assistance Program of the World Bank

IEA International Energy Agency

INR Indian rupee

LCD Liquid-crystal display

LED Light-emitting diode

LOLH Loss of load hours

LOLP Loss of load probability

MDT Mean down time

MTR Maximum time to repair

MTSR Mean time to start repairing

MTTR Mean time to repair

O&M Operation and maintenance

PV Photovoltaic

Pvt. Ltd. Private company limited by shares

SHS Solar home system

STC Standard test conditions

T&D Transmission and distribution

UP Uttar Pradesh

Symbols

A Ampere

Ah Ampere-hour

$\mathbf{CO_2}$ Carbon Dioxide

$\mathbf{I_{ch}}$ Charging current

$\mathbf{I_{load}}$ Load current

$\mathbf{L(t)_i}$ Load profile as function of time t in hamlet i

M(t) Overlapping part of solar generation profile and load profile

$\mathbf{P_{PV}}$ Energy produced by the PV panel

P(t) Power profile of solar generation

S(t) Power profile of the storage unit

V Volt

$\mathbf{V_d}$ Distribution voltage

$\mathbf{V_{PV}}$ PV panel voltage

W Watt

Wh Watt-hour

Wp Watt-peak

h hour

ϕ_{SC} Self-consumption index

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I S. Numminen, P. D. Lund. Frugal energy innovations for developing countries – a framework. *Global Challenges*, 1, 1, 9–19, doi:10.1002/gch2.1012, September 2016.

II J. Levänen, M. Hossain, T. Lyytinen, A. Hyvärinen, S. Numminen, M. Halme. Implications of frugal innovations on sustainable development: evaluating water and energy innovations. *Sustainability. Special Issue "Sustainable Development Goals: A Call for Frugal Innovations for a Resource-Scarce World"*, 8, 4, 1–17, doi:10.3390/su8010004, December 2015.

III S. Numminen, S. Yoon, J. Urpelainen, P. D. Lund. An evaluation of dynamic electricity pricing for solar micro-grids in rural India. *Energy Strategy Reviews*, 21, 130–136, doi:10.1016/j.esr.2018.05.007, August 2018.

IV S. Numminen, P. D. Lund, S. Yoon, J. Urpelainen. Power availability and reliability of solar pico-grids in rural areas: a case study from northern India. *Sustainable Energy Technologies and Assessments*, 29, 147–154, doi:10.1016/j.seta.2018.08.005, October 2018.

V S. Numminen, P. D. Lund. Evaluation of the reliability of solar micro-grids in emerging markets – issues and solutions. *Energy for Sustainable Development*, 48, 34–42, doi:10.1016/j.esd.2018.10.006, 1 February 2019.

Author's Contribution

Publication I: "Frugal energy innovations for developing countries – a framework"

The author was responsible for background research, collecting and analyzing frugal innovation cases and drafting the manuscript. The author also contributed to the conception of energy frugality and writing the paper.

Publication II: "Implications of frugal innovations on sustainable development: evaluating water and energy innovations"

The author had the main responsibility of analysing the solar energy technology case and writing sections related to it. The author also contributed to research design and writing the paper.

Publication III: "An evaluation of dynamic electricity pricing for solar micro-grids in rural India"

The author participated in technical design of the research experiment, in the data analysis and in writing the paper. The author conducted field work and had the main responsibility of the data analysis regarding the self-consumption index (Table 4) and system interruptions (Table S7).

Publication IV: "Power availability and reliability of solar pico-grids in rural areas: a case study from northern India"

The author was responsible for inventing the method for studying reliability, building data analysis scripts, conducting field work, making laboratory tests, analysing the data and the results. The author co-authored the article.

Publication V: "Evaluation of the reliability of solar micro-grids in emerging markets – issues and solutions"

The author developed the idea of the paper with the co-author, and was responsible for research design, methodology and analysing the data and the results. The author also conducted interviews and field visits, compiled the reliability assessment framework and co-authored the article.

Language check

The language of my dissertation has been checked by Anya Siddiqi from Aalto Language Centre, and Elisa Hauhia and Daniel Rajala. I have personally examined and accepted/rejected the results of the language check one by one. This has not affected the scientific content of my dissertation.

1. Introduction

1.1 Overview

The consumption of natural resources and energy has risen along with increasing welfare and population. By the end of this century, it is expected that the global energy consumption will have risen from 16.2 TW in 2007 to 47 TW, even according to conservative calculations [1]. During the last century alone, the usage of ore and minerals rose 27-fold, whereas the use of fossil fuels has risen 12-fold [2, p. 89]. Such massive overconsumption of natural resources has resulted in severe environmental and climate problems that currently threaten life supporting ecosystems.

For all types of materials, the per-capita consumption in developed countries is several times higher than in the less developed countries [3]. However, the energy consumption in the developing world is growing rapidly because of population growth and raising welfare, which often is linked to the new middle classes striving for western-type of living standards. Future consumption habits worldwide will have a crucial effect on the environment of our planet. For example, if all the citizens of India used fossil fuels per capita as much as US citizens, the global CO_2 emissions would increase by 55% [4].

Despite this phenomenon, millions of people still suffer from energy deprivation and energy poverty: 2.7 billion people live without access to clean cooking facilities, and one billion without access to electricity [5], mainly in the sub-Saharan Africa and the developing regions of Asia. It is our urgent quest to find novel and sustainable energy solutions for these regions. In addition to sustainability, affordability deserves special attention in this context as poverty is a prevailing condition in these regions [6]. Affordable and sustainable domestic energy services for food preparation, space and water heating, lighting, and communication would be of high relevance in these countries.

Related to the requirement for affordability, so-called frugal innovations have been introduced as a concept in which economic and material constraints act as driving forces for finding smart and simple solutions for day-to-day problems, either by the underprivileged people themselves or by enterprises with business prospects. In essence, frugal innovations and systems embrace simplicity, also in the energy sector. Frugal innovations can be manufactured with fewer resources and sold with lower price than similar, more sophisticated and complex products, thus better responding to the demands of the impoverished [7].

Energy frugal processes would address the above-mentioned energy challenge, and could be related to the whole value-chain of energy. Energy frugality may also mean learning processes to use energy more efficiently or to supply energy services with less resources, or even lifestyles that are attentive to expenditures on energy [8]. However, on a global scale, energy frugality is mostly not a lifestyle choice, but a necessity dictated by reality. In the form of reverse innovation [9], energy frugality could also encourage resource frugality in rich societies [1].

The relevance of frugal innovations to alleviate energy poverty has not been widely studied. In particular, systematic assessments of frugal energy technologies in low-income contexts are not available. This dissertation is built around this research gap. The focus here is on analyses of technical systems that involve frugal features. Of particular interest are solar micro-grids in India, where such systems could raise the living standard of millions on people in remote and rural areas.

1.2 Aims and scope

The main motivation of this thesis was to better understand the relevance of frugal energy innovations in providing sustainable and affordable energy services to impoverished people in emerging economies. First, a systematic way for the identification of frugal energy innovation was proposed to better identify and deploy them (Publication I). Such a work had not been earlier done due to the novelty of the concept of frugal innovation. In this context, sustainable development also needs to be considered as an important dimension (Publication II).

Small solar photovoltaic systems employing the micro-grid concept has emerged as a potential frugal technology. Solar micro-grids are capital-intensive and to render these more viable to low-income target groups, it would be extremely vital to both maximize the benefits from the solar installations as well as avoid any extra operational and maintenance costs.

The second set of research questions emerged from this context as the knowledge to assess these dimensions appeared to be very limited. Therefore, the reliability of solar micro-grids and the factors affecting the level of reliability were investigated through a set of field trials with solar micro-grids in northern India (Publication IV and Publication V). This study revealed not only key factors affecting reliability, but also major gaps in available procedures to assess reliability. To fill these gaps, a new systematic method for reliability assessment was devised, also with the hope that this would encourage businesses to pay more attention to reliability-related issues in the future.

In addition to a lack of reliability considerations, the user interaction of solar micro-grids has also attracted insufficient attention. Maximizing benefits from a solar micro-grid system is often related to optimal sizing and design of the major components of the system. In this dissertation, a unique field trial with several rural households was undertaken to evaluate the possible influence of electricity use patterns on households through price incentives, in other words, by increasing demand at high supply times and vice versa (Publication III). In this way, through better demand response, the energy benefits from a solar micro-grid could potentially be increased and the system costs could also be decreased. For this purpose, advanced smart meters were employed which were locally manufactured in a frugal way.

The contents of this dissertation derive from five original publications which address the above aims. The publications are presented in the list of publications. The dissertation is divided into seven chapters. In Chapter 1, the overview and the background are provided as well as the outline of the dissertation. Concepts of frugal innovations and solar micro-grids are described in Chapter 2. The research methods are presented in Chapter 3. Chapter 4 presents the main results, and Chapter 5 discusses the theoretical and practical implications of the dissertation. Finally, Chapter 6 concludes the dissertation.

2. Frugal innovations for sustainable energy

This chapter discusses the theoretical concept of frugal innovation with its implications for sustainable development. Then, solar micro-grids are presented and their connection to frugal energy services in developing countries.

2.1 The frugal innovation concept and sustainability

The concept of frugal innovation has recently emerged in the business regime to signify smart and simplified solutions that offer affordable services for the large underserved populations in developing countries [10] [11] [12]. The first frugal products that reached wider popular attention were designed by large multinational and international corporations (e.g. General Electric, Tata, Nokia). For example, the simplified and portable electrocardiogram was to revolutionize the medical sector in areas without access to reliable power supply. The product was sold at half the price of large hospital equipment providing the same diagnoses [13]. The second group of frugal innovations refer to solutions created by these who themselves live in circumstances with a shortage of economic or material resources, or some functional service [14]. For example, the famous clay-made cold storage for alimentary products may not ever have been invented, if the national power supply had been uninterrupted in the Indian countryside [15].

Briefly, frugal innovations deliver "more with less" [16], because frugally engineered products are designed with the strictest cost-conscious mindset by involving smaller amounts of raw materials and components during the manufacturing and assembly phases. Frugal innovation appears to also have a great potential in promoting global energy-saving and environmental protection [1] through the reduced use of resources [17] [7]. The possibilities for energy frugality also lie at the user end, for example, through an integration of energy harvesting units and through solutions that embrace low or zero standby power levels and energy efficiency. Like this, frugal innovations may contribute to attaining several Sustainable Development Goals, which are ambitious global targets for 2030, set by the United Nations in 2015 [3]. In particular, goals that call for more sustainable consumption and production patterns (Goal 12) and climate change mitigation (Goal 13) may be addressed, as well as Goals 14 and 15 which consider natural habitats protection.

Nevertheless, the number of practical studies are still limited which would assess the sustainability of frugal innovations, taking all of their benefits and weaknesses holistically into account [18] [19]. Generally, frugal innovation is altogether not a coherently defined term; it has also been used for marketing dubious products that overlook next-stage usage possibilities [20].

In the energy service sector, frugal innovations could include low-cost and efficient cooking stoves or pico-scale electricity (Publication I), these might alleviate energy poverty of the millions of people without access to clean cooking facilities and electricity, thus directly addressing the Sustainable Development Goal 7. Frugal energy technologies may also alleviate poverty (Goal 1), promote education opportunities (Goal 4) and improve health (Goal 3). Impact analysis would always require localized scrutiny, however. It also matters whether the energy solution could power income-generation activities, which might foster socio-economic development in the communities (Goals 8 and 9).

One aspect which has garnered only a little interest in frugal innovation studies is their technical quality. The questions of quality, or reparability, deserve attention because short product lifetimes may result in excessive amounts of waste that may nullify other sustainability benefits. Ideally, frugal innovation embraces quality, in contrast with other resource-constrained innovations [21]. Large corporations, having developed the most well-known examples of frugal innovations, may have equipped their design teams with sufficient economic and intellectual resources as well as incorporated quality assurance and standards compliance into product design processes. Therefore, sometimes frugal innovations are considered to possess an inherently high technical quality [22]. However, when a variety of smaller players enter the frugal innovation market, the introduction of inferior quality products becomes more likely.

The concern over a lack of product quality is particularly relevant for energy technologies because they may be crucial to basic services, such as food preparation or water access. Unreliability of energy supply may have drastic consequences for example in a health centre. In addition, reliability of energy supply service affects customer experience which is directly connected with the economic viability of an energy project [23]. Comprehensive reliability tests (e.g. laboratory tests presented in [24] for a frugal wind turbine) may not always be possible in all resource-constrained circumstances due to budget limitations, but some level of understanding of the service reliability would be vital.

2.2 Photovoltaic solar micro-grids providing frugal energy services

Photovoltaics (PV) convert solar energy directly into direct current (DC) electricity, which can be used immediately or saved in a storage system for later use. Many developing countries are located in tropical and sub-tropical areas favourable for exploiting solar energy due to elevated irradiation levels. However, wide regional variation exists due to geography, weather conditions, micro-climate and the concentration of airborne particles (dust, pollution) that affects solar cell output. A photovoltaic power system can serve an individual household, or several users at once when connected to a solar micro-grid.

Micro-grids hold a considerable potential to improve electricity access in developing regions [25] [26]. The lack of access affects particularly rural areas, as around 80% of people without access live in rural areas [27]. International Energy Agency (IEA) estimates that 70% of people lacking access in these areas could be served in the lowest cost manner with micro-grids and other off-grid solutions, in order to reach the global energy access target by 2030 [28]. Grid extension would cover the remaining 30%.

Micro-grids have been especially appreciated as reliable alternatives to failure-prone national power grid supply systems [29]. In the state of Uttar Pradesh in India, for example, grid power was on average available only for 12 hours per day [30] in 2018. However, the number of studies proving the real reliability of micro-grids is limited [31] [32], even though measured results would help to capture the full potential of the technology. This dissertation also presents an assessment of the reliability of solar micro-grids currently operating in India (Section 4.2).

Micro-grids may also have a global environmental sustainability benefit compared with any fossil-fuel powered energy system because typical micro-grids utilise renewable energy sources, such as solar, wind or biomass [33]. Furthermore, micro-grids are energy efficient, because the supply station is located nearer to the location of the power consumed; all power distribution always requires energy. Micro-grids are considered valuable for their empowering effects on local communities [34] and for their security of supply as they are not dependent on fossil fuel price fluctuations [29].

Figure 2.1 illustrates the technical configuration of a small-scale micro-grid ("pico-grid") system that serves six households. The battery is in the central position in the micro-grid because it stores the solar energy produced during the daytime to ensure its availability for customers at night-time. The power management unit at the central charging station ensures that power is available for users in the allocated time, and protects the supplying components from overuse or overcharge. The capacity of this particular micro-grid is so small, that it is called "pico-grid". Only low-power electronic appliances can be used and the maximum instantaneous power output is limited to 30 Watts.

Generally, micro-grids can have nearly an unlimited capacity, depending on the configuration. They can also function in connection with the centralized main grid while providing ancillary services for the grid [35]. This study focuses primarily on stand-alone micro-grids.

While micro-grids have enormous theoretical possibilities for providing sustainable energy services, several practical problems may deter from their expansion. First of all, many countries in the developing world may lack a sufficient regula-

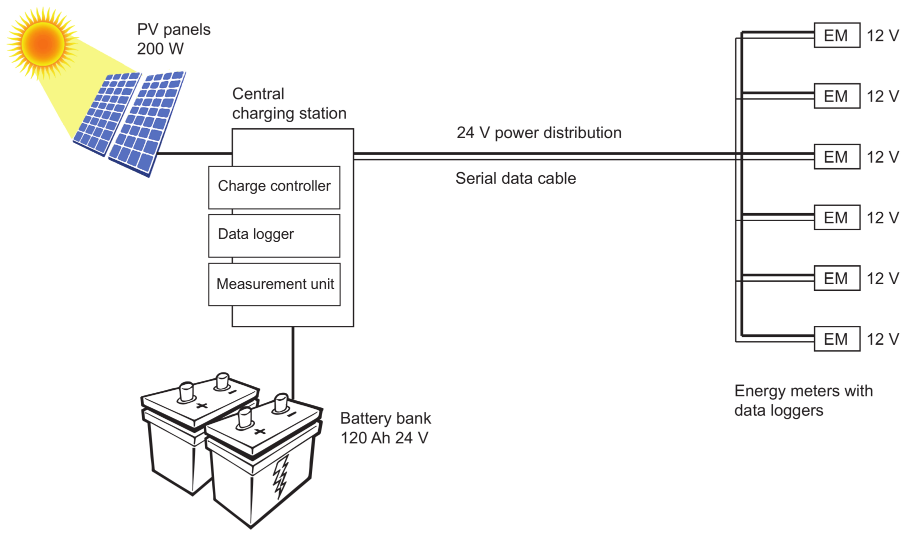

Figure 2.1. Exemplary micro-grid schema: pico-grid with system intelligence, central supply with solar panel and battery and six households served. Reprinted with permission from Publication IV. Copyright 2018 Elsevier.

tory environment [36] and appropriate business models [37] for exploiting their full potential. Economic viability is a relevant question, because if the customers are extremely impoverished (e.g. families connected to the pico-grid earned 46 dollars/month, on average [38]), gaining business profits may be very difficult [39]. Therefore a micro-grid needs to be designed frugally and cost-consciously because the PV panel, the battery, the controlling power electronics, the distribution system and maintenance management are significant investments for the system operator.

However, frugal system design should not be utilized at the expense of quality. Quality requirements and quality control of renewable power systems are still in their infancy in many countries, such as in India [40] [41] which poses a threat for long-term durability and life-long lasting of new energy systems. There is evidence that along with the global solar boom, products of an inconsistent quality are being sold and used in markets in developing countries [42] [43] [44]. Indeed, technical quality problems have led micro-grid customers to drop the service in northern India [45], and in some countries, the lack of equipment quality has destroyed the population's trust on a renewable energy technology [46] or the whole renewable sector [47].

There are not many studies on the frugality aspect of micro-grids. First of all, labelling a more complex energy system (such as a solar micro-grid) as a frugal innovation is less straightforward compared with a simple single-unit technology (such as a solar cooker [48]). Nevertheless, the pre-paid energy meter as a part of a solar pico-grid may be an example of a frugalized energy system component due to its simple electronic design. In addition, the meter promotes a frugal use of electricity through the consumption limitation (30 Watts) and through the pre-payment function, which is particularly suited to extremely low-income people with irregular wages. These two features enable naming the pico-grid a frugal innovation (see Publication I).

Demand side management (DSM) has also been used by other micro-grid operators in rural India to frugalize their power systems, thus saving total system costs. For example, Mera Gao Power limits the power availability to 6–7 hours per day [49] which allows a smaller PV and battery capacity installed. Including storage is the most straightforward demand side management method [50], but increasing the battery capacity quickly becomes unbearably expensive. Pricing incentives have proven to be a functional demand side management method in many established power infrastructures for balancing the power peak demand (unit price of electricity being higher e.g. in the peak hours), see, for example [51]. However, pricing methods have not been tested in frugal micro-grids for their functionality and possible relevance for system cost reduction. This dissertation contains an analysis of the benefits of a dynamic pricing incentive method on the solar pico-grid (Section 4.1.3).

3. Methods used in the thesis

Key methods used in this thesis were field visits to villages served by solar micro-grids; interviews with micro-grid business operators and other experts; systematic analyses of measured data; laboratory tests; and literature reviews of frugal innovation, sustainable energy and energy access.

Micro-grid installation visits allowed observing the technical equipment and installation work and how they perform and how they are used in the actual contexts. Visits also allowed to verify or invalidate suspicions and also to discuss observations with technical personnel and customers.

Interviewing was an efficient method to confidentially discuss particular issues in the business ecosystem and to collect information which is not available in literary sources. Systematic solar pico-grid customer interviews were conducted, too, because it is important to understand how low-income people evaluate the benefits of micro-grid systems, to be able to assess their value for the users and technical developmental needs.

For this dissertation, a particular frugal innovation case, "a solar pico-grid with dynamic pricing" was studied using year-long technical data from on-site measurements in villages in northern rural India. Availability of measured data allows system values (such as energy balance and reliability) to be calculated numerically which provides information on system operations. Such detailed analyses are not possible without measured data. Data analyses also allowed confidently investigating whether dynamic pricing is a beneficial feature in this kind of power system.

Laboratory tests for the pico-grid system components enabled understanding some of their relevant electronic properties (e.g. energy efficiency) and confirming whether the components operate according to intended configuration.

3.1 Observing solar micro-grid installations and visits to rural villages

For collecting data for this thesis, several solar micro-grid installations in rural northern India were visited in their actual operating environments among the low-income communities, and their operators and technicians were interviewed. Visits allowed making technical observations and comparing different micro-grid systems in their actual usage contexts. The main outcomes of the field visits are presented in Table 3.1.

Field visits allowed discussing the observations with field personnel (technicians and other technical staff, sales personnel and field management) as well as the energy users. As distances were sometimes long, also the travelling times were good opportunities to less formally discuss business issues, practical challenges, cultural aspects and policy matters.

The visits were carefully prepared maximising the collection of systematic data. Often, field visits boosted the re-formulation and specification of research questions and provoked new ones.

Table 3.1. Data collection visits in northern India

Time	Purpose and location	Outcome
April 2015	Interviews with the management of the solar pico-grid operator Boond and the off-grid industry association CLEAN in New Delhi.	Introduction to frugal energy business and frugal engineering. Overview of Indian off-grid energy industry. Three in-depth interviews. 10 hours interview recordings.
	Visiting three villages where Boond operates frugal energy business in Unnao, Uttar Pradesh.	200 photos, 5 hours recordings of interviews with energy users, plant management and staff members. 1 notebook with observations.
June 2016	Visiting hamlets served by solar pico-grids in Unnao. Visiting all 7 hamlets and 43 households with the purpose of understanding the operational aspects of the pico-grid.	15 interviews (technicians, field staff, villagers and grid operators). 500 photos, 2 notebooks with observations, 4 hours recordings. Specification of research approach for Publication IV
	Visit to Mlinda foundation sites, for observing three further micro-grids in their original location in Gumla, Jharkhand	Interviews with operators and customers. 250 photos, 10 hours interview recordings.

Table 3.1. Data collection visits in northern India

Dec 2016	Visiting 7 hamlets and 43 households served by solar pico-grids. Inspecting and photographing each energy meter. Understanding anomalies in the analysed measurement data.	20 interviews or short meetings with technicians, enumerators and customers. All 7 local grid operators interviewed. 800 pictures, 2 notebooks with observations, 5 hours interview recordings. Data analysis for Publication III and Publication IV
	Visiting two other villages where Boond had installed micro-grids with pre-paid energy metering.	100 photos. Understanding the energy meter product development process
Feb 2018	Indian Energy Access Summit 2018, New Delhi	Interviews with off-grid companies and experts in consultancy, universities and manufacturing and financing sectors about topics regarding solar micro-grid reliability. Active networking. Organisation of interviews and field visits. 10 hours interview recordings
	Visit to EmSys electronics and SELCO premises, Bangalore	50 photos, 5 hours interview recordings
	Two field trips to other micro-grid locations in Uttar Pradesh for observing the reliability related aspects and problems	150 photos, 5 hours interview recordings. Data to Publication V

The seven hamlets where the solar pico-grids were installed were visited twice during the measurement period. Both times, all 43 households were visited, with particular attention being paid to inspecting the energy meters and the central charging station components. In particular, observed anomalies in data could be discussed with technical staff, local grid operators and the concerned customers. The timing of the second visit in December (low solar irradiation winter season in Uttar Pradesh) allowed confirming how low-power related problems appear in data. At the same time, it was possible to observe how the weekly customer interviews and regular technical maintenance activities were conducted.

3.2 Interviews

The reliability assessment study of solar micro-grids (see Publication V) was based on the analysis of systematic interview data with companies operating micro-grid energy business in India. Finally, the number of interviews conducted exceeded 20, including company representatives and other experts.

The semi-structured interview method [52] allowed to adjust the preliminary set of questions to the interview situation and adapt the questions to different companies. All interviews were recorded and later on transcribed and analysed in detail. To give publicity to the interview study and to attract more experts to participate, the project was given visibility on the Internet and via social media. Companies were contacted directly via emails, and with the support from the Indian off-grid industry association Clean Energy Access Network (CLEAN) [53].

The interview data management followed the grounded theory guidelines [54, pp. 683–690]. First, a set of questions were decided upon. Then, the first interview round was conducted and the answers were critically evaluated. Research questions were reassessed in this phase because it was quickly concluded that due to the newness of industry the availability of reliability-related data was rather limited. Finally, a representative from each company was interviewed twice. Typically, the second interview was made by phone and missing details were requested by email.

A recommendation letter from the supervising professor was a useful attachment that explained the purpose of the study being purely academic. All interviewees were promised full anonymity to feel more comfortable in sharing information on the reliability of their systems. Sometimes companies could not share all details due to contracting.

Pico-grid customers were interviewed, too, because of the importance of understanding how the target customer group would evaluate the benefits of the system. Importantly, customers could assess the developmental needs of the system. Systematic weekly interviews were conducted by an Indian research company Morsel India. See Section 3.3.2. The questions asked are in Appendix.

3.3 Case study: solar pico-grid with dynamic pricing in rural villages in India

For this dissertation, a particular frugal innovation case, "a solar pico-grid with dynamic pricing" was studied in detail during a one-year-round field measurement experiment. The research project was a collaboration between Aalto University, Columbia University and an Indian energy service company Boond Engineering & Development Pvt. Ltd. who had already operated low-power micro-grid business in rural areas in northern India.

Boond was responsible for the design of the solar micro-grid as well as for the identification of suitable hamlets (small habitations, but not administrative villages) and the involvement of households in the experiment. Finally, seven solar-powered micro-grids were installed in seven habitations in the Unnao district of the state of Uttar Pradesh. The hamlets were selected with a distance long enough from each other so that people would be assumed not to interact and communicate. In each hamlet, 5–7 households were connected to a pico-grid. Boond took care of the technical maintenance and repair and contracted a villager to take care of the basic maintenance and customer service (such as cleaning the PV panels and selling the pre-paid energy credits).

The hamlets were un-electrified at the start of the study. The nearby village, Chakal Wanshi, had a national grid power distribution system but the service was characterized by irregular power outages and systematic supply failures. According to the local people, the power was available for around 12 hours a day.

3.3.1 Technical setup

The pico-grid power was distributed to households with direct current (DC) distribution power line from the central charging station which was typically located at the house of the locally contracted grid operator. Smart energy meters (Figure 3.1) were installed in each connected household for controlling the output so that only a maximum of 30 W could be extracted instantaneously. In addition, the energy meter output was direct current (DC) with 12 V, so Boond provided the appliances because 12 V DC is suitable only for a limited selection of market

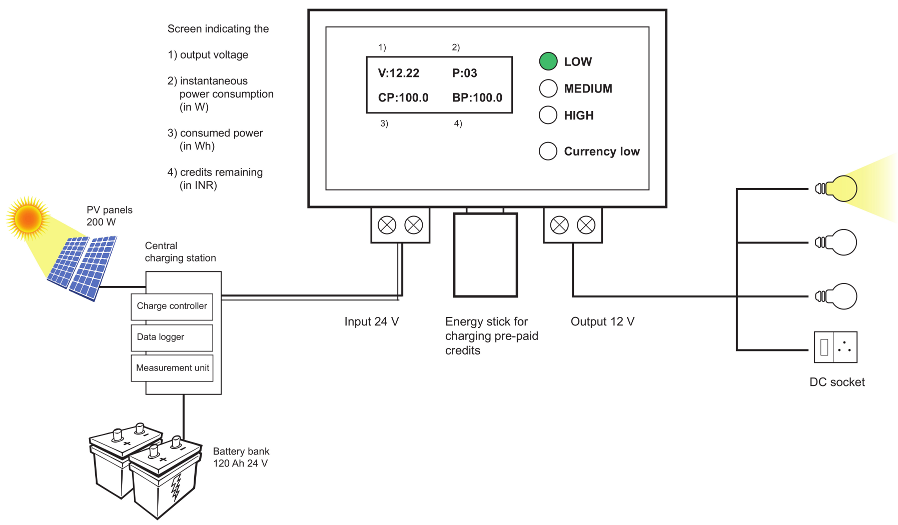

Figure 3.1. Graphic of the energy meter user display and the connection to the user's appliances and to the central charging station. Reprinted with permission from Publication III. Copyright 2018 Elsevier.

appliances.

For the purpose of this study, customers received a specific set of appliances free of charge (3 LED bulbs à 3 W attached to walls of their houses in preferred places, a fan, and a socket for using mobile phone chargers and other small appliances) but the customers had to pay for their electricity use. Customers could charge their pre-paid "energy sticks" in advance from the grid operator and monitor their recharge balance from the energy meter display. Pre-paid mode is a typical feature in new micro-grids in India [55] because it is more applicable to unstable incomes than a post-paid system, and also allows more efficient payment collection [56] [57].

The electricity price was indicated by three lights (green-yellow-red) on the front pane of the energy meter. The electricity price was inversely proportional to the battery voltage, according to the voltage limits demonstrated in Figure 3.2. The normal operating condition and the system distribution voltage was 24 V. The central charging stations were configured to automatically stop the power injection to the grid once the battery bank voltage drops below 21.6 V. The station would continue to supply power again once its voltage has exceeded the reconnection voltage 25.6 V.

According to our initial hypothesis [58], the dynamic pricing would encourage the customers to shift the consumption to the moments with more available energy in the battery. To test this hypothesis, we specified a randomized control trial, where two different operating modes varied on a weekly basis. In the static pricing mode (control), the price of electricity was fixed to the "low" price range (INR 10/100 Wh). In the dynamic pricing mode (treatment), the price varied between low price, medium price (INR 15/100 Wh) and high price (INR 20/100 Wh). The treatment and control modes varied randomly on a weekly basis at a hamlet level. All households within a single hamlet were always under the same condition, however. In the middle of the year a survey was conducted

Figure 3.2. Electricity price levels defined by the battery bank voltage. Figure: EmSys Electronics

for villagers to ensure that all energy users (sometimes illiterate) understood the pricing logic and the price differences. The level of comprehension was satisfactory.

The consumption was expected to be diminished during periods of low energy production. In other words, dynamic pricing may reduce the intensity of charge and discharge cycles of the battery bank and thus reduce the amount of stress put on the valuable system component. Battery cost was approximately 10–15% of the total system cost in this experiment [38]. Battery also dictates the lifetime of the whole system (4–5 years of battery life is expected in these working conditions). The life expectancy of tubular batteries, chosen for these micro-grids, are counted in cycles [59, ch. 16.49]. If dynamic pricing would demonstrate to be effective, we may have found a promising method to protect the battery and to increase its working life. Of course, the battery lifetime is largely determined on how the battery is maintained, and on shielding, protection and the ambient temperature. However, results of this study would give directions to further development possibilities of similar small power systems (e.g. economic capacity sizing and control and protection optimization).

3.3.2 Data available and the systematic analysis

The data logger in the central charging station stored these values: date, time, solar panel voltage (in volts, V), battery bank voltage (V), charging current (in amperes, A), discharging current (A) to and from the battery bank and load current to the grid (A) on a five-minute basis. The energy meters in each household recorded the following values: date, time, power consumption (in watts, W), meter output voltage (V) and energy price on a ten-minute basis. Before the actual measurements started in January, 2016, there was a trial period of six months when the installed systems and the technical configurations were tested, so that they would optimally serve the research purposes.

The technical data was downloaded manually from the energy meters and the central charging stations by the enumerators of Morsel India, an Indian research company, on a weekly basis. Enumerators uploaded the data and stored it as .txt format files in a data cloud.

A thorough baseline study was conducted on the energy users background prior to the study. In addition, Morsel enumerators interviewed all customers using an interview template every Monday in the local language (Hindi) to assess customers' satisfaction with micro-grid services. In mid 2016, the initial set of questions [58] were complemented with questions on power reliability outages (See Appendix for the final set of questions).

In addition, the enumerators reported key technical problems that had occurred in the villages, such as breakups of energy meters or other components. Enumerators' reports were relevant supportive information.

A systematic analysis for the solar pico-grid data between January 11, 2016 and December 31, 2016 was conducted. The first 11 days were neglected due to technical initiation errors. The measured data totalled nearly 3 million data points (including over 8,000 measurement points per day summed over all seven hamlets), which required software-assisted data analysis.

The data allowed several interesting findings to be made. In this thesis, the analysis was limited to the identification of particular energy (energy balance and the self-consumption index) and the discontinuities in the power supply for understanding its reliability.

3.3.3 Energy balance

The daily energy production and consumption values were calculated per hamlet and per household for each measurement day, by using the consequent measured values for voltages and currents and the measurement timestamps. For example, the total energy L_i sent on a particular day i to the hamlet from the central station could be achieved by multiplying the value of the distribution voltage $V_d = 24\,V$ by the centrally measured values for the load current $I_{load,i}$ and integrating them over the particular measurement day i. Similarly, the energy produced by the PV panel $P_{PV,i}$ on the day i can be calculated by using the PV panel voltage values $V_{PV,i}$ and the daily charging current values $I_{ch,i}$. Data being available on both the supply and the demand side enabled the identification of the energy losses as well.

3.3.4 Testing the impact of the dynamic pricing function

To understand how the selected dynamic pricing function implemented in the small power system produces a demand response effect in the system, values of the grid self-consumption ϕ_{SC}, according to [60] were calculated on a weekly basis. In this study, the self-consumption index ϕ_{SC} is expressed as

$$\phi_{SC} = \frac{\int_{t_1}^{t_2} M(t)dt}{\int_{t_1}^{t_2} P(t)dt} \tag{3.1}$$

where $M(t)$ is the overlapping part of the generation and load profiles. $P(t)$ is the solar energy generation profile. If $L(t)$ is the load profile and $S(t)$ the power profile of the storage unit, $M(t) = min\{L(t), P(t) + S(t)\}$. When the storage is charged, $S(t) < 0$ and when discharged, $S(t) > 0$. The integration limits t_1 and t_2 are chosen according to daylight hours (the voltage of the panel $V_{PV} > 0$).

Self-consumption ϕ_{SC} was selected as the indicator, as it describes how much of the produced solar power is consumed instantaneously by the total grid load. If $\phi_{SC} = 1$ (maximum), all produced energy is used right away. If $\phi_{SC} = 0$ (minimum), all produced energy is stored for later use, or wasted if the storage is not connected.

In other words, higher ϕ_{SC} values would indicate less stress put on the battery. If statistically significant improvement of the values for ϕ_{SC} during dynamic pricing mode weeks (treatment) were demonstrated in comparison with the ϕ_{SC}

values in the static pricing mode (control) weeks, dynamic pricing might be a recommendable option for demand management also in other similarly small power systems.

Self-consumption should not be confused with self-sufficiency index (solar fraction) which indicates the amount of instantaneous solar energy usage if also other energy sources (such as main grid power) are available. In this power system, solar is the only energy source so the solar fraction values would every day approach one.

3.3.5 Identification of supply interruptions

A special method was created for the identification of power outages in the data. The design engineer confirmed that an energy meter would instantly stop recording values when it ceases to receive power from the central station, as the grid central storage is its only power source. Therefore, a lack of regularity in the flow of data points recorded by the energy meters would imply an interruption in the power supply. Obvious reasons for such situations are: lack of power in the battery; a manual switch off of the central charging station by someone, such as the technician; or a technical problem in the equipment. A lack of recorded values could also be due to a line cut in physical distribution grid connected to a household meter or a technical problem in the particular energy meter itself.

An analysis script was written to compare the timestamps of successive measurement points, to list delays to the 10-minute nominal frequency of the recordings, and to log the consequent lengths of the delays. In parallel, the central station measurement data was systematically analysed, in order to understand the momentary status of the central station and, in particular, what had been the battery bank voltage when the recording was stopped.

To add to the reliability of the results, the identified recording interruptions that were shorter than 2 minutes were completely neglected, as they were concluded mainly to represent measurement latency. Interruptions shorter than 15 minutes were also neglected, to ensure that deviations between measurement units would not affect the results. A share of these shortest interruptions may have been experienced in households as shorter power gaps (e.g. flickering lights), however, for a more detailed power quality assessment a more sophisticated measurement setup would have been required.

As the enumerator stored the data weekly (every Monday) to .txt files, the data had to be double-checked not to confuse the gaps due to data transfer with the searched recording delays. Even though the amount of measured data would have allowed the negligence of one day per week without it losing statistical relevance, power outage analysis had to include also Monday data, to also detect the power outages that had started on Mondays.

Finally, the delays were listed chronologically and categorized by length (shorter than 15 min, from 15 minutes to 1 hour, from 1 hour to 3 hours and longer than 3 hours), in the same fashion as the measured grid outages in the national system are grouped [61] to allow the comparison of the quality of the two systems.

The identification of reasons for different power outages was iterative. First, the battery voltage at the beginning of the outage was analysed. When the battery energy level was too low, low battery was marked as the reason (even though other faults may have affected in parallel). No clear difference with the number and duration of outages was identified between control and treatment weeks. Therefore, the weekly pricing mode differences were ignored in the following analyses on the reasons for power outages.

In search of other reasons, field observations and interviewing the technicians were important data sources. For example, physical locations of weak connection points in the grid configurations and time periods when they had caused technical problems were pointed out by technicians during the field visits. These problems could be therefore pinpointed in the data with some manual work. In addition, during field visits, it was confirmed that the grid operators occasionally manually shut down the grid in certain hamlets. When these incidents were regular, they could be identified with high reliability in data. Furthermore, when the energy meter output voltages at the beginning of interruptions were inspected, periods for deviation from the nominal 12 V output voltage were discussed with technicians, to better understand how a device breakup appears in the data.

In addition, the weekly customer interview data was used for better understanding the reasons behind outages. However, customer reports were not as useful of a source, because the customers could not recall the periods without power in sufficient detail. Nonetheless, interview data was systematically analysed to support other research findings.

3.3.6 Validity of the data analysis

The amount of data collected was considerable, for statistically relevant conclusions to be made, even though due to technical errors 14% of data points were missing at household level and 19% at hamlet level. Some data losses were potentially caused by the fact that data had to be manually downloaded from the meters by a member of the field staff. Nonetheless, the dynamic pricing test was successful, because the system showed correct pricing in the households according to the pre-defined specifications.

Also the power reliability analysis method was trustworthy despite the technical problems overshadowing the experiments. 15% of the time when a power outage occurred, there was no central station data at all, meaning the central station had been out of order at those times. More interestingly, only the data of hamlets 1–5 could be reliably analysed. The data from Hamlet 6 and Hamlet 7 could not be analysed due to multiple data logging issues, device breakups and suspicious user actions. A margin for uncertainty is included in the identification of reasons for power outages, especially those considered originating in human actions and when a conclusion was drawn from informal interviews and visual inspections. However, all such observations were confirmed by measured data, before conclusions could be drawn.

3.4 Laboratory tests for frugal energy system components

Representative samples of the energy meter, the central charging station and the led light bulb were tested at a laboratory to understand key electronic properties. In laboratory experiments all external influences can be eliminated and the ambient temperature and humidity levels can be kept constant in standard test conditions (STC).

In 2015, before actual field experiments started, a prototype of the pico-grid energy meter was tested. The measured values were load stability, internal resistance, internal efficiency and the measurement error. In addition, the data logging functionalities were tested.

The reactivity of the energy meter to different output loads was tested with a BK Precision 8540 DC controllable load by gradually increasing the output one watt at a time until the energy meter shutdown. The energy meter was tested also for its responsiveness to different input voltages by using a DC voltage source.

The prototype test results were sent to the energy meter manufacturer before purchasing the actual energy meters for the field trial. Suggestions for improvement were limited to issues that would facilitate research, for example on the measurement and recording accuracy of the logged data.

In March 2017, after the field experiment period, a sample of the energy meter that had actually been used in the hamlets, was tested for its internal efficiency and load stability. Particular attention was paid to how the data log reports situations of low input powers. This would allow to understand the origin of the particular "communication error" message displayed on the screen, which had been regularly reported by the customers.

In addition, a sample of the central charging station was tested for its responsiveness to input voltage variation. The test confirmed that the cut-off voltage and reconnection voltage values of the supply were in accordance with set-up specifications. Similarly, a LED light bulb was tested for its reaction to voltage variations. The illumination quality was good until a threshold voltage of 6.6 V (nominal 12 V).

3.5 Reliability indicator for micro-grids

Reliability is highly relevant in power system service assessments, because it directly affects customer satisfaction. The reliability levels of solar micro-grids were studied in Publication V.

In traditional power grid engineering, there are several standardized measures for the assessment of power system reliability [62]. In stand-alone power systems, the power reliability consists roughly of two elements: energy reliability and technical reliability [63]. Energy reliability refers to optimal sizing of the micro-grid, which ensures power availability for customers when needed, or scheduled (promised). Energy reliability becomes more critical the smaller the system gets because the power storage reserves are smaller. Several guidelines for system sizing exist, see for example [64] and [65].

A popular measure for energy reliability is the Loss Of Load Probability (LOLP). LOLP indicates the probability for lost loads due to inadequate power generation [66]. A somewhat similar indicator is the Loss Of Load Hours (LOLH) which is simpler to identify, because load estimation might be a complex undertaking [67]. LOLH describes how often power was not available compared to when promised.

Technical (un)reliability indicates the time which is needed to overcome any technical failure. Such problems are not addressed by LOLP, LOLH or related indicators. The total Mean Down Time (MDT) is a popular indicator for technical reliability. For the most accurate evaluation of the technical reliability of a complex power system, the failure probabilities of each containing component would be needed. The total technical reliability of a power system could be calculated as the product of reliability values of each consisting component [68, pp. 5–8], if the data is available.

4. Results

First, a theoretic definition for frugal energy innovations is offered (basing on a wide analysis of various off-grid energy technologies), as frugal innovations in the energy sector had been an unclear concept. The possible relevance of frugal innovations contributing to sustainable development goals is also explored.

Secondly, the thesis includes an analysis of a particular frugal solar micro-grid that incorporates advanced frugal features, including pre-paid metering and a dynamic pricing function.

Finally, an assessment is presented of the reliability levels of various solar micro-grids in India, and a method provided for the reliability assessment of solar micro-grids in rural areas in developing countries.

4.1 Frugal energy innovations (Publications I – III)

4.1.1 Definition

In Publication I, a set of common criteria for frugal and sustainable energy innovations was compiled, including technologies that may serve energy-deprived people in developing countries in an affordable and sustainable manner. The work was based on a broad literature research, mainly from academic sources. In addition, other sources were consulted, such as books, popular articles and reports, as well as websites of organisations promoting energy access. First, sources mentioning an energy system solution being "frugal" were searched for; frugal innovations could be found at least in the following categories:

- Frugal energy business model (e.g. by SELCO [69], see also Section 4.1.2)
- Frugal energy technology (e.g. micro-grid of Husk Power System [70])
- Frugal energy system component (e.g. micro-grid distribution poles made of bamboo [71])
- Customized low-power products with an integrated off-grid renewable energy production unit (e.g. portable solar energy packs for health worker in remote areas [12])

Two interrelated attributes arose in all literary sources: frugal engineering and affordability in service. Frugal engineering is a mind-set resulting in simpler products in some new manner, through functional or structural simplifications [72]. Through simplicity, the above list could be complemented with systemic innovations, such as the direct current (DC) mode of distribution in power systems. DC distribution embraces simplicity, because there is a need to only synchronize the voltage and not the frequency [73] [74] as in the traditional alternating current (AC) distribution. Other parts in the DC distribution system, still, may be more complex (e.g. protection schemes) [75] which complicates a direct comparison of different networks without more information on their characteristic. However, DC has a second simplicity benefit which is the reduced number of power conversion phases required in PV-supplied systems resulting in significant energy efficiency gains [76] [77]. Energy efficiency makes DC distributed PV power grids more energy frugal by architecture.

Affordability implies both lower production costs and the resulting affordability of the service. These two (frugal design and affordability) are strong criteria for frugal innovations, which are also applicable to the energy sector. Durability is particularly highlighted, because the cost-consciousness involved in the frugal engineering may potentially threaten the technical quality aspects which,

Table 4.1. Features of frugal and sustainable energy solutions serving those at the bottom of the economic pyramid. Table based on results presented in Publication I. Reproduced with permission. Copyright 2016 John Wiley & Sons.

Main criteria	Comments
Affordability	Provision of a more affordable service for the customers
	Lower manufacturing costs
Device composition follows frugal design principles	Minimal use of resources
	Simplicity
	Durability
Frugal energy consumption	Energy-saving user behaviour
	Modest energy output levels
Local appropriateness	Socially and culturally fit for local user preferences
	Skills available for operation and maintenance
Environmental sustainability	Use of local renewable energy sources
	Recycled materials
	Avoiding harmful substances

nevertheless, directly produces usability of the energy system. Thus, frugal innovation is separated from other low-cost innovations, such as cost innovation and good-enough innovation that may not be as strict with quality requirements [21]. Table 4.1 summarises the key criteria for frugal and sustainable energy solutions.

Examples of other innovations in the energy sector could be found in the literature, clearly meeting the two strong criteria, although they had rarely been labelled as "frugal" earlier. For example, solar cookers [78] [79] are smart, simple technologies that can be crafted from low-cost materials that are widely available all around the world, such as reflective foils and wooden materials. These frugal energy technologies can be used in areas where energy access options are either non-available, unsustainable or expensive, including in informal housing settings, refugee camps or other contexts without permanent energy supply infrastructures.

Frugal energy consumption criteria in Table 4.1 refers primarily to the low energy levels offered by the frugal energy solutions. Solar pico-grid (Section 3.3) offers only a lighting and mobile phone charging service, and the opportunity to use some small electronic appliances. Furthermore, it has a limit of maximum instantaneous power draw (30 W). Frugal micro-grids may also temporally limit the output levels, which was a common feature in Indian micro-grids. 24/7 access was a rarity, as demonstrated by Figure 4.1.

Naturally, the question remains: in the long-term do systems limited to lighting and mobile charging capabilities later allow higher-capacity loads to be used for, for example, productive activities. However, frugal innovations in energy need not to be limited to pico-scale energy levels. A couple of recent reports present innovative stand-alone renewable energy-based solutions to power income-generation activities in India in sectors including agriculture, food processing, crafts and service [80] [81]. These solutions are promising particularly as they are customized in each local context with appropriate considerations of ownership models, financial models and the surrounding ecosystem.

Local appropriateness was selected as one of the criteria, because there are several examples of imported technologies not being accepted by a local community as local user preferences for the technology had been omitted [82] [83]. Intro-

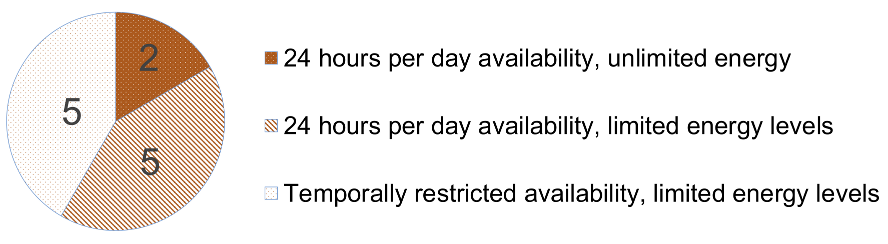

Figure 4.1. Power and service availability currently offered by micro-grid entrepreneurs in India (12 companies interviewed). Reprinted with permission from Publication V. Copyright 2019 Elsevier.

ducing electricity, for example, may not automatically make people change their traditional cooking habits [84]. Or despite solar cookers being an emissions-free way of preparing food, their dissemination is relatively marginal, possibly due to their incompatibility with preferred daily routines of people [85] [86].

The locality aspect with energy technologies is also connected with repairability and maintenance. Dependence on foreign manufacturer services may result in long energy service outages [87]. The importance of technologies being repairable becomes higher in countries where product return systems and warranty mechanisms are not common [46], and in remote geographic locations (where off-grid systems typically are used) [88]. Sometimes local maintainability is allowed through simpler (frugal) system design because they may be more easily repaired by local inhabitants who may not always have formal technical education.

Environmental sustainability is always important for energy systems, in particular during current conditions when the bulk of energy production leads to environmental degradation (such as air pollution and climate change), both on a local and global level. For instance, a micro-grid provided by Husk Power System is often named as a frugal innovation as it exploits locally available waste for producing energy by a locally manufactured technology system. However, the solution may not involve the cleanest gasification process of biomass [89]. Local availability of energy sources is relevant as well as the local environmental capabilities in coping with the possible side effects of energy production. Therefore, environmental sustainability was selected as one of the criteria in Table 4.1.

4.1.2 Frugal innovation and sustainable development

A solar energy technology, a customized solar home system (SHS) sold by a non-profit foundation SELCO, was analysed in Publication II for its contribution to attaining Sustainable Development Goals (SDGs) [3]. Basing on relevant SDGs, the sustainability of the SHS was assessed from environmental, social and economic perspectives. The SHS was compared with the existing solution that it was to replace: kerosene lantern. The analysis implied that the frugal energy solutions have several implications on sustainable development, for example through their tendency to exploit renewable energy and offer affordability in service for low-income customers.

The environmental sustainability benefits of frugal solar energy business are considerable. The sales of 71,000 solar home systems, led to annual reductions of 22,000 tons of CO_2 emissions, as a result of avoided kerosene consumption [90]. The environmental and local health benefits of pico-scale lighting via the reduced need for using kerosene-fuelled lamps are acknowledged also in [91].

In addition, the frugal business innovation contributes to the social and economic aspects of sustainable development. First, the frugal business model promotes equality between the members of that society, because it allows lower income customer groups to purchase the product and gain access to electricity.

Namely, SELCO organises loans for low-income and non-credible customers with local banking institutions ensuring they can purchase solar home systems on a loan basis. Secondly, the access to electricity helps the small entrepreneurs to run their businesses during the night time (for example, a relevant issue for the street vendors) and households to use a higher quality illumination service than with kerosene lanterns. Furthermore, the health benefits of solar power are highly significant, because the kerosene lanterns emit dangerous exhaust fumes.

However, there are conceptual problems in directly equating the two terms frugality and sustainable development. As frugal energy systems often are small in size, they can benefit only a single household or one entrepreneur at a time. For that reason, the larger community-level sustainability benefits may be better reached with larger systems, such as community micro-grids that simultaneously benefit several families. Centralized energy systems might be more sustainable for long-term economic and social development than solar home systems.

A further problem with directly equating frugality with sustainability is that frugal innovations are often analysed from the product perspective. The relevance of any energy technology is always a highly local question. For example, the total CO_2 reductions after a purchase of a solar home system cannot be completely known by examining only one energy source, such as the solar home system. The changes in the household energy portfolio need to be analysed: whether the shift to the renewable energy system effectively decreased the kerosene consumption, or whether the purchase of the new technology simply resulted in an increase of the total energy consumption of the family, while maintaining the level of kerosene consumption. Nevertheless, the families connected to a pico-grid reduced their kerosene consumption by around 50% after the introduction of the solar pico-grid to the village (Publication III).

Regarding battery-based energy sources, there is also a further aspect connected to sustainable development, which concerns the proper disposal and recycling of the batteries. Batteries contain hazardous materials, such as lead, which causes dreadful consequences for the environment and human health if improperly disposed. The Indian national depositing system has ensured a rather efficient collection of used batteries from the field by the informal sector [92]. However, the collected batteries are not always processed in registered centres, but by the informal e-waste recycling sector. Waste treatment by the grey market was only recently addressed in Indian e-waste legislation [93]. The lack of regulation and control has damaged ground waters, soil and air in many densely-populated areas in India [94]. However, at least SELCO, analysed in Publication II, has guaranteed a proper collection of the distributed batteries after their useful life [90].

4.1.3 Relevance of the dynamic pricing function in solar pico-grids to increased solar energy use

Variable pricing of electricity is an advanced demand side management (DSM) method in power systems that may allow balancing load peaks, thus allowing a smaller generation capacity to be installed [95]. A reduction of costs is particularly important in contexts where customers have low purchasing powers. In our study, we tested whether dynamic (real-time) pricing of electricity in the pico-grid system would have a beneficial (load-balancing) effect (see Section 3.3 for test setup details).

Overall, the pico-grid field experiment was successful. However, in light of this study, we cannot propose dynamic pricing as providing technical value or improving user experience. The reasons for the null finding were related to the application of the system and its technical configuration.

The primary reason for the null finding can be traced back to the extremely modest consumption levels by the pico-grid customers, as shown in Table 4.2. An average household consumed only 17 Wh per day, which is equivalent to keeping two light bulbs on for three hours a day. The system capacity would have allowed for consumption over 40 times higher. The total demand remained

Table 4.2. Energy production, consumption and total losses in hamlets. In parentheses, the value divided by the number of households in the hamlet. Table based on results presented in Publication IV. Reproduced with permission. Copyright 2018 Elsevier.

Daily energies (in Wh)	Hamlet 1 (6)	Hamlet 2 (5)	Hamlet 3 (7)	Hamlet 4 (7)[1]	Hamlet 5 (6)	Average (30)
PV production	527	469	513	449	376	467
Energy to load	191 (32)	196 (39)	126 (18)	172 (25)	162 (27)	169 (27)
Energy to load[2]	202 (34)	196 (39)	128 (18)	164 (23)	254 (42)	189 (30)
Total load[3]	104 (17)	88 (18)	124 (18)	104 (15)	91 (15)	102 (17)
Unidentified loss per hamlet	29	59	NaN	11	21	30
T&D loss[4]	45%	55%	2%	40%	44%	37%

[1] Number of energy users in Hamlet 4 was 7, even though the measured data for outages identification could be used only for 6 households.

[2] Energy to load, average over days when there were no power outages

[3] Based on data measured by energy meters

[4] Energy meter internal consumption losses included

rather invariable across hamlets, and there were no significant differences between the static and dynamic weeks.

Technically, the minimal consumption led the electricity price to remain in the low price mode for 88% of the time during the treatment mode weeks (when the price was supposed to vary). The price remained unchanged because the central controller seldom received a signal from the battery voltage side to raise the energy price. High mode (red light) was activated for only 3% of the time. Therefore, testing the applicability of the dynamic pricing was not possible. Neither the technical parameter tested, the self-consumption index (see Table 4 in Publication III), nor the general customer satisfaction were improved when the pico-grids were under the treatment mode in comparison with the control mode.

Actually, dynamic pricing appeared to have a slightly negative influence. Customers reported technical problems with lighting being somewhat more frequent during the treatment mode. This implies that the technical origin lies within the system components transmitting the price signal to the households (in central controllers, energy meters and the data cables) because the price signal components were only activated during the treatment mode weeks. A laboratory test for the energy meter revealed an inherent high frequency noise which obviously resulted in a share of the interference problems. Therefore, data cable shielding is recommended.

Customers had not been specific about the actual types of lighting problems, but they are most likely power quality issues. Power quality problems are visually demonstrated by lights blinking in the households. However, data analysis showed that the shortest recording interruptions (from 2 minutes to 15 minutes) were more frequent in the treatment mode. This confirms that the price signalling equipment was somewhat faulty.

To be better able to test the dynamic pricing, higher consumption levels would have been necessary. More users with similarly frugal consumption, or other customers with more elevated demands (however, probably not living in these hamlets) could have been connected. In addition, different pricing threshold voltage levels (Figure 3.2), that would have made the medium price and the high price voltage ranges more probable, would have been a good choice. Furthermore, informal interviews with customers revealed that the red light glowed only right before a power outage, so, in practice, the red light did not demonstrate an energy price rise, but warned of an upcoming shutdown.

Neither the research team nor the energy service company expected such a low total consumption. In general, customer satisfaction with the pico-grid services was good according to the weekly interviews. Low pico-grid power consumption may be caused by an increased use of other electricity sources. The number of private solar home systems (SHS) increased from three to at least 15 during the year (43 households in total), based on field observations and informal interviews. In some hamlets, nearly all of the customers owned some kind of private electricity source, such as a portable or self-configured electrical battery, single solar module or a solar home system. It is typical that the extremely impoverished people of such hamlets possess a variety of small energy sources between which they alternate on a day-to-day and an hour-to-hour basis [96].

Nevertheless, low pico-grid electricity consumption may be simply connected with the difficult economic situation in the communities. An average family earns only $46 per month which most likely results in an extreme cost-consciousness in all sectors of life. The weekly kerosene consumption in hamlets decreased from 2.5 litres to 1.24 litres per household during the year of the study, possibly also because pico-grid powered lighting is slightly cheaper than burning kerosene for lighting (economic comparison presented in Publication I). In addition, families who illuminated the rooms with LED lights, gained better illumination quality and avoided the indoor air pollution problems caused by kerosene consumption. These might be taken as direct positive impacts of the pico-grid service. Broader socio-economic development impacts, however, might not be foreseeable through a pico-scale lighting and mobile-phone charging only service, as demonstrated in a study among customers of another pico-scale micro-grid in Uttar Pradesh [97]. Poverty reduction, for example, would require a holistic development plan and cooperation and commitment with many community partners and stakeholders [98].

4.2 Reliability of supply in solar micro-grids in rural India (Publications IV – V)

Publications IV and V show the results on the investigations of the reliability aspects of micro-grids, provided by private Energy Service Companies (ESCOs) in India. Gaining information on reliability and problems related to it would be valuable for helping to develop the sector. It is also relevant to test the alleged superior reliability of the micro-grids over the local centralized power grids, to be able to recommend micro-grids as an option for energy access. The numeric reliability analyses are scarce.

Firstly, this section presents numeric reliability levels of solar micro-grids (including the pico-grid) in rural northern India, basing on measured data and interviews. Secondly, key reasons for technical problems and downtimes are presented: the information on the origin of various power outages will aid in developing the system and better serving the customers. Furthermore, relevant design aspects are discussed which should be taken into consideration when designing a solar micro-grid in rural developing country contexts.

Thirdly, a simple framework for a uniform assessment of the reliability of renewable off-grid systems (such as micro-grids) is presented, which suits the low-income business contexts.

4.2.1 Numeric evaluation

A unique set of measured data from a solar micro-grid ("pico-grid", technical details presented in Section 3.3) was analysed for the number of power outages. As a result, a pico-grid connected household experienced, on average, eight outages per month. Over the whole year, there were 156 days with outages (200 without), on average. Surveying the total durations of the outages, electricity was finally available to the households for 87% of the time (between 84% and 94% in different hamlets). Table 4.3 shows the variation in reliability levels in different hamlets.

These numbers indicate that the pico-grid offers more reliable service than the local government grid supply, which, depending on the estimation, is available from 50% [30] to 67% [99] of the time. Both systems (pico-grid and national grid) are supposed to serve their customers 24 hours per day (full availability). In both systems, the power outages were unscheduled. However, the actual pico-grid reliability may be further reduced from 87%, as only five hamlets data was considered. The technical systems of the two remaining hamlets suffered from frequent technical failures so their data was totally excluded from the analysis. The power availability in pico-grids also varied seasonally. Section 4.2.2 discusses the reasons for outages in the pico-grids.

Other Indian micro-grids appeared to perform slightly better than the pico-grid, according to the estimations of the representatives of seven different companies (12 companies interviewed, see Publication V). Five companies were not able, or did not want to offer any numeric estimation. Basing on the answers given, the average availability of the solar micro-grids was 95% (5% downtime), the median being 96% (4% downtime). The maximum value was 99.98% and the minimum 83%. These rough approximations for system down-

Table 4.3. Number of monthly power outages in a household (all, longer than 15 minutes, and those longer than 3 hours separated) In parentheses, the number of household analysed per hamlet. Table based on results presented in Publication IV. Reproduced with permission. Copyright 2018 Elsevier.

	Hamlet 1 (6)	Hamlet 2 (5)	Hamlet 3 (7)	Hamlet 4 (6)	Hamlet 5 (6)	Average (30)
Outages (>3h)	5.1	6.0	3.3	7.9	4.6	5.3
Outages (All)	10.8	8.5	4.8	10.8	7.2	8.3
Availability	85%	87%	94%	86%	84%	87%
N days without outages (<1h)	110	249	270	198	172	200

times were calculated in the following manner. For example, if the operator estimated that there are 10 hours of no-supply per month, while the grid was supposed to deliver electricity for 8 hours per day, the downtime value is $(10\text{hours/month})/(8\text{hours/day} \cdot 30\text{days/month}) \cdot 100\% = 4\%$.

However, the reliability of the estimations given by companies could be questioned as they are based on approximations and not on measured data. Some interviewees probably left component failure-induced downtimes unmentioned. An exemplary statement by a micro-grid operator illustrates the level of precision: "[solar water pumping is available] whenever the sun [is] shining, which [could be] any day of the year". The interviews also reveal that the relationships with the ESCOs and the customers are based on a strong mutual understanding of the harsh and low-income operating conditions for both parties. From this perspective, statements (as depicted above) describing the micro-grid reliability levels may be sufficient. Business contexts are also characterized by the fact that legally binding contracts are rarely signed between the company and a customer. Everything is settled more or less verbally.

4.2.2 Design and power plant management aspects for increased reliability

Figure 4.2 demonstrates key reasons for power outages in pico-grids as averaged over all five hamlets based on the extensive data analysis. Roughly half (53%) of them were due to a lack of solar energy stored in the battery in the winter season (mainly December) when solar irradiation levels are low in Uttar Pradesh [100] (representation for 20% of all outages in pico-grids). Power outages occurred on a daily basis during the month of December and could last all day. Low battery can be labelled as a design-related capacity issue (22% of incidents observed in pico-grids) that could have been solved by engineering the system differently from the onset, for example, by making secondary power sources or storage systems available, if economically feasible.

Other solar micro-grid operators operating in Uttar Pradesh (Publication V) reported similar power insufficiency problems. Only two companies out of the twelve interviewed did not experience low battery problems, because they had connected a diesel generator as a backup supply. In practice, customers of most solar micro-grid operators may need to use alternative energy sources during winter.

The remaining power outages in the pico-grid as a result of a low battery, which occurred during other months of the year (33% of all outages), could not be validated as renewable energy insufficiency issues, when taking the hamlets' low consumption levels into account. Even the hamlet with the highest consumption levels (Hamlet 5, 42 Wh per household on days when power was flowing uninterrupted, see Table 4.2), would not have exceeded system capacity limits. One important aspect here is that the total Transmission and Distribution (T&D) losses in pico-grids were as high as 37% (Table 4.2), the number including

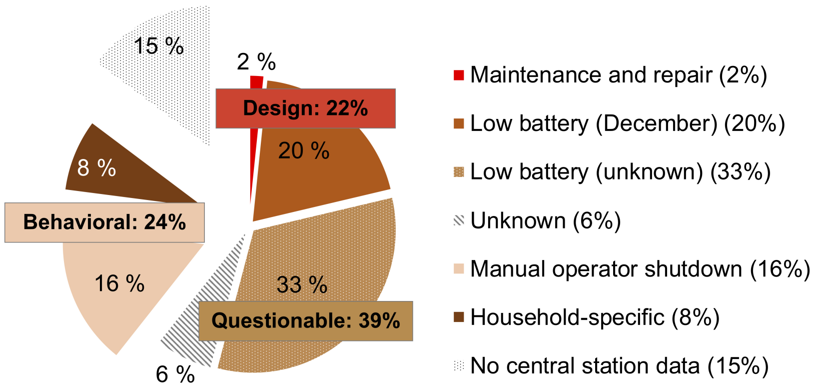

Figure 4.2. Key reasons for power outages pico-grids leading to an average 3 hours of power outages per day (averaged over all hamlets and the whole year). Figure based on results presented in Publication IV. Reproduced with permission. Copyright 2018 Elsevier.

distribution losses, physical battery losses, energy meter internal (thermal) losses and unidentified losses.

In laboratory tests, the energy meter was measured to have an elevated internal load-dependent consumption, the amount being around 30% of the load. For example, with any 10 W consumption, the energy meter itself would consume an extra 4 W. The prototype had demonstrated a better internal efficiency, which remained between 0.77 and 0.75, whereas the actual energy meter efficiency varied between 0.64 and 0.71. Nevertheless, the standby consumption of 1 W remained within the recommended limits for standby powers of household devices IEA [101], and was significantly lower than that of a computer (5 W) or a wireless router (4 W) [102].

However, energy meter inefficiency losses could not explain all T&D losses. Informal interviews and data analysis confirmed that villagers who had access to the locations of the batteries had occasionally charged their mobile phones directly from battery poles (Figure 4.3), thus avoiding paying for electricity. Such power theft activity is particularly harmful as it damages the charge balance in the battery and contributes to its premature degradation [59]. Nonetheless, the extent of such power theft activities is difficult to prove due to a lack of guaranteed evidence, but as 39% of outages had no identifiable reason for their occurrence, a share of them is assumed to be connected with illegal actions. This number (39%) includes both a lack of battery time (33%) and the remaining outages (6%) that had absolutely no technical or other explanation.

The interviewed operators of other solar micro-grids also emphasized illegal activities (component tampering, overloading, power line tapping) causing service downtimes. One interviewee had discovered a new power theft attempt on a daily basis. Power theft is an unfortunate phenomenon in India [103] [104] [105] that also affects micro-grids [106, pp. 461–462]. Only two companies

Figure 4.3. Vulnerable pico-grid system units (from left to right): Battery bank was subject to power theft; Energy meters were prone to technical failures and tampering; Distribution system connection points sometimes had to be repaired after an accidental interaction with a passer-by (e.g. a vehicle or a human). Photos: Sini Numminen 2016

interviewed proudly announced never having experienced misuses. Pico-grid customers, on the other hand, mostly tried to tamper with their own energy meters. There were six cases in different households (total 43 households) where the customers tried to by-pass their energy meters, thus trying to avoid paying for electricity. Such attempts had resulted in a break down of their meter only and did not affect the whole grid.

Furthermore, there was a further, completely unexpected, user activity that caused power outages in the pico-grid. Namely, local grid operators in a couple of hamlets had closed down the grids for the night (and sometimes also during the day when everyone was out of the house) to save energy. In Hamlet 2, customers had specifically asked the operator to switch off the grid, because they had mistakenly thought that the glowing LCD screen and the price-indicating glowing light consume their energy credits (which was not the case). Such manual outages covered 24% of all incidents. Variation between hamlets is presented in Figure 4.4. In some other hamlets, the operators conducted the manual grid outages particularly at the end of the year during the low battery season. The operators explained that they were serving the customers' needs, because scheduled power outages are definitely less inconvenient than unscheduled ones. However, these "behavioural" type power outages in Figure 4.2 should not be called "outages" in a similar sense as other outages. They are curious implications of frugal low-income conditions where users exercise control over their energy systems. The operating energy company (Boond) had instructed the local grid operators not to switch off the grid supply to ensure data storage, but this probably had not been fully understood or had been ignored.

User education may be the most cost-effective measure for increased reliability by underlining the collective consequences of various activities (including power theft or tampering). In particular, the maintenance of trustworthy relationships

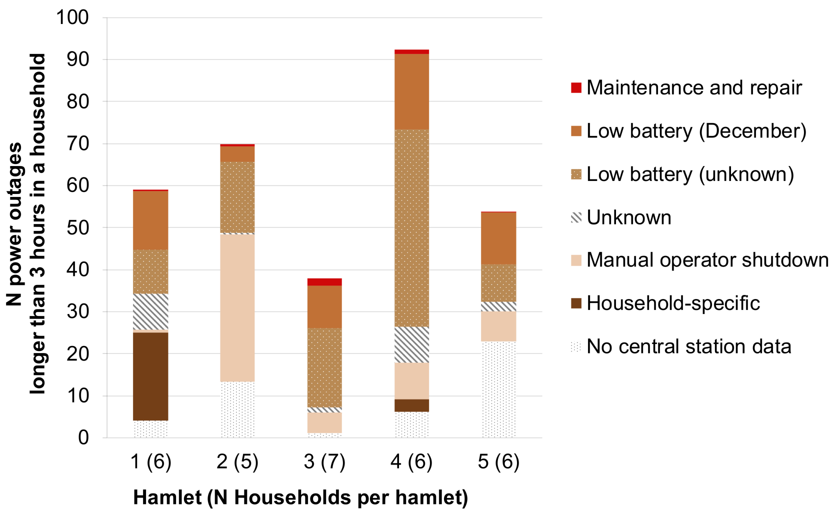

Figure 4.4. Number of power outages (>3 h) per household over the whole measurement period and their key reasons. Figure based on results presented in Publication IV. Reproduced with permission. Copyright 2018 Elsevier.

with those who offer to store and maintain the system components (the battery, for example) is particularly important. The battery, one of the most vulnerable system components, should be protected from any unnecessary intervention. An example of a unique theft prevention method, "peer-pressure", was used by a couple of micro-grid companies. In the case of a customer-induced power outage, neighbouring households would also become disconnected (those connected to the same distribution box). In such a case, the neighbours would pressure the culprit to discontinue his/her activities. The "peer-pressure" method was stated as being efficient, but only to a certain extent, because social status may define the behaviour permitted by different villagers. In general, local cultural factors require appropriate attention as the fundamental reasons behind off-grid electrification project failures have been related to a lack of understanding of the user side [107] [108] [109] [110].

Table 4.4 includes various innovative solutions implemented by micro-grid companies to prevent reliability-related problems. For example, a smart solution against component tampering was placing a system unit behind the PV panel, as the villagers were never discovered tampering with the panels for one reason or another. An effective method against power tapping may be underground distribution cabling. It is expensive, but recommended, if sufficient initial capital is available.

Table 4.4. Problems effecting service reliability in micro-grids, and suggested solutions. Table based on results presented in Publication V. Reproduced with permission. Copyright 2019 Elsevier.

Reliability problem	N	Possible design solutions (non-exhaustive) to keep up power supply
Electrical design aspects		
Capacity not sufficient for 365 days a year due to alternating local weather conditions	10	Hybrid energy solutions; seasonal frugal use or energy; load prioritization
Unexpected failure of a critical component e.g. inverter due to low quality	5	Choosing system units with sufficient quality; buying critical components or their spare parts to storage; systems requiring simpler maintainability
Unexpected power losses due to internal inefficiencies of electrical equipment	0	Choosing energy efficient system units; careful installation work
Practical design aspects (installation)		
Low quality installation work	0	Careful installation work; well-chosen mounting elements and fasteners
Accidental human / animal intervention with crucial components	4	Prohibiting or complicating access
Plant management aspects		
Overloading with high-consuming appliances	9	User education; load limiters; DC distribution (less loads available); higher system capacities; system topologies against theft
Experimenting with critical components such as control units, distribution boxes or energy meters	8	User education; consumer satisfaction; safety stickers for visual inspections; placing system intelligence in inaccessible places; tamper-proof devices, for distribution boxes see e.g. [111]
Power tapping directly from supply components (battery)	6	Prohibiting access (metal boxes, not wooden); user education

Table 4.4. Problems effecting service reliability in micro-grids, and suggested solutions. Table based on results presented in Publication V. Reproduced with permission. Copyright 2019 Elsevier.

Power tapping from distribution lines	3	DC distribution; protecting cables with rubber bands; underground cabling; load limiters in distribution cables; system topologies that build peer pressure against theft
Exceptional events		
Extreme weather conditions (heavy rain, storms etc.)	6	Weather monitoring; back-up supplies

4.2.3 Reliability assessment framework

When measured data is not available in a comparable manner, more descriptive methods may be a satisfactory option for reliability assessment. According to interviews with the energy system companies (ESCOs) operating micro-grids, reliability problems were often not recorded in a systematic manner, which is partly understandable as the companies operate in extremely difficult financial and practical conditions [112]. Nonetheless, it is important to encourage reliability also for smaller and frugal power systems to better serve their users.

Therefore, a new reliability assessment framework was proposed for renewable micro-grids in Publication V (Table 4.5). The framework allows a light but systematic data collection from the off-grid companies without expensive measurement devices. All the data to be collected is (or should be) available. The framework is applicable for all renewable off-grid power systems. It is notable that Table 4.5 lists information to be collected, but does not recommend normative reliability levels as such. They are left for further studies.

Significantly, the framework reflects a customer perspective for a more reliable power. For example, load prioritization functions should be detailed and openly announced by the operator, because such functions may overvalue a customer group over another. In addition, the framework highlights other system features, which are also intuitive to understand for non-technical people, such as the system autonomy. The indicator may portray the supply security more intuitively than merely its storage capacity in Ampere-hours (Ah). System autonomy is the number of days that the backup storage sustains its service when there is no renewable power supply available or connected. A periodical lack of renewable energy may be a problem in power systems that are supplied with only one energy source, such as solar power.

In particular, the framework serves as a suitable discussion framework for all those involved in the energy project: donors, investors, company management and staff members, subcontractors, and even customers interested in the reliability in service. For example, if the system autonomy (in days) appears to be insufficient, a design engineer could be consulted to propose options for its increase. Battery capacity enlargement is not always the only option for higher reliability. Sometimes new control functionalities, a hybrid supply, or alternative business models (e.g. providing complementary services for solar micro-grid in the low-irradiation winter season) could also be investigated.

The framework suggests that a total reliability number is calculated as a sum of energy reliability and technical reliability (Loss-of-load-hours LOLH + Mean Downtime MDT). However, that calculation, is simply indicative. More valuable in this framework is the collection of important reliability-related aspects that better describe the background reasons for downtimes. For example, the Mean Time to Start Repairing (MTSR) requires attention, because delays in transporting spare parts may result in long service downtimes of power systems in off-grid areas [113] [88]. Micro-grid company representatives (Publication V) reported up to 15 days of MTSR. Sometimes lengthy downtimes were caused by a "vendor lock-in" where the vending company controlled the availability of a spare part, which prolonged the total duration of a repair activity.

When light is shed on such context-dependent challenges, all the stakeholders involved (donors, investors, staff members, even customers) will possess a chance to better understand localized problems and to contribute to solving them.

Table 4.5. Reliability assessment framework for renewable off-grid power systems. Table based on results presented in Publication V. Reprinted with permission. Copyright 2019 Elsevier.

Reliability aspect	Note	Unit
Energy service description (company promise)		
Supply schedule:	Start and end of power supply in daily cycle per customer group	Daily schedule (hours and minutes)
Power and energy levels:	Power amount per customer group	Watts (W) or Watt-peaks (Wp)
Maintenance schedule:	Schedule of no-supply hours due to regular maintenance	Dates or weekdays and schedule (hours and minutes)
Load prioritization functions:	Priorities set between customer groups during energy insufficiency or technical failure	(descriptive)

Energy reliability

Table 4.5. Reliability assessment framework for renewable off-grid power systems. Table based on results presented in Publication V. Reprinted with permission. Copyright 2019 Elsevier.

Loss of load hours (LOLH):	Number of hours of no supply due to energy insufficiency divided by the number of hours promised	%
Number of lost customers:	Percentage of customers disconnected during low power	%
Schedule of low supply seasons:	Seasonal periods when renewable supply does not meet the load	Dates. Share of annual no-supply days (%)
System autonomy:	Storage ability to supply in periods of low power	Number of hours
Technical reliability		
Mean downtime (MDT):	Total time of no supply due to component breakup, repair or system maintenance divided by the total time promised	%
Mean time to start repairing (MTSR):	Speed of repair personnel to arrive after first notice (also first-aid service rapidity)	Number of hours
Mean time to repair (MTTR):	Speed of repair operations	Number of hours
Maximum time to repair (MTR):	Replacement or repair time of components with lowest availabilities	Number of hours
Protection measures:	Anti-theft and other measures implemented against illegal actions and exceptional external events	(descriptive)
Component degradation and system lifetime		
Battery lifetime (nominal and real):	Nominal and an estimation of the real lifetime in the actual use environment	Number of days
Vulnerable components:	Description of vulnerable blocks in the energy system installed	(descriptive)
Total reliability		

Table 4.5. Reliability assessment framework for renewable off-grid power systems. Table based on results presented in Publication V. Reprinted with permission. Copyright 2019 Elsevier.

Total estimated system downtime:	Approximate annual time of no power out of the scheduled supply = LOLH + MDT	%

5. Discussion

This chapter contributes to the academic discussion on the topic of sustainable energy access, and describes the type of practical knowledge it may offer for energy practitioners. Finally, some recommendations are presented for further studies.

5.1 Theoretical implications

This dissertation enriches the academic debate on frugal innovations and sustainable energy access by offering a formal definition for frugal energy innovations, while highlighting issues that are particular and relevant to energy access: sustainability, technical performance, and local maintainability. This work also presents insights on various aspects of frugal innovation related concepts, such as energy frugality, energy efficiency, environmental protection, and sustainable development that may assist in further conceptualizations.

The result from the field measurement with the solar pico-grid provides an example level for reliability of a power system in the lowest energy access tier (Tier 1). The Council on Energy, Environment and Water (CEEW) defines reliability by the maximum number of blackout days per month [30]. For Tier 1 (maximum 50 W consumption), this is four, meaning 48 blackout days per year. Pico-grid customers experienced over three times the amount during the year (156 days with blackouts, on average). In contrast, reliability was left completely undefined in the multi-tier energy access framework by the World Bank's Energy Sector Management Assistance Program (ESMAP) for the lowest energy consumption tiers [114]. The measured information from the pico-grid reliability may contribute to the discussion on quality and reliability recommendation levels for minimum energy needs.

5.2 Practical implications

The technological insights into frugal energy innovations may be applied to other off-grid systems and other low-income electricity use contexts. The results gained through the detailed technical analysis of the solar pico-grid might be useful for design engineers of micro-grid system components. The system provider itself has already used the results for further product development [96][1]. In addition, Section 4.2.2 includes a list of typical technical problems in solar micro-grids in India that can potentially reduce service reliability. Companies' innovative solutions used to tackle these problems were presented in this work. Solutions are technical, but also managerial and customer-centred. The findings develop an understanding of bottlenecks and practical problems on village micro-grid installations, and may benefit present and future system designers, operators, and energy users.

A major contribution of this dissertation is the reliability assessment framework for renewable off-grid power systems. Assessing an off-grid energy project by using the framework may encourage reliability thinking and help to identify typical reliability-related problems. Furthermore, the framework might be a valuable tool for various institutions focusing on the quality issues of renewable off-grid systems.

The general insights into the micro-grid use contexts may also be of practical value for those who plan frugal energy business. Renewable power business in rural India is economically extremely challenging [39] and the pico-grid experiment echoed the same reality through the extremely low consumption levels on behalf of the customers. One result of this poverty in the communities is that the families may possess several small energy sources, such as portable batteries, solar home systems, or self-configured systems between which they alternate on a daily and hourly basis [96]. Pico-grid pre-paid meters are also charged occasionally, when the families have collected some small investable amount of cash. Customers also continued to intermittently use kerosene lanterns. The various implications of poverty and energy poverty characterize the business ecosystem, while still simultaneously offers opportunities for innovating further frugal solutions.

5.3 Recommendations for further research

The study highlights the importance of conducting technical performance studies for installed off-grid renewable solutions operating in developing countries, in particular, for their durability, system lifetime, and reliability. The new reliability assessment framework should be tested in different micro-grid contexts in other countries. Experiences should be reported and the framework should

[1]A recommendation for further reading is the thesis of L. Simmonds regarding the development of the user interface of the pico-grid energy meter [96].

be specified, when necessary. For instance, the framework could also include recommendations or benchmark values for different reliability aspects. For this, further studies on existing micro-grids reliabilities would be needed to be able to propose achievable and realistic recommendations. Nevertheless, benchmark levels offered may better be different for different power system types, such as PV-only and hybrid systems; or based on the number of daily hours served; or according to system capacities or energy services like in tier-based frameworks [30] [114].

In parallel, the end-user satisfaction should be studied. Publication V highlighted the importance of achieving a deeper understanding of customers' perception of the various deviations in power availability and reliability in terms of issues, such as scheduling, energy levels and load prioritization. The number of such studies are limited.

In order to better understand the possible relevance of off-grid energy systems for sustainable development, there are several recommended research streams. Even though it is known that solar electricity is a more environment-friendly option than fossil-fuel based sources, it would be necessary to test the aggregated household-level usage of the set of various energy technologies and not just only focus on one technology. The introduction of a new energy service (such as a solar micro-grid electricity) may not automatically mean a complete shift away from previously used sources, such as kerosene or privately-owned diesel generators. Energy-use patterns are rather non-linear, and there is a lack of relationship between the amounts of energy used and the amount of equipment owned [115]; neither are the factors that affect households' solar technology adoption well understood [45]. Detailed analysis of how different households with different socio-economic and cultural backgrounds used pico-grid services (Publication III) was out of the scope of this study. However, such analysis would provide interesting novel information on energy use patterns of impoverished customers.

Further testing of frugal demand-side-management methods in stand-alone power systems would also be recommended. The same kind of dynamic electricity pricing method might be tested in power systems with higher capacity and consumption levels to understand the value of this kind of frugal innovation.

The global role of micro-grid technologies was left partly unanswered in this dissertation. Will they remain solely as backup solutions until energy infrastructures with higher capacities are constructed in areas without electricity access? Although the lack of support provided to the micro-grid sector has nearly stagnated its development in India [116], and causes apprehension towards the future of the micro-grid companies, nevertheless, many of the companies interviewed for this dissertation considered their business prospects to be rather bright. Especially the smallest capacity micro-grid providers did not believe the government grid power quality would significantly improve to the extent that it would shrink their future customer base. The observation is supported by the fact that even if offered for free, a rather high percentage of population in Uttar Pradesh – around 20% – would reject the connection to the main grid

Figure 5.1. A single village may be served by both a government distribution system (concrete pole, on the left) and a micro-grid system (steel pole, on the right). Photo: Sini Numminen, 2018

for its perceived low quality of services [30]. On the other end, companies that had technically prepared their micro-grids for grid-connection were equally optimistic about their future prospects, being then able to sell solar-powered back-up services.

The Indian energy sector is currently going through many reforms, the largest of them being the governmental plan targeting at connecting all households by 2019 to the national power grid [117]. In parallel, the role of the distribution companies is changing, for instance, through customer migrations towards various power sources (such as private solar home systems) [118]. To maximize energy access, further micro-grid research would be necessary, because several studies have concluded that instead of competing against one another, on-grid and off-grid systems could complement each other [119] [120]. The situation, as depicted in Figure 5.1, where two power systems simultaneously serve a single village, is not an infrequent sight in micro-grid connected villages in India at the moment. It might be interesting, not only for local Indian micro-grid actors, but also for practitioners in many other countries, to study more deeply ways for different power systems to operate in parallel, not only for the sake of energy efficiency, but also to examine the ways that different energy infrastructures compositions are jointly used by the local people, such as the purpose for which certain technologies are applied and based on which determinants. The results would benefit the technology designers and business operators, as well as the millions of energy-deprived users in developing countries. Such studies may also assist in formulating policy mechanisms for increased energy access and energy poverty alleviation.

6. Conclusions

The starting-point of this dissertation was in energy poverty, which is still wide-spread in many countries. Energy poverty is also often linked to economic welfare determining which energy sources people can afford and prioritize. Frugal energy innovations, based on simplifications in designing products and energy systems and thus delivering more affordable energy services, might be an approach to address this problem. This work dealt both with general methods to identify such frugal energy innovations as well as a specific technology, namely, the solar micro-grid, to provide a concrete technological solution to local needs.

The method for identifying frugal energy innovations employed a five-criteria listing highlighting affordability in service, but also energy technology specific aspects, such as local appropriateness, durability, and environmental sustainability. Technologies that deliver energy for basic needs, including specifically food preparation and basic electricity services, affect people's everyday life, thus implying that frugal energy systems need to be designed with a people-centric and long-term approach. Importantly, a new energy system should meet local users energy-use preferences in their cultural context to ensure the deployment of technologies. In addition, durability is highlighted, because a technical failure may more severely affect the end-users, especially if the energy technology acts as the primary source of energy. For battery-based energy systems (e.g. solar home systems and micro-grids), proper recycling of distributed batteries should be ensured. A list of criteria for frugal and sustainable energy solutions was derived in this dissertation which complements the emerged frugal innovation studies in the field of energy. This checklist could be used to design frugal energy solutions that hold potential for being sustainable and adapted by the users in the long-term.

The main part of the dissertation focused on solar micro-grids, in particular, on their reliability issues and usability, which are important factors to increase their use among the rural population in developing countries. Extensive field studies were accomplished in northern India to gain empirical data for the analyses in this work.

The reliability of frugal energy innovations, in this work, mainly photovoltaic micro-grid systems, has received surprisingly little attention internationally, despite being a central factor for the success of delivering an energy service. Furthermore, reliability of a technical system ensures customer satisfaction and commitment, therefore also connecting it to business sustainability. The field tests with solar micro-grids in northern India showed that power was available to the households over 87% of the time over the year, which is higher than that of the national power grid in the region studied (50%). Based on an extensive analysis of measured and interview data in seven villages, a major part of outages (reason for 20% – 63% of all identified power outages), were actually due to low solar irradiation levels in the winter season, which would be typical to northern India. The wide range (values ranging from 20% to 63%) implies uncertainties in interpreting the causes of power outages.

The energy insufficiency problem might be solved through hybrid systems or backup supplies. The customers' satisfaction was in general good, mainly because of improved lighting quality compared to the previous lighting solution (kerosene lanterns). Sustainability benefits from solar PV systems included a reduced need of fossil kerosene, reduced exhaust gas emissions, and improved indoor air quality.

The reasons for non-weather based system failures could be tracked to component failures (17% – 21%), and improper or unintended user actions (24% – 63%). We found that people unexpectedly used and modified the technical systems for private purposes for reasons not always well articulated, but mostly likely to avoid paying for the electricity or not fully understanding all the technical functionalities. Technical illiteracy due to being not accustomed to western technical practices, sometimes caused misunderstandings. For example, the glowing light on the energy meter screen of the solar micro-grid control panel may mistakenly be understood as indicating that energy credits were being consumed. Consequently, consumers in some villages asked the operators to switch off the whole grid for the night.

These findings proved the complex nature of frugal energy business among impoverished people and the importance of understanding the role of technology in a local context, even though the basic technology, such as a solar micro-grid, may sound straightforward and robust. We would also recommend keeping critical power system components, such as batteries, well away from any unauthorized private use. Many solar micro-grid components are subject to harsh conditions in villages, thus highlighting the importance of protective measures. In addition, a relatively high internal (thermal) consumption of power was observed in some power system components, which may reduce the actual power delivery. Hence, addressing the energy efficiency of the frugal energy technology and its components would also be important in future systems.

The local businesses elsewhere in northern India interviewed for this study faced similar problems related to the instability of certain components (particularly AC inverters) and power theft. Nevertheless, we found that these local actors were often innovative and frugal in finding technical and management-related solutions to these problems. The longest solar micro-grid system downtimes were often caused by difficulties in transporting technical spare parts to the remote areas. Reliability may also be affected by unavailable skilled personnel to handle the problems that might be technical, or managerial, and which were sometimes dependent on the season. Above all, a significant share of the solutions to the reliability problems appeared to be local.

The reliability levels were rarely measured systematically by the solar micro-grid operators. Nevertheless, the results in this dissertation demonstrate that deviations from maximum reliability were found in all solar micro-grids. The interviewees estimated that the power was available on average 96% of the time, which may be overestimated based on the findings of this dissertation. The lack of data may also indicate that the reliability aspects are not yet adequately and locally framed. Furthermore, as low-income customers seem to be rather tolerant of supply interruptions, feedback on various reliability aspects to technology suppliers would not be self-evident. Reliability evaluations would, however, be important to further develop power systems and suitable energy business models. To mitigate reliability-related issues, an off-grid power system reliability assessment framework was elaborated in this work presenting relevant facts and figures that may reveal critical points that cause system downtimes. The method uses existing resources and knowledge to facilitate carrying out a reliability assessment and to encourage reliability thinking.

Importantly, the assessment method developed highlights the customer perspective and is intended to be used by all stakeholders (operators, donors, investors, even customers) involved in the electrification project to find solutions to the localized problems. We recommend that the project management of such projects adopt a realistic view on the critical issues causing service downtimes. For example, in the above cases, PV-only systems may not be able to offer full power availability locally (here northern parts of India), meaning the need for a secondary energy source for periods of low solar conditions. As a further step in the research, the proposed framework could be tested in real conditions with more systems to refine the most important reliability-related issues. In this dissertation, no numeric benchmark levels for reliability were offered, because reliability failures appeared to be very system-dependent. Despite this, benchmark levels could be sought for, for instance, for different power system types; or based on the number of daily hours served. In parallel, user analyses would be useful for better understanding which reliability deviations are the most critical ones. Such practical assessments might help in designing better services, but also formulating more effective support mechanisms and policies to locally enhance these frugal innovations.

The system performance may also be affected by the way customers use electricity in solar micro-grids, which are autonomous power systems. For example, users' power demand during a high solar yield could be beneficial for a frugal power system, whereas during low solar conditions, lower demand levels might be preferred. This kind of demand response model was tested in this study in solar micro-grids in northern India to increase the system performance and indirectly also the power reliability. We employed advanced Indian-made frugal energy metering with pre-paid functions, which would be suitable for rural people with low and irregular wages. However, the field trial showed a null finding contrary to initial expectations; namely, there was no clear user response in power use versus pricing of the power supply. The main reason found for this somewhat surprising result was that low-income customers minimized their electricity usage irrespective of (spot) price of electricity. The low demand resulted in the benefits of the potentially promising functionality being indemonstrable. Customers saved their pre-paid electricity credits, did not re-charge many times, and continued the simultaneous use of small energy sources which are probable implications of prevailing economic poverty, to which solutions are not technical. However, system designers and operators should offer appropriate user education when introducing a new energy technology with advanced functions. Another implication is that offering such pricing incentive methods to balance peak loads might be more relevant in power systems with higher electricity consumption than in the pico-scale systems tested in this work.

Frugal innovation encompasses many technology options and involves a strong behavioural component. Frugal innovation holds potential not only in poverty alleviation, but also contributing to sustainability, because frugality promotes resource efficiency through simplicity, such as a smart elimination of unnecessary components. Furthermore, this leads to cost reductions for system operators and impoverished customers. This study highlighted the importance of technical performance studies for real frugal energy solutions, particularly for their reliability and user interfacing. User preferences may not always be well understood; this may also affect the usability and reliability of the systems. User-centred technology and service design approaches might ensure sustainability longer-term.

References

[1] D. G. Nocera, “Can We Progress from Solipsistic Science to Frugal Innovation?,” *Daedalus*, vol. 141, pp. 45–52, July 2012.

[2] M. Wilenius, *Tulevaisuuskirja : Metodi Seuraavan Aikakauden Ymmärtämiseen*. Helsinki, Finland: Kustannusosakeyhtiö Otava, 1 ed., 2015.

[3] UN, “The Sustainable Development Goals Report 2018,” tech. rep., United Nations, New York, US, 2018.

[4] IEA, “IEA Energy Atlas. CO2 Emissions from Fuel Combustion in 2016.” http://energyatlas.iea.org/?subject=1378539487 (accessed 22. Jan. 2019).

[5] IEA, *World Energy Outlook 2018*. Paris, France: International Energy Agency, 2018.

[6] G. Whitesides, “The frugal way. The promise of cost-conscious science,” *The Economist*, Nov. 2012.

[7] B. C. Rao, “How disruptive is frugal?,” *Technology in Society*, vol. 35, pp. 65–73, Feb. 2013.

[8] Y. Strengers, “‘Off the Grid: Re-assembling domestic life’ (2015) by Phillip Vannini and Jonathan Taggart,” *Energy Research & Social Science*, vol. 10, pp. 289–291, Nov. 2015.

[9] V. Govindarajan and C. Trimble, *Reverse Innovation: Create Far From Home, Win Everywhere*. Boston, Massachusetts: Harvard Business Review Press, Apr. 2012.

[10] C. K. Prahalad, *The Fortune at the Bottom of the Pyramid : Eradicating Poverty through Profits*. Upper Saddle River, New Jersey, USA: Pearson Education, Inc. Publishing as Prentice Hall, 2005.

[11] R. Tiwari and C. Herstatt, “Assessing India’s lead market potential for cost-effective innovations,” *Journal of Indian Business Research*, vol. 4, no. 2, pp. 97–115, 2012.

[12] R. R. Basu, P. M. Banerjee, and E. G. Sweeny, “Frugal Innovation: Core Competencies to Address Global Sustainability,” *Journal of Management for Global Sustainability*, vol. 1, pp. 63–82, Aug. 2013.

[13] The Economist, “First break all the rules. The charms of frugal innovation,” *The Economist*, Apr. 2010.

[14] M. P. e Cunha, A. Rego, P. Oliveira, P. Rosado, and N. Habib, “Product Innovation in Resource-Poor Environments: Three Research Streams,” *Journal of Product Innovation Management*, vol. 31, pp. 202–210, Mar. 2014.

[15] S. Praceus, “Conceptual foundations of user innovation,” in *Consumer Innovation at the Base of the Pyramid*, Forschungs-/Entwicklungs-/Innovations-Management, pp. 33–43, Springer Fachmedien Wiesbaden, 2014.

[16] R. Tiwari and C. Herstatt, “’Too Good’ to Succeed? Why Not Just Try ’Good Enough’! Some Deliberations on the Prospects of Frugal Innovations,” Working Paper 76, Global-innovation.net, Oct. 2013.

[17] E. Rosca, M. Arnold, and J. C. Bendul, “Business models for sustainable innovation – an empirical analysis of frugal products and services,” *Journal of Cleaner Production*, vol. 162, pp. S133–S145, Sept. 2017.

[18] J. Levänen, M. Hossain, T. Lyytinen, A. Hyvärinen, S. Numminen, and M. Halme, “Implications of Frugal Innovations on Sustainable Development: Evaluating Water and Energy Innovations,” *Sustainability. Special Issue "Sustainable Development Goals: A Call for Frugal Innovations for a Resource-Scarce World"*, vol. 8, Dec. 2015.

[19] E. Rosca, J. Reedy, and J. C. Bendul, “Does Frugal Innovation Enable Sustainable Development? A Systematic Literature Review,” *The European Journal of Development Research*, vol. 30, pp. 136–157, Jan. 2018.

[20] A. Gupta, “Frugal innovation is not just about affordability: Minds on the Margin,” *DNA. Sunday*, July 2014.

[21] M. B. Zeschky, S. Winterhalter, and O. Gassmann, “From Cost to Frugal And Reverse Innovation: Mapping the Field and Implications for Global Competitiveness,” *Research-Technology Management (RTM)*, vol. 57, pp. 20–27, July–August 2014.

[22] K. Bound and I. W. Thornton, *Our Frugal Future: Lessons from India’s Innovation System*. Nesta London, July 2012.

[23] D. Schnitzer, D. S. Lounsbury, J. P. Carvallo, R. Deshmukh, J. Apt, and D. M. Kammen, “Microgrids for Rural Electrification: A critical review of best practices based on seven case studies,” tech. rep., United Nations Foundation, Feb. 2014.

[24] K. Latoufis, T. Pazios, and N. Hatziargyriou, “Locally Manufactured Small Wind Turbines: Empowering communities for sustainable rural electrification.,” *IEEE Electrification Magazine*, vol. 3, pp. 68–78, Mar. 2015.

[25] C. Bhushan and A. Kumakarandath, “Mini-grids. Electricity for all,” tech. rep., Centre for Science and Environment, New Delhi, India, 2016.

[26] GNESD, *Renewable Energy-Based Rural Electrification: The Mini-Grid Experience from India*. New Delhi, India: Prepared by The Energy and Resources Institute (TERI) for the Global Network on Energy for Sustainable Development (GNESD), 2014. OCLC: 907365874.

[27] M. Wiemann, S. Rolland, and G. Glani, “Hybrid mini-grids for rural electrification: Lessons learned,” tech. rep., Association for Rural Electrification (ARE), Brussels, Belgium, May 2014.

[28] IEA, “Energy Access Outlook 2017. From Poverty to Prosperity,” tech. rep., International Energy Agency, Paris, France, 2017.

[29] S. C. Bhattacharyya and D. Palit, “Introduction,” in *Mini-Grids for Rural Electrification of Developing Countries* (S. C. Bhattacharyya and D. Palit, eds.), Green Energy and Technology, pp. 1–8, Springer International Publishing, 2014.

[30] A. Jain, S. Tripathi, S. Mani, S. Patnaik, T. Shahidi, and K. Ganesan, “Access to Clean Cooking Energy and Electricity. Survey of States 2018,” CEEW Report, Council on Energy, Environment and Water (CEEW), New Delhi, India, Nov. 2018.

[31] J. Terrapon-Pfaff, C. Dienst, J. König, and W. Ortiz, "How effective are small-scale energy interventions in developing countries? Results from a post-evaluation on project-level," *Applied Energy*, vol. 135, pp. 809–814, Dec. 2014.

[32] S. Pachauri, "Reaching an international consensus on defining modern energy access," *Current Opinion in Environmental Sustainability*, vol. 3, pp. 235–240, Sept. 2011.

[33] M. Franz, N. Peterschmidt, M. Rohrer, and B. Kondev, "Mini-grid policy toolkit. Policy and Business Frameworks for Successful Mini-Grid Roll-outs," tech. rep., European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF), Eschborn, Germany, 2014.

[34] J. Holmes and T. Van Gevelt, "Energy for development – the concept," in *Smart Villages: New Thinking for Off-Grid Communities Worldwide* (R. Heap, ed.), Cambridge, UK: Banson/Smart Villages Initiative, 2015.

[35] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *Power and Energy Magazine, IEEE*, vol. 5, no. 4, pp. 78–94, July/August 2007.

[36] S. G. Banerjee, F. A. Moreno, J. Sinton, T. Primiani, and J. Seong, "Regulatory Indicators for Sustainable Energy. A Global Scorecard for Policy Makers," World Bank Other Operational Studies 26099, The World Bank, Washington D.C., US, 2016.

[37] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E. K. Ackom, X. Vallve, and S. Szabó, "Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 1148–1161, Aug. 2018.

[38] S. Numminen, S. Yoon, J. Urpelainen, and P. Lund, "An evaluation of dynamic electricity pricing for solar micro-grids in rural India," *Energy Strategy Reviews*, vol. 21, pp. 130–136, Aug. 2018.

[39] A. L. D'Agostino, P. D. Lund, and J. Urpelainen, "The business of distributed solar power: A comparative case study of centralized charging stations and solar microgrids," *Wiley Interdisciplinary Reviews: Energy and Environment*, Feb. 2016.

[40] S. Numminen and P. D. Lund, "Evaluation of the reliability of solar micro-grids in emerging markets – Issues and solutions," *Energy for Sustainable Development*, vol. 48, pp. 34–42, Feb. 2019.

[41] J. Siemer, "Trust is good, quality control would be better," *Photon International*, vol. 8, pp. 56–61, Aug. 2018.

[42] S. A. Chowdhury and M. Mourshed, "Off-grid electrification with solar home systems: An appraisal of the quality of components," *Renewable Energy*, vol. 97, pp. 585–598, Nov. 2016.

[43] E. T. Youngren, "Shortcut to Failure: Why Whole System Integration and Balance of System Components are Crucial to Off-grid PV System Sustainability," in *2011 IEEE Global Humanitarian Technology Conference (GHTC)*, pp. 247–252, Oct. 2011.

[44] A. Brüderle, "Solar Lamps Field Test Uganda. Final report," tech. rep., Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) Gmbh, Kampala, July 2011.

[45] M. Aklin, P. Bayer, S. Harish, and J. Urpelainen, "Economics of household technology adoption in developing countries: Evidence from solar technology adoption in rural India," *Energy Economics*, vol. 72, pp. 35–46, May 2018.

[46] S. Hirmer and H. Cruickshank, “Making the deployment of pico-PV more sustainable along the value chain,” *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 401–411, Feb. 2014.

[47] D. Akinyele, J. Belikov, and Y. Levron, “Challenges of Microgrids in Remote Communities: A STEEP Model Application,” *Energies*, vol. 11, p. 432, Feb. 2018.

[48] S. Numminen and P. D. Lund, “Frugal energy innovations for developing countries – a framework,” *Global Challenges*, vol. 1, pp. 9–19, Sept. 2016.

[49] S. C. Bhattacharyya and D. Palit, “Mini-grid based off-grid electrification to enhance electricity access in developing countries: What policies may be required?,” *Energy Policy*, vol. 94, pp. 166–178, July 2016.

[50] P. J. Boait, “Demand Management for Off-Grid Electricity Networks,” in *Mini-Grids for Rural Electrification of Developing Countries* (S. C. Bhattacharyya and D. Palit, eds.), Green Energy and Technology, pp. 135–144, Springer International Publishing, 2014.

[51] K. Ito, T. Ida, and M. Tanaka, “Moral Suasion and Economic Incentives: Field Experimental Evidence from Energy Demand,” *American Economic Journal: Economic Policy*, vol. 10, pp. 240–267, Feb. 2018.

[52] University of Leichester, “Interviewing for Research - Asking the Questions.” https://www.le.ac.uk/emoha/howtointerview/wordpdf/questions.pdf.

[53] CLEAN, “Clean Energy Access Network.” http://thecleannetwork.org/, 2018.

[54] J. F. Gubrium and J. A. Holstein, *Handbook of Interview Research: Context & Method*. Thousand Oaks, California, US: Sage Publications, 2001.

[55] M. Fatima and A. Srivastava, “A Review on Microgrid: Architecture, Model and Existing Ventures in India,” *International Journal of Enhanced Research in Science Technology & Engineering*, vol. 3, no. 2, pp. 242–247, 2014.

[56] M. Welsch, M. Bazilian, M. Howells, D. Divan, D. Elzinga, G. Strbac, L. Jones, A. Keane, D. Gielen, V. S. K. M. Balijepalli, A. Brew-Hammond, and K. Yumkella, “Smart and Just Grids for sub-Saharan Africa: Exploring options,” *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 336–352, Apr. 2013.

[57] A. Niez, “Comparative Study on Rural Electrification Policies in Emerging Economies. Keys to successful policies,” Information Paper doi:10.1787/5kmh3nj5rzs4-en, International Energy Agency, Paris, France, Mar. 2010.

[58] S. Numminen, S. Yoon, and J. Urpelainen, “A Frugal Innovation Approach to Dynamic Electricity Pricing in Rural India: A Field Experiment. Pre-Analysis plan.” Evidence in Governance and Politics (EGAP), http://egap.org/registration/1662 (accessed 22. Apr. 2016), Jan. 2016.

[59] T. Reddy, *Linden’s Handbook of Batteries*. New York, US: McGraw-Hill Education, 4 ed., Nov. 2010.

[60] R. Luthander, J. Widén, D. Nilsson, and J. Palm, “Photovoltaic self-consumption in buildings: A review,” *Applied Energy*, vol. 142, pp. 80–94, Mar. 2015.

[61] “Prayas (Energy Group). Electricity Supply Monitoring Intiative. Analysis Reports.” http://watchyourpower.org/uploaded_reports.php (accessed 25. Jan. 2019).

[62] J. D. Kueck, B. J. Kirby, P. N. Overholt, and L. C. Markel, “Measurement practices for reliability and power quality. A toolkit of reliability measurement practice,” Tech. Rep. ORNL/T M-2 004/91, Prepared by Oak Ridge National Laboratory and managed by UT-BATTELLE, LLC for the U.S. Department of Energy, Tennessee, USA, 2004.

[63] P. Díaz, M. A. Egido, and F. Nieuwenhout, "Dependability analysis of stand-alone photovoltaic systems," *Progress in Photovoltaics: Research and Applications*, vol. 15, pp. 245–264, May 2007.

[64] A. Kumar, A. R. Singh, Y. Deng, X. He, P. Kumar, and R. C. Bansal, "A Novel Methodological Framework for the Design of Sustainable Rural Microgrid for Developing Nations," *IEEE Access*, vol. 6, pp. 24925–24951, 2018.

[65] P. Mohanty and T. Muneer, "Smart Design of Stand-Alone Solar PV System for Off Grid Electrification Projects," in *Mini-Grids for Rural Electrification of Developing Countries*, Green Energy and Technology, pp. 63–93, Springer, 2014.

[66] G. Gambirasio, "Computation of Loss-of-Load Probability," *IEEE Transactions on Reliability*, vol. R-25, pp. 54–55, Apr. 1976.

[67] E. Lorenzo and L. Navarte, "On the usefulness of stand-alone PV sizing methods," *Progress in Photovoltaics: Research and Applications*, vol. 8, pp. 391–409, July 2000.

[68] M. Rausand and A. Høyland, *System Reliability Theory: Models, Statistical Methods, and Applications*. John Wiley & Sons, Inc., 2 ed., 2004.

[69] N. Radjou, J. Prabhu, and S. Ahuja, *Jugaad Innovation : Think Frugal, Be Flexible, Generate Breakthrough Growth*. Jossey-Bass, 2012.

[70] Y. A. Bhatti and M. Ventresca, "The Emerging Market for Frugal Innovation: Fad, Fashion, or Fit?," Working Paper ID 2005983, Social Science Research Network, Rochester, NY, Jan. 2012.

[71] R. Gupta, A. Pandit, A. Nirjar, and P. Gupta, "Husk Power Systems: Bringing Light to Rural India and Tapping Fortune at the Bottom of the Pyramid," *Asian Journal of Management Cases*, vol. 10, pp. 129–143, Sept. 2013.

[72] C. Lim and T. Fujimoto, "Frugal innovation and design changes expanding the cost-performance frontier: A Schumpeterian approach," *Research Policy*, Oct. 2018.

[73] E. Hossain, E. Kabalci, R. Bayindir, and R. Perez, "Microgrid testbeds around the world: State of art," *Energy Conversion and Management*, vol. 86, pp. 132–153, Oct. 2014.

[74] D. Palit and S. Malhotra, "Energizing rural India using micro grids: The case of solar DC micro-grids in Uttar Pradesh State, India," in *Third International Conference: Micro Perspectives for Decentralized Energy Supply*, vol. Micro Perspectives for Decentralized Energy Supply: Proceedings of the International Conference, (Bangalore, India), 2015.

[75] E. Planas, J. Andreu, J. I. Gárate, I. n. Martínez de Alegría, and E. Ibarra, "AC and DC technology in microgrids: A review," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 726–749, Mar. 2015.

[76] A. A. Asif, R. Singh, and G. K. Venayagamoorthy, "Ultra-low cost and solar storm secured local DC electricity to address climate change challenges for all economies," in *2016 Clemson University Power Systems Conference (PSC)*, pp. 1–7, Mar. 2016.

[77] P. Kaur, S. Jain, and A. Jhunjhunwala, "Solar-DC deployment experience in off-grid and near off-grid homes: Economics, technology and policy analysis," in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, pp. 26–31, June 2015.

[78] F. Yettou, B. Azoui, A. Malek, A. Gama, and N. L. Panwar, "Solar cooker realizations in actual use: An overview," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 288–306, Sept. 2014.

[79] N. L. Panwar, S. C. Kaushik, and S. Kothari, “State of the art of solar cooking: An overview,” *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 3776–3785, Aug. 2012.

[80] SELCO, “Sustainable Energy and Livelihoods. A collection of 50 livelihood applications,” tech. rep., SELCO Foundation, Bangalore, India, Oct. 2018.

[81] S. Waray, S. Patnaik, and A. Jain, “Clean Energy Innovations to Boost Rural Incomes,” tech. rep., Council on Energy, Environment and Water (CEEW), New Delhi, India, Oct. 2018.

[82] B. K. Pattnaik and D. Dhal, “Mobilizing from appropriate technologies to sustainable technologies based on grassroots innovations,” *Technology in Society*, vol. 40, pp. 93–110, Feb. 2015.

[83] E. Park and J. Y. Ohm, “Appropriate Technology for Sustainable Ecosystems: Case Studies of Energy Self-Reliant Villages and the Future of the Energy Industry,” *Sustainable Development*, vol. 23, pp. 74–83, Mar. 2015.

[84] J. T. Murphy, “Making the energy transition in rural east Africa: Is leapfrogging an alternative?,” *Technological Forecasting and Social Change*, vol. 68, pp. 173–193, Oct. 2001.

[85] P. P. Otte, “Solar cookers in developing countries—What is their key to success?,” *Energy Policy*, vol. 63, pp. 375–381, Dec. 2013.

[86] S. A. Quadir, S. S. Mathur, and T. C. Kandpal, “Barriers to dissemination of renewable energy technologies for cooking,” *Energy Conversion and Management*, vol. 36, pp. 1129–1132, Dec. 1995.

[87] J. Leary, A. While, and R. Howell, “Locally manufactured wind power technology for sustainable rural electrification,” *Energy Policy*, vol. 43, pp. 173–183, Apr. 2012.

[88] F. Fuso Nerini, M. Howells, M. Bazilian, and M. F. Gomez, “Rural electrification options in the Brazilian Amazon: A multi-criteria analysis,” *Energy for Sustainable Development*, vol. 20, pp. 36–48, June 2014.

[89] T. Lyytinen, “Sustainable Business Models of Small-Scale Renewable Energy Systems: Two Resource-Scarce Approaches for Design and Manufacturing,” in *Sustainable Design and Manufacturing 2017* (G. Campana, R. J. Howlett, R. Setchi, and B. Cimatti, eds.), Smart Innovation, Systems and Technologies, pp. 493–504, Springer International Publishing, 2017.

[90] “Case study summary: SELCO Solar Pvt Ltd, India,” tech. rep., Ashden Awards, 2009.

[91] “Energy and Carbon Benefits of Pico-powered Lighting,” Eco Design Notes 4, Lighting Africa and The World Bank Group, 2014.

[92] Y. Gupt and S. Sahay, “Managing Used Lead Acid Batteries in India: Evaluation of EPR-DRS Approaches,” *Journal of Health and Pollution*, vol. 5, pp. 52–63, June 2015.

[93] P. Pathak, R. R. Srivastava, and Ojasvi, “Assessment of legislation and practices for the sustainable management of waste electrical and electronic equipment in India,” *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 220–232, Oct. 2017.

[94] A. Sepúlveda, M. Schluep, F. G. Renaud, M. Streicher, R. Kuehr, C. Hagelüken, and A. C. Gerecke, “A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India,” *Environmental Impact Assessment Review*, vol. 30, pp. 28–41, Jan. 2010.

[95] G. Strbac, "Demand side management: Benefits and challenges," *Energy Policy*, vol. 36, pp. 4419–4426, Dec. 2008.

[96] L. Simmonds, *Power to the People – Designing a Better Prepaid Electricity Service for Rural Indian Villages*. MA Thesis, Aalto University School of Arts, Design and Architecture, 2018.

[97] M. Aklin, P. Bayer, S. P. Harish, and J. Urpelainen, "Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India," *Science Advances*, vol. 3, p. e1602153, May 2017.

[98] S. Alexander, "Energy Solutions Shouldn't Just Tick Boxes, They Should Transform Communities." https://nextbillion.net/energy-solutions-shouldnt-just-tick-boxes-they-should-transform-communities/ (accessed 4. Jan. 2018), June 2017.

[99] "Prayas (Energy Group). Electricity Supply Monitoring Intiative. Document summaries 2017 (calculated from the data on interruptions larger than 15 minutes in rural areas in Uttar Pradesh)," http://watchyourpower.org/uploaded_reports.php (accessed 6. Aug. 2018).

[100] S. Srivastava, O. Singh, and G. Pandey, "Estimation of global solar radiation in Uttar Pradesh (India) and comparison of some existing correlations," *Solar Energy*, vol. 51, pp. 27–29, July 1993.

[101] IEA, "More Data Less Energy," tech. rep., International Energy Agency, Paris, 2014.

[102] A. de Almeida, P. Fonseca, B. Schlomann, and N. Feilberg, "Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations," *Energy and Buildings*, vol. 43, pp. 1884–1894, Aug. 2011.

[103] A. Upadhyay, "How One Woman Tried to Stop a $10 Billion Theft," *Bloomberg.com*, Sept. 2017.

[104] S. S. S. R. Depuru, L. Wang, and V. Devabhaktuni, "Electricity theft. Overview, issues, prevention and a smart meter based approach to control theft," *Energy Policy*, vol. 39, no. 2, pp. 1007–1015, 2011.

[105] G. Sreenivasan, *Power Theft*. New Delhi, India: PHI Learning Private Limited, 2 ed., 2011.

[106] H. Louie, *Off-Grid Electrical Systems in Developing Countries*. Springer International Publishing, 2018.

[107] B. K. Sovacool and I. M. Drupady, *Energy Access, Poverty, and Development : The Governance of Small-Scale Renewable Energy in Developing Asia*. Abingdon, Oxon, GBR: Ashgate Publishing Group, 2012.

[108] F. S. Javadi, B. Rismanchi, M. Sarraf, O. Afshar, R. Saidur, H. W. Ping, and N. A. Rahim, "Global policy of rural electrification," *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 402–416, Mar. 2013.

[109] S. Hirmer and H. Cruickshank, "The user-value of rural electrification: An analysis and adoption of existing models and theories," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 145–154, June 2014.

[110] L. Gollwitzer and J. Cloke, "Lessons from Collective Action for the Local Governance of Mini-Grids for Pro-Poor Energy Access," LCEDN Briefing Paper 1, Low Carbon Energy for Development Network (LCEDN), Loughborough University, Leicestershire, UK, May 2018.

[111] K. Patel and R. K. Mishra, "A Novel Design to Prevent Electricity Theft from Pole Mounted Distribution Boxes," in *National Power Systems Conference (NPSC)*, (Bhubaneswar, India), IEEE, 2016.

[112] R. Tongia, "Microgrids in India: Myths, Misunderstandings, and the Need for Proper Accounting," Tech. Rep. 022018, Brookings India, New Delhi, India, Feb. 2018.

[113] H. Louie, P. Dauenhauer, M. Wilson, A. Zomers, and J. Mutale, "Eternal Light: Ingredients for Sustainable Off-Grid Energy Development," *IEEE Power and Energy Magazine*, vol. 12, pp. 70–78, July 2014.

[114] M. Bhatia and N. Angelou, "Beyond Connections: Energy Access Redefined.," Conceptualization Report 008/15, Energy Sector Management Assistance Program (ESMAP) of the World Bank Group, Washington D.C., US, 2015.

[115] I. Bisaga and P. Parikh, "To climb or not to climb? Investigating energy use behaviour among Solar Home System adopters through energy ladder and social practice lens," *Energy Research & Social Science*, vol. 44, pp. 293–303, Oct. 2018.

[116] S. D. Comello, S. J. Reichelstein, A. Sahoo, and T. S. Schmidt, "Enabling Mini-Grid Development in Rural India," *World Development*, vol. 93, pp. 94–107, May 2017.

[117] Government of India, "Guidelines for Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya)," Tech. Rep. F.No. 44/2/2016-RE, Government of India, Ministry of Power, New Delhi, India, Oct. 2017.

[118] A. Josey, S. Dixit, A. Chitnis, and A. Gambhir, "Electricity Distribution Companies in India: Preparing for an uncertain future," discussion Paper, Prayas (Energy Group) Pune, Maharashtra, India, 2018.

[119] D. Palit and K. R. Bandyopadhyay, "Rural electricity access in South Asia: Is grid extension the remedy? A critical review," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1505–1515, July 2016.

[120] J. Urpelainen, "Grid and off-grid electrification: An integrated model with applications to India," *Energy for Sustainable Development*, vol. 19, pp. 66–71, Apr. 2014.

Appendix

Weekly survey questions for pico-grid customers

1W101) Are you the household head? 1 Yes 0 No

W101A) IF NOT, What is your relationship to the head? _______

W201) How much money have you spent on electricity purchases past week?
_____ RUPEEES

W202) Did you purchase a new electric appliance past week? 1 Yes 0 No

W202b) If yes, what did you purchase? _________________

W203) How many hours of electric lighting per day have you had past week?
_____ HOURS/DAY

W204) How many hours of fan operation per day have you had past week?
_____ HOURS/DAY

W205) How many hours of mobile charging per day have you had past week?
_____ HOURS/DAY

W206) During the past week, when did you typically

Charge your mobile phone? Starting time ______ How long (HH:MM) _______
Use fan? Starting time ______ How long (HH:MM) _______
Use electric lighting? Starting time ______ How long (HH:MM) _______

W207) How many times have you had technical problem with lights past week?
_____ NUMBER

W208) How many times have you had technical problem with fan past week?
_____ NUMBER

W209) How many times have you had technical problems with mobile charging past week?
_____ NUMBER

W210) How do you feel about the price of electricity?

1. Very expensive 2. Somewhat expensive
3. Neither expensive nor cheap 4. Somewhat cheap
5. Very cheap

W211) How difficult is it to use Boond's pre-paid system for electricity?

1. Very difficult
2. Somewhat difficult
3. Neither easy nor difficult
4. Somewhat easy
5. Very easy

W212) Overall, how satisfied are you with Boond's service?

1. Very unsatisfied
2. Somewhat unsatisfied
3. Neither satisfied nor unsatisfied
4. Somewhat satisfied
5. Very satisfied

W213) Have you faced technical problems with the energy meters during the past week?

1 Yes 0 No

W213b) If yes, Could you please describe the problem?

W213c) When did the problem start and when did it end?

Start time ______ (am/pm) _________________ (DD/MM)
End time ______ (am/pm) _________________ (DD/MM)

W213d) Has the problem been solved?

W213e) What was the cause of the problem?

1 Energy overload
2 Central system broke down
3 Power line cut
4 Weather (rain)
5 Other: ________________

W214) Has the power been available all the time during the last week?
1 Yes 0 No

W214b) If not, when did the power cut(s) start and when did it/they end?

Start time ______ (am/pm) _________________ (DD/MM)
End time ______ (am/pm) _________________ (DD/MM)

W214c) Is the power available now?

1 Yes 0 No

W214d) Do you know what was/were the cause(s) of the problem(s)?

1 Yes 0 No

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