Eetu Ahonen

Energy frugality: Solar powered microgrids

School of Science

Thesis submitted for examination for the degree of Master of Science in Technology.
Espoo, 9.3.2015

Thesis supervisor and advisor:

Prof. Peter Lund

Aalto-yliopisto
Perustieteiden
korkeakoulu

AALTO UNIVERSITY
SCHOOL OF SCIENCE

ABSTRACT OF THE
MASTER'S THESIS

Author: Eetu Ahonen

Title: Energy frugality: Solar powered microgrids

Date: 9.3.2015 Language: English Number of pages: 8+53

Department of Applied Physics

Professorship: Advanced Energy Systems Code: Tfy-56

Supervisor and instructor: Prof. Peter Lund

In this work, solar powered microgrids are investigated as an application of energy frugality. Energy frugality means solving the energy needs of the poor by frugal innovations. Microgrids are small electricity networks that include both local production and consumption.

A techno-economic analysis of microgrid cases with different parameters and locations was performed. The tools included PVSyst program for technical simulations, simple DC grid model for grid analysis and Retscreen program for economic feasibility study.

The optimal size for a microgrid depends on the target one wants to achieve. Economic feasibility study suggests that increasing the ratio of consumption to production would increase the feasibility of a microgrid. It was found that the energy produced with solar powered microgrid is competitively priced compared to other available options. The LCOE for electricity produced with the microgrid was 0.42 Eur/kWh in the Indian case and 0.109 in the Finnish case. The Indian and Finnish microgrid cases had an IRR of 8% and 2.9%, respectively. Based on these results, we can say that a solar microgrid would be economically feasible.

In developing countries solar microgrids help alleviate energy poverty as true energy frugal innovations. In developed countries they can be used to increase the reliability of electricity network or to increase the renewable energy production at a competitive cost.

Keywords: Energy frugality, reverse innovation, energy poverty, energy, microgrid, solar energy

AALTO-YLIOPISTO
PERUSTIETEIDEN KORKEAKOULU

DIPLOMITYÖN TIIVISTELMÄ

Tekijä: Eetu Ahonen

Työn nimi: Energianiukkuus: Aurinkoenergialla toimivat mikroverkot

Päivämäärä: 9.3.2015 Kieli: Englanti Sivumäärä: 8+53

Teknillisen fysiikan laitos

Professuuri: Energiatieteet Koodi: Tfy-56

Valvoja ja ohjaaja: Prof. Peter Lund

Tässä työssä aurinkoenergialla toimivia mikroverkkoja tutkitaan energianiukkuuden (engl. *energy frugality*) sovelluksena. Energianiukkuudella tarkoitetaan niukkojen innovaatioiden käyttämistä energiaköyhyyden vähentämiseksi. Mikroverkot ovat pieniä sähköverkkoja, joissa on sekä paikallista kulutusta että tuotantoa.
Työssä tehtiin teknillistaloudellinen analyysi erilaisista mikroverkoista. Analyysin työkaluina olivat PVSyst-ohjelma, jolla simuloitiin tuotantoa ja kulutusta, yksinkertainen tasasähköverkkomalli, jolla mallinnettiin verkkoa ja Retscreen-ohjelma, jota käytettiin taloudelliseen analyysiin.
Mikroverkon optimaalinen koko riippuu siitä, mitä tavoitellaan. Taloudellinen analyysi antaa viitteitä siitä, että lisäämällä paikallisen kulutuksen suhdetta tuotantoon, mikroverkon kannattavuus paranee. Työssä havaittiin, että aurinkoenergialla toimivan mikroverkon tuottaman energian hinta on kilpailukykyinen muihin vaihtoehtoihin verrattuna. Mikroverkolla tuotetun sähkön vertailukelpoinen hinta (LCOE) oli Intian mikroverkoille 0,42 Eur/kWh ja Suomen mikroverkoille 0,109 Eur/kWh. Mikroverkkoprojektien efektiivinen korko oli 8% Intiassa ja 2,9% Suomessa. Näiden tulosten perusteella voidaan sanoa, että aurinkoenergialla toimiva mikroverkko olisi taloudellisesti kannattava.
Kehittyvissä maissa aurinkoenergialla toimivat mikroverkot auttavat vähentämään energiaköyhyyttä todellisina energianiukkoina innovaatioina. Teollisuusmaissa niillä voidaan lisätä sähköverkon luotettavuutta tai uusiutuvan energian osuutta kilpailukykyiseen hintaan.

Avainsanat: energiaköyhyys, energia, mikroverkko, aurinkoenergia, käänteinen innovaatio, energianiukkuus

Preface

This master's thesis has been written at the Aalto University Department of Applied Physics in the New Energy Technologies group for examination at the Aalto University School of Science. Tekes—the Finnish Funding Agency for Innovation has funded the work through the NewGlobal project.

I would like to thank my supervisor and advisor professor Peter Lund for the support and advice during the process of writing this thesis. I would also like to say my thanks to the whole New Energy Technologies research group at Aalto University Department of Applied Physics, especially Mr. Jyri Salpakari for numerous advice and help during the research process and Dr. Imran Ashgar for helping with the microgrid demonstration project. I would also like to thank my flatmates for the support during the finishing phase of my thesis.

Espoo, 2.3.2015

Eetu Ahonen

Contents

Abstract **ii**

Abstract (in Finnish) **iii**

Preface **iv**

Contents **v**

Glossary **vii**

Acronyms **viii**

1 Introduction **1**

2 Energy frugality **3**
2.1 Frugal and reverse innovation 3
2.2 Definition of energy frugality 3
2.3 Energy sector in India 4
2.3.1 Energy access 6
2.3.2 Indian solar program 7
2.3.3 Energy frugal Indian businesses 7

3 Solar power **8**

4 Microgrids **11**
4.1 Motivation for microgrids 11
4.2 Examples of operating microgrids 12
4.3 Microgrid issues 13
4.4 Business models 15
4.5 Solar microgrids in India 15
4.5.1 Technical description 16
4.6 Solar microgrids in Finland 16
4.6.1 Electricity sector in Finland 16

5 Methods **18**
5.1 Software used 18
5.1.1 PVSyst 18
5.1.2 RETScreen 20
5.2 Grid model 21

6 Results **24**
6.1 Solar microgrids in India 24
6.1.1 Simulations with PVSyst 24
6.1.2 Grid analysis 31
6.1.3 Economic analysis 33

6.2 Solar microgrids in Finland 41

7 Summary of results 46

8 Conclusions 48

References 49

Glossary

BOP The base of the pyramid; a population segment with annual incomes less than $3000 per capita per year. Term first coined in [39].

disruptive innovation An innovation that transforms the market by creating a new market based on different assumptions and eventually overtaking the existing market.

energy frugality Using frugal innovations to solve energy poverty in developing countries.

energy poverty Lack of access to modern energy services and dependence on solid biomass fuels for cooking and heating.

frugal innovation A product or service specifically designed to meet the needs of low income customers in a resource scarce environment.

grid parity A situation, where electricity produced with an energy source becomes competitive with grid electricity produced by other means.

microgrid A small electricity network that contains both generation and loads, and can work in islanded or grid-connected mode.

reverse innovation A frugal innovation applied to a developed country context.

Acronyms

AC	alternating current
DC	direct current
DER	distributed energy resource
DoD	Department of Defense
DSO	distribution system operator
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
JNNSM	Jawaharlal Nehru National Solar Mission
LCOE	levelised cost of electricity
LPG	liquified petroleum gas
NPV	net present value
PV	photovoltaic
SDG&E	San Diego Gas & Electric
SEB	state electricity board
SHS	solar home system
SOC	state of charge
STC	standard test conditions
TSO	transmission system operator
UPS	uninterruptible power supply

1 Introduction

Over 1.3 billion people representing 18% of world population have no access to electricity and 2.6 billion people lack clean cooking facilities. 95% of them live in sub-Saharan Africa or developing Asia and 84% of them live in rural areas. By definition, these people are considered to live in energy poverty as they lack access to modern energy services. Due to population growth, the number of people living in energy poverty is estimated to increase, despite continued efforts for electrification. [18]

Providing access to modern energy services is paramount to solving other issues in developing countries. Lack of modern energy services hinders progress to escape poverty and limits opportunities for income generation. Women and girls spend countless hours collecting firewood or other energy resources instead of going to school or doing paid work, which retards progress in gender equality and education. Furthermore, it contributes to climate change because in absence of other options, fossil fuels are inefficiently used for lightning or cooking. [11]

During the last few decades, global energy consumption has steadily grown and the growth is expected to continue in the foreseeable future. With growing energy consumption, greenhouse gas (GHG) emissions grow too. In order to limit GHG induced global temperature rise to the Intergovernmental Panel on Climate Change (IPCC) recommended 2°C, GHG emissions have to be reduced significantly relative to the current level [50].

In order to provide affordable energy access to everyone and to combat climate change, sustainable energy solutions are essential. Previous electrification efforts have failed to reach rural areas and the low-income customers, in other words, the base of the pyramid (BOP). Their low purchasing power means that it is not economically viable to extend the electric mains network to cover them, at least from the electric company's point of view. Therefore, new and radically different means for electrification are required.

Energy frugality is about solving the energy needs of the BOP market customers in a novel way that is at the same time sustainable, adapted to resource scarce environment and inclusive for the low-income customers. For example, a photovoltaic (PV) based microgrid installed in previously un-electrified village can be categorised as an energy frugal innovation. However, the concept of energy frugality can also be extended to a developed country context. For instance, microgrids in developed countries could be used to increase the penetration of renewable energy and to decrease the GHG emissions.

In this work, solar powered microgrids are investigated as an application of energy frugality. The concept of energy frugality is defined. A small literature review of microgrids is presented. A technoeconomic analysis of microgrids situated in developing and developed world context is performed. The aim of this work is to find an optimal size for a solar powered microgrid in developing as well in developed country context, based on the analysis.

This work is divided as follows. Firstly, the concept of energy frugality is defined and the situation of electrification and the field of energy frugality in India is described. Secondly, the concept of microgrid and related issues are described.

Thirdly, the methods used in the analysis are presented. Fourthly, the results of the analysis are given and reviewed. Lastly, conclusions and summary are presented.

This thesis is part of the Tekes—the Finnish Funding Agency for Innovation NewGlobal project. The project is a multidisciplinary research project that aims to make "Finland a world class frugal and reverse innovator." [52]

2 Energy frugality

2.1 Frugal and reverse innovation

Frugal innovation is a product or service that has been specifically catered (somewhat similarly as *appropriate technology* [45]) for the needs of the low-income customers in developing countries, in other words, the BOP market. A frugal innovation turns resource constraints—financial, material or institutional—into advantages. By constraining, the designers and engineers need to think the absolute essentials of a product and strip the product of it's unnecessary features. The field of frugal innovation has been eagerly investigated in recent years. For a more thorough description of frugal innovation, see for example [55, 41, 57].

Eventually, a frugal innovation can become a reverse innovation. This means that a product originally created for emerging markets in developing countries has "trickled up" to a developed country due to the low price, sustainability or frugality—in the traditional sense—of the innovation. Ideally, a reverse innovation creates new market demand and might even substitute an existing product, thus becoming a disruptive innovation. [10]

One of the most cited frugal innovation might be the Indian budget priced car Tata Nano, often claimed to be the cheapest car in the World [35, 9]. It has also experienced a reverse innovation, as the car is now being introduced into Europe and U.S. [32]. Other frugal innovations include General Electric's handheld electrocardiogram that costs $1000 and ultrasound device costing $15000 originally developed for the Chinese market. They have also been succesfully introduced to the western market, becoming reverse innovations. An interesting frugal and reverse innovation is the Indian Aravind cheap eye surgery. By standardising and streamlining the eye surgeries and other operations to an almost assembly line -like fashion, they are able to do over 2000 surgeries per year per doctor at a fraction of the cost in other hospitals. They also produce the lenses needed for the operations. The reverse innovation part is that the lenses and the services are now exported to other countries, developing and developed alike. [34, 46, 41].

2.2 Definition of energy frugality

Energy frugality is a wide-ranging and multi-disciplinary concept. It encompasses technological, sosio-economic and cultural aspects that need to be taken into account when creating energy frugal innovations. Defining energy frugality is difficult as it is not an established term, and the domain of the field is not yet clear.

In short, energy frugality means creating and using frugal innovations to tackle energy poverty in developing countries, especially in rural areas, where energy poverty is most prevalent. However, energy frugality also includes the application of innovations to a developed country, in which they can be used to reduce dependence on fossil fuels, improve reliability and increase sustainability.

A frugal innovation is specifically designed to developing countries. It is usually labour-intensive because inexpensive labour is readily available in developing countries. Frugal innovation has low capital-intensity as credit or funding for the project can be difficult to secure. Furthermore, they use little raw materials, especially the ones that need to be imported, as rural areas are not adequately served by the global markets providing those materials.

Perhaps most importantly, the innovation has to be offered at an affordable price for the low-income customers. We can illustrate this with a service-cost -diagram (Figure 1). With a low cost, a low level of service can be provided. With a higher cost, better and better services can be offered, but with rising service level the cost gets progressively more and more expensive. Only the rich, representing the people in developed countries, can afford the best services. Energy frugality, or frugality in general can be defined as being below certain level of cost, but still providing the necessary level of service.

In order to flourish, innovations have to be profitable. The economic feasibility of an energy frugality project can be assessed with the calculation of levelised cost of electricity (LCOE), net present value (NPV) or simple payback period. These are described in more detail in section 5.1.2.

In addition to economic feasibility, the application of an innovation has to be sustainable. This includes both environmental and social sustainability. That said, energy frugal projects have to contribute to decreasing fossil fuel usage, pollution and GHG emissions. It also has to use local labour, knowledge and materials, thus being also *inclusive* for the local villagers. A summary of energy frugal criteria is presented in Table 1.

Examples of energy frugal products include the Kenyan Kinetic and the international Liter of Light. The Kinetic is based on a percussion shaker that—shaken for 12 minutes—provides power for an hour. The power can be used to illuminate a reading light or limited mobile phone charging [13]. The Liter of Light is an international open-source project to provide cheap daytime lightning to urban slums. The idea is to refract sunlight through a plastic bottle that perforates the roof of the slum dwelling. This is far more cheaper than installing a skylight window, and also protects from the heat of the sun [24].

More traditional power sources that can be categorised as energy frugal include small scale wind, hydro and solar power. Wind power systems with an installed capacity of few kilowatts can be considered energy frugal. Energy frugal hydro power installations are divided in two categories: micro hydro, with installed capacity up to 100 kW and pico hydro, up to 5 kW.

2.3 Energy sector in India

Indian energy sector, especially electricity generation and transmission and distribution are plagued by long-time underinvestment in infrastructure. This is a result politically mandated heavily subsidised sale of electricity for rural and agricultural consumers. Because the state electricity boards (SEBs) are required to sell electricity under market prices, they run constantly at a deficit and therefore cannot make the required investments in infrastructure. Electricity theft and corruption are also rampant. This leads to a situation where electricity generation lags behind the

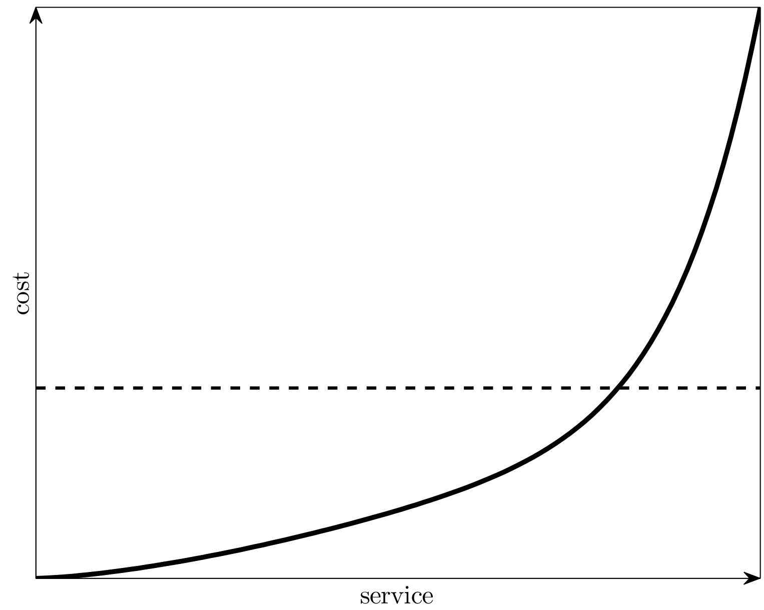


Figure 1: Cost of a product as a function of level of service. Energy frugality defined as a product below certain level of cost (dashed line), but still retaining a sufficient level of service.

Table 1: A summary of criteria for a project or product to be categorised as energy frugal and evaluation methods for these.

Criterion	Evaluation
Affordability	appropriate price and quality
Economic feasibility	LCOE, NPV, IRR, payback period
Environmental sustainability	Reduces fossil fuel usage, decreases pollution and GHG emissions
Frugality	labour-intensive, resource-scarce, low capital-intensity
Inclusive	Locals committed to the project through investment
Social sustainability	Uses local labour and materials

ever-growing demand and transmission and distribution losses are high. The SEBs are forced to implement rolling blackouts during peak hours. Unplanned blackout and brownouts are common, too. [21]

The deterioration of power quality has led industrial consumers dependent on reliable power to install their own power systems, often called *captive power*. With the new 2003 Electricity Act, the excess electricity produced by the captive power plants can be sold to the grid. [21] This has helped to narrow the gap between supply and demand, and as of 2014, captive power plant provide almost 40 GW of power representing about 15% of the total installed capacity in India.

2.3.1 Energy access

280 to 400 million Indian people repsesenting 25% to 30% of the Indian population live without access to electricity [17, 22]. Majority of those live in rural areas: the electrification rates are considerably higher in urban than rural areas; 94% in urban areas compared to 67% in rural areas. Furthermore, those who have access to electricity, find the grid unstable and blackouts frequent, especially during the evenings when the demand and need for electricity is highest. Despite decades of efforts, electricity availability and electrification rates are still far below world average. This is somewhat due to the fact that until 2004 Indian government measured electrification per villages connected to the grid rather than per household electrified. This might have given a false impression of progress. [17, 22, 11]

Electricity use is usually unmetered and billed by a fixed monthly fee, especially in rural areas. The custom is a result of high distribution losses which are a result of widespread electricity theft. The unmetered electricity supply does not encourage to conserve energy, but to consume it when it is available. [14]

Between households, great variations in energy consumption exist. As one could expect, more affluent households spend more energy than households with lower incomes. Furthermore, urban per capita energy consumption is higher than rural consumption. In urban areas, energy poverty is strongly linked to income poverty, but in rural areas also affluent households can be energy poor. This means that energy poverty cannot be addressed only by income poverty reduction, but other measures for improving energy access are needed. [25]

Energy poverty is therefore still prevalent, especially in rural areas, where traditional solid biomass fuels are used for cooking and heating, and kerosene for lightning. Needless to say, these fuels are time consuming to gather (firewood), expensive (kerosene) and dangerous, emitting small particulate matter into the air and having a considerable risk of fire. More affluent households or households with better energy access, can have their cooking needs met with liquified petroleum gas (LPG), which burns much cleaner. [11]

Rural households spend—on average—a greater proportion of their income on energy than their urban counterparts. A study found that rural households spend 12 to 18 % of their income on energy, whereas urban households spend around 6 to 8 %. [25]

2.3.2 Indian solar program

India is blessed with considerable solar energy potential, as solar insolation and population density are high; a perfect combination for solar power. The daily average solar energy incident varies from 4 to 7 kWh/m^2. With about 300 clear sunny days, this means that India receives about 5000 PWh of solar energy per year. [33] With such solar energy potential, solar power based energy production is a viable option for rural electrification in India.

The Indian government has also realised the potential in solar energy and has launched an ambitious solar energy program called Jawaharlal Nehru National Solar Mission (JNNSM), that aims to add 10 gigawatts of solar power to the grid by 2017 and 20 GW by 2022. Grid parity for solar energy is set to be achieved in 2017. The program also plans to increase off-grid solar energy usage with installation of solar home systems (SHSs), solar microgrids and solar thermal collectors. [47, 38]

2.3.3 Energy frugal Indian businesses

Interest in energy frugality in India is rising. The appalling situation of the state-driven energy sector with it's frequent blackouts and slow progress in electrification has driven enthusiastic entrepreneurs to set up private companies to remedy the situation. Examples of these companies include Boond Energy Ltd. and MeraGao Power.

Boond (sanskrit for "drop") is a socially oriented enterprise that provides solutions for rural electrification in India. Their products include SHSs, biogas cook-stoves, solar operated water pumps and solar based streetlights. [6] They have a workforce of 18 employees and a revenue of around $500 000 [20].

MeraGao Power is a company providing microgrids as a service (see section 4.4 for microgrid business models) in Uttar Pradesh, India. The company builds, owns and operates the installed microgrids and sells the produced electricity to clients. [1] The company has 11 employees and a revenue of around $ 250 000 [15].

3 Solar power

A tremendous amount of solar radiation reaches Earth every hour. The power that reaches the surface of Earth is called *irradiance*, usually measured in watts per square metre (W/m^2). The solar energy that is received on a given surface during a given period of time is called the *solar insolation* or *irradiation*, e.g. "hourly irradiation". It is measured in units of energy per area, for instance in megajoules per square metre (MJ/m^2). Part of the radiation is reflected or scattered back to space, but a portion of it is absorbed to the surface receiving it. The proportion of absorbed and reflected radiation depends on the reflectivity of the surface. This absorbed radiation can be transformed into a more usable form of energy, such as heat or electricity, using solar collectors or photovoltaic (PV) panels.

A PV solar cell is based on the photovoltaic effect, in which photons from sunlight cause the electrons residing in the valence band of the semiconductor to jump into the conduction band. This creates a hole (effectively a positive charge carrier) in the valence band. The electron in the conduction band is now free to move, as it is no longer held in place by the covalent bonds between the atoms in the valence band. Similarly, the hole left by the electron can be filled with other valence band electrons nearby, thus allowing the hole to move and effectively becoming a positive charge carrier.

The charge carriers (holes and electrons) can move by thermal diffusion or drift, driven by an electric field. In thick solar cells (such as crystalline silicon), diffusion is the dominant process, as there is no electric field present. The diffusion length of the charge carriers (the length that the electron-hole pair travels before recombining) is large compared to cell thickness. In a thin film cell (amorphous silicon, dye sensitized cells), the dominant process is drift as the diffusion length is short because the carriers recombine at the defects present in the cell. Thus the electric field created over the p-n junction drives the drift. The solar cell itself is a semiconductor p-n junction and when the charge carriers have travelled to the edges of the junction, the electric field present there carries them away, thus creating a current.

By combining enough cells into a module, a usable amount of direct current (DC) electricity can be obtained. Typically, under standard test conditions (STC) a module produces 100 to 400 watts [49]. Currently, commercial PV modules are made from crystalline silicon wafer cells or thin-film cells based on cadmium telluride, copper indium gallium seledine or amorphous silicon [48].

PV modules are arranged in arrays. The power of a PV installation made of several arrays can range anywhere from tens of W_p to several MW_p, where the p stands for *peak*. There are two distinct types of installations: *stand-alone* and *grid connected*. A stand-alone system is designed to produce energy for a local load. Usually there is a battery for energy storage. On the other hand, a grid connected system is mainly designed to operate as a power plant, feeding electricity to the grid.

Figure 2 shows the components of a typical stand-alone PV installation. A stand-alone system contains the panels, a battery, some control devices for battery charging and other features and possibly an inverter for AC loads. A grid connected (Figure 3)

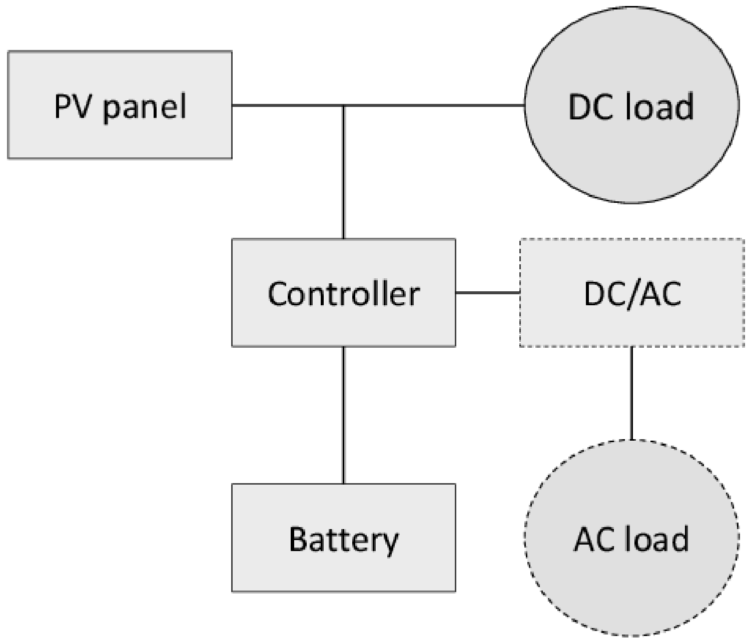


Figure 2: A simplified schematic of a stand-alone solar PV installation. Inverter and AC loads are optional.

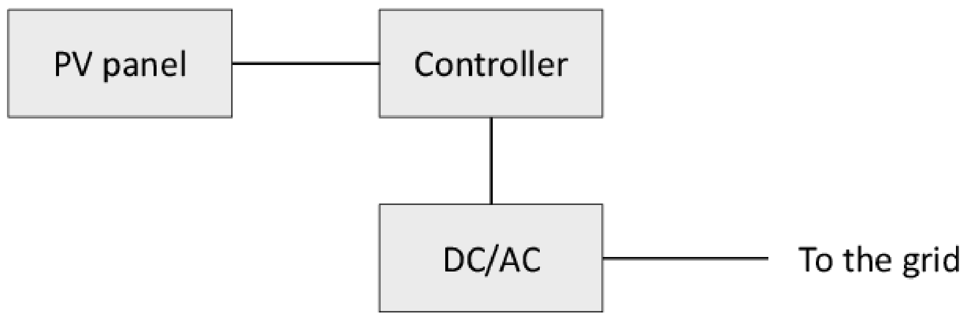


Figure 3: A simplified schematic of a grid connected solar PV installation

system typically contains only the panels and an inverter feeding electricity to the grid.

Stand-alone systems, usually termed as SHS, have seen use in developing countries, where they are viewed as a viable option for rural electrification. Successful implementation of SHSs has been demonstrated by Grameen Shakti in Bangladesh [11]. In developed countries, SHSs has been mainly marketed for use in recreational dwellings. Grid connected system have seen use both in developed and developing countries.

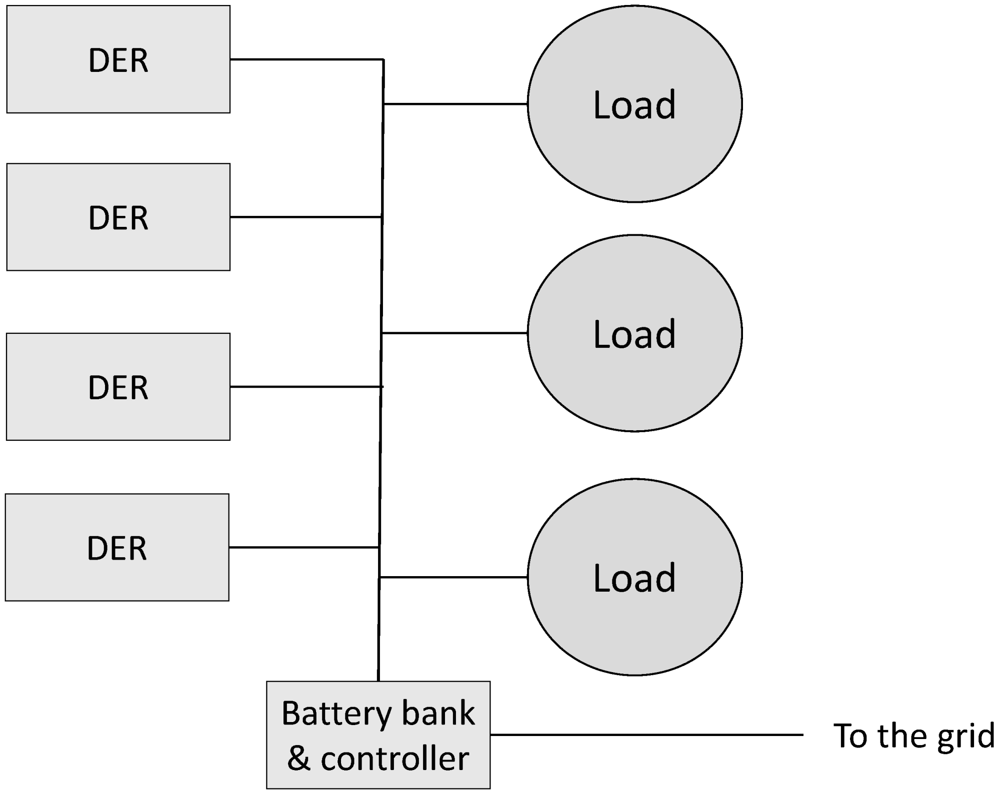


Figure 4: A schematic of a possible microgrid configuration. DER stands for distributed energy resource.

4 Microgrids

A microgrid is a small electricity network operating at a relatively low voltage. It contains both electricity generation and consumption and can work both in a grid connected mode or islanded mode. In grid connected mode, the microgrid is connected to the low voltage distribution network, feeding any excess electricity to the national grid (macrogrid) or drawing power from the macrogrid, when local consumption exceeds local production. In islanded mode, the microgrid is working stand-alone and not connected to the national grid. It provides power only for the local loads. Microgrids can consist of multiple distributed energy resources (DERs), such as windmills, solar panels, fuel cells, small hydro power plants or diesel generators. Usually microgrids also have some means of energy storage, typically batteries. Figure 4 shows the typical composition of a microgrid. Usually microgrids employ DC but there are also alternating current (AC) microgrids.

4.1 Motivation for microgrids

The motivation for microgrids is to increase the amount of renewable energy used for electricity production, increase electricity supply reliability and to provide an effortless way for demand-side management of power consumption.

In a traditional centrally supplied electricity network, power flows radially from the central power plant to the consumers (industries and households) in the “fringes” of the grid. The variation in loads is accommodated in the supply-end: generators switch on and off in the power plant as needed. However, renewable energy, especially wind and solar, tend to be intermittent and uncontrollable. They are thus not especially suitable for traditional electricity generation. By connecting the intermittent generation to a microgrid, the power flow to the macrogrid is smoother as the microgrid has some energy storage and local loads.

Another issue with centralized electricity production and large international power grids is reliability. Though, in developed countries, the main grid is on average extremely reliable, sometimes catastrophic power outages can happen. It has been proposed that the increasing size and complexity of the grid results in higher risk for a network-wide blackout [8]. By combining distributed generation with microgrids, the complexity and size of the grid can be decreased and reliability increased. Furthermore, a microgrid can act as an uninterruptible power supply (UPS) in case of grid failure in the macrogrid.

As mentioned above, traditionally, variations in electricity consumption have been taken care of in the supply-end. However, with rising fuel prices, electricity companies have realised the high costs of peak power. Peak power is needed for only short amounts of time during the year, meaning that the power plants have a low capacity factor. Thus, the electricity produced by them is very costly. Reducing peak power demand appears therefore very appealing. In developed countries, however, the consumers are not used to restrictions on their freedom to use energy. Furthermore, the energy sector is usually highly regulated, and tariffs such that they do not encourage to reduce peak demand. With microgrids, it is possible to implement demand-side management without the need to curtail energy consumption: the microgrid can use local and stored electricity when the consumption—on macro scale—is high and then charge up the batteries during lower consumption, effectively reducing peak load. Thus the microgrids appear as a sheddable load for the distribution system operator (DSO) or transmission system operator (TSO). [54, 16]

In developing countries, where the macrogrid is unreliable or completely nonexistant, microgrids have great potential. They can—similarly as in developed countries—act as an UPS. Moreover, in rural areas they can be the sole electricity source, working constantly in islanded-mode, thus contributing to rural electrification. In developed countries, microgrids have already seen interest in applications where the uninterrupted supply of electricity is a necessity, such as in hospitals or military bases [3]. In these, microgrid systems with renewable production replace existing fossil fueled electricity generation.

4.2 Examples of operating microgrids

In addition to the microgrids operated by Boond in India (see section 4.5), there are several other operating microgrids around the world, in developed and developing countries alike. According to Navigant Research, there are over 400 microgrids planned, proposed, under development or operating around the world.

Borrego Springs, California, United States is a remote community served by only one electrical feeder line. This makes the electricity supply of the community somewhat unreliable especially during adverse weather which can damage the feeder line. In order to increase reliability and reduce peak loads, the electric company serving the community, San Diego Gas & Electric (SDG&E), converted part of the community electricity grid into a microgrid. This is an example of unbundled utility business model for a microgrid (see sec. 4.4). [30]

The microgrid consists of about 4.6 MW of total generation capacity, two 1.8 MW diesel generators and about 700 kW of rooftop PV. It serves 615 customers around the community. Electricity is stored on three levels: a 500 kW/1500 kWh Li-ion battery is situated at the macrogrid connecting substation, three 50 kWh batteries are located around the grid and six 4 kW/8 kWh home energy storage units serve specific individual customers. [4]

The Borrego Springs microgrid project has been succesfull in achieving it's objectives. For example, the peak loads have been reduced by more than 15% and the operation in island mode and transitions have been demonstrated succesfully. [4, 30, 5]

The U.S. Department of Defense (DoD) operates a variety of microgrids or systems close to a microgrid. However, most of them do not include renewable energy. The U.S. DoD used microgrids include Naval Support Facility Dahlgren within the Naval District Washington (14 MW of capacity), Fort Detrick (2.5 MW electrical capacity and also steam and chilled water) and Marine Corps Air Ground Combat Center Twentynine Palms (7.2 MW CHP and 3.2 MW Solar PV). [3]

4.3 Microgrid issues

Microgrid implementation has still some regulatory and technical issues. Issues of ownership of the microgrid itself and the role of the owner needs to be clarified. For example, the owners of microgrids with sizable production might be categorised as electricity companies, with all the ensuing legal responsibilities. For a home consumer, this would be too much to bear. In some countries (such as in the EU) [40, 2] the distribution network ownership and the ownership of electricity production have been separated by law, which might be an obstacle for microgrid adoption. Technical issues include, for example, synchronisation during the reconnection of an islanded microgrid, power quality control and safety principles, especially regarding islanding. Legal and technical issues are covered in more detail in literature. [28, 43, 27, 54]

The reconnection of the microgrid to the macrogrid is an especially complex issue. In order to combine to AC networks, they need to have the same frequency and phase, and control of these is not always possible in a microgrid. This issue can be circumvented by adopting an AC-DC-AC interface or converting the microgrid completely to DC, which has no syncronisation issues. [26, 44]

Table 2: A summary of unresolved issues regarding microgrid usage.

Issue	Type	Possible solution
Safety during unintentional islanding	Technical	Anti-islanding systems
Reconnection	Technical	DC microgrids, converters at the grid interface
Power quality control	Technical	More sophisticated power electronics
Ownership	Legal & economic	Business models
Impact on macrogrid	Technical & economic	Restrict power movement out of the microgrid

4.4 Business models

Business models for microgrid usage are an important issue to consider, as microgrid operation by for-profit organisations has begun only recently. The issue of business model is related to the regulatory issues because the operator of the microgrid is usually responsible for the microgrid, in a regulatory sense. If the operator is not the owner of the microgrid, this complicates the picture.

There are various possible business models that can be applied to microgrid use. For instance, if the microgrid is owned by the consumers, a firm can create value by selling the microgrid and its components to the consumers and offer also maintenance services. The services can actually be the most important revenue source for the company, in this case this is called a product-service system business model.

The consumers themselves might create a (non- or for profit) cooperative, that operates the microgrid and collects tariffs. This might be a favourable option as it increases the inclusivity of the projec as the users of the microgrid have a stake at hand. Inclusivity is an important part of energy frugality (see sec. 2.2). Studies [11] have also found inclusivity to be an explaining factor for the success of an energy frugal project.

On the other hand, the microgrid can also be owned by the incumbent DSO and a firm can sell the microgrid to them, but then maintenance services might not be as important. This is an example of more traditional product-centered business model from the point of view of the microgrid selling company. From the DSO's point of view this is upgrade to their earlier service or product. It can also be called as a *vertically integrated utility business model*, as the DSO operates and owns the microgrid completely.

It is also possible for a company—when regulations permit—to act as an intermediary between the consumers and the DSO. In this model, the company operates and owns the microgrid and takes care of the interaction with the DSO, buying electricity and negotiating connection. It provides electricity and increased reliability to the consumers that are part of the microgrid and charges a fee for this. This is called the microgrid-as-a-service model.

A combination of the models presented is also a possibility. In the *unbundled utility business model*, the incumbent electrical utility (possibly the DSO) owns and maintains the distribution facilities of the microgrid (i.e. the wires and the controlling devices) but some third party or the customers own the generation and storage resources. [30]

4.5 Solar microgrids in India

Aalto University is in collaboration with Columbia University, NY in a project that aims to increase rural electrification by offering microgrid connections for the villagers. In co-operation with Boond Ltd. (see sec. 2.3.3) microgrids are installed in villages that have unelectrified households. The villagers are given the opportunity to connect to the microgrid. Basically, this is a microgrid-as-a-service business model.

4.5.1 Technical description

The microgrids installed in India Uttar Pradesh (and elsewhere) by Boond Ltd. consist of three systems: central charging station, power distribution system and end-user load system. The central charging station includes the solar panels and the battery bank. Power distribution system is the DC grid between the central station and the households. The distribution system has an unregulated voltage of 48 to 96 volts. The end-user load system consists of the household energy meter with USB billing system and the loads of the household (LED-lightning and mobile phone charging). The energy meter also acts as a DC-DC converter and the households loads operate at a regulated 12 volt DC. Sometimes the system is supplemented with an anchor load, such as a water pump for irrigation.

The microgrids typically contain about 10-30 households (corresponding to a daily consumption of 1 to 5 kWh) and solar panels with peak power of around 1-2 kW. Battery bank sizes vary from 100 to 200 ampere hours.

Boond uses a pre-paid billing system. The household has to “charge” their USB billing dongle in a Boond office. After paying and “charging” the dongle with the information of the paid amount, the dongle is connected to the household energy meter. Energy meter loads the information from the dongle and shows how much electricity the household can use before the pre-paid amount of electricity is used and the dongle has to “charged” again.

4.6 Solar microgrids in Finland

In developed countries such as Finland, a microgrid can be constructed, for example, for a single apartment building, a city block, a public building (such as office building or a shopping center), between several townhouses located in the same neighbourhood or a small remote community. These constitute as natural boundaries for a microgrid and still contain enough consumption for the microgrid to be a sensible investment. In addition to these, microgrid could be installed in hospitals, military bases or datacenters, where the reliability of electricity supply is of utmost importance.

In order to minimise the effect of microgrid on macrogrid stability, one should try to minimise the amount of power injected back to macrogrid from the microgrid. This approach has also been taken as the basis in this work.

4.6.1 Electricity sector in Finland

Finland has a highly advanced electricity sector. Even though the production and distribution of electricity are separated by law [2, 40], the electricity sector is dominated by big companies, as the distribution of electricity is seen as a natural monopoly.

The electricity sources are diverse. The sources with the greatest share are nuclear, hydro and hard coal. Figure 5 shows the complete breakdown of the shares. Fossil fuels constitute a fourth of the electricity production, compared to about

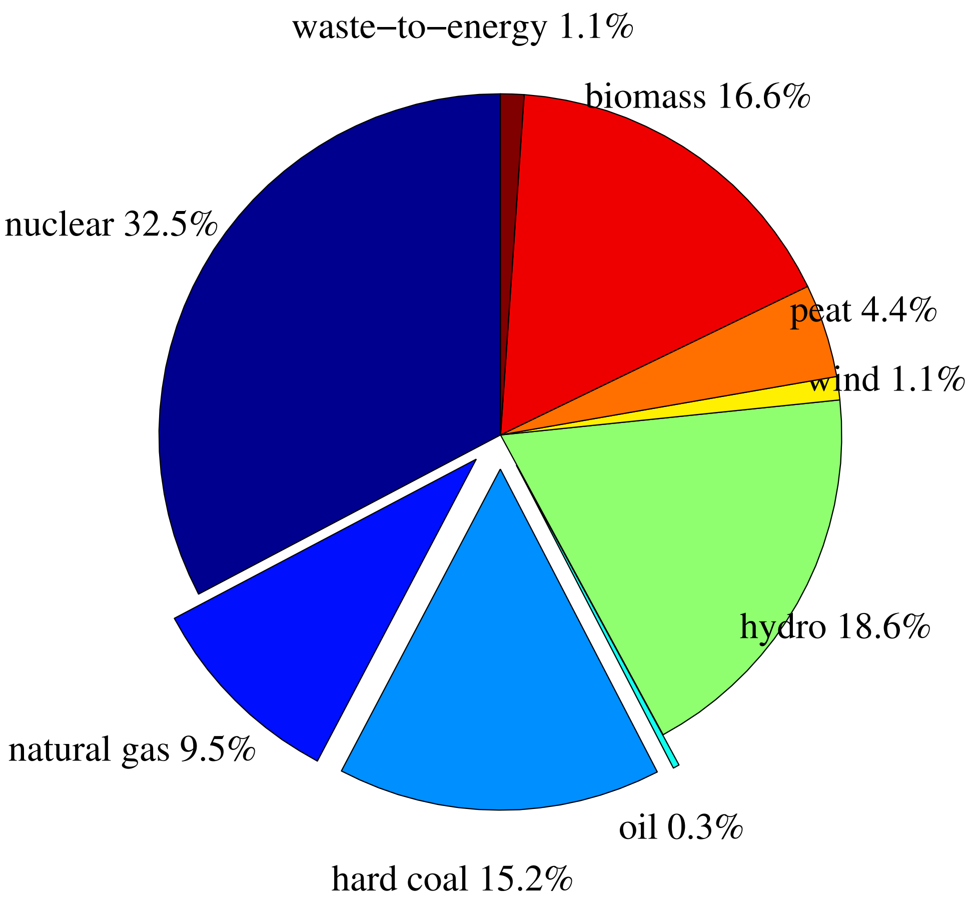


Figure 5: Shares of electricity sources in Finland in 2013. [37] Fossil sources have been highlighted in the figure and they constitute about a fourth of electricity production. Note that biomass includes also black liquor streams from pulp industries.

45% of the total energy consumption [36]. As we can see, energy sources typical in microgrids (solar, wind) are almost completely nonexistant.

Despite the advanced level of the electricity distribution and production system, sometimes blackouts happen. Even a short (less than 5 min) blackout can cause significant economic losses. Introducing microgrids to Finland could help to increase the reliability of electricity network and virtually eliminate short blackouts. Microgrids could also help increase the now almost nonexistant renewable energy production in Finland and reduce GHG emissions.

5 Methods

The analysis had three main methods. PVSyst software was used for technical simulations of the solar energy production and consumption. Retscreen software was used for economic analysis of the microgrid projects. The simple DC grid model derived was used for analysing the grid voltage behaviour.

5.1 Software used

5.1.1 PVSyst

PVSyst is a sofware for simulating PV production and PV system operation. It also provides means for sizing PV system and economic analysis. The software contains comprehensive databases of meteorological data and PV modules. Main features include preliminary studies and project design.[42]

Using the project design feature, user can create a project situated at a specific meteorological site and perform simulations with different system parameters. System parameters include number and type of PV modules, module orientation, battery bank, user needs (i.e. load profiles) etc. The simulation uses a time resolution of one hour and is capable of simulating a specific year or a generic year based on long-term climate data.

Simulation results contain several dozens of simulation variables. These include solar fraction (the fraction of consumption covered by solar derived electricity), battery state of charge, lost and missing energy etc.

For calculating the PV module production, PVSyst uses hourly meteorological data (synthetically created from monthly data or real hourly data) to calculate the effective incident irradiation falling on the PV panels. Firstly, horizon, i.e. far shadings are taken into account. Far shadings affect the beam component of the horizontal irradiation. If the meteorological data contains diffusive irradiance, it is used, otherwise it will be created using Liu and Jordan's correlation diffusive irradiance model [29]. Secondly, a transposition model is used for calculating the incident irradiance on a tilted plane, from the horizontal irradiance data. PVSyst uses the Perez model [19] for this. It treats beam, diffusive and albedo (ground reflection) components separately. Thirdly, all these components are subjected to near shading effects and incidence angle modifier factor, yielding the flux effectively usable for PV conversion.

For simulating the PV module operation, PVSyst uses the Shockley one diode model. [12] Shockley one diode model applies primarly for one cell, but assuming identical cells it can also be applied for whole modules. Current supplied by the module is given by the equation

$$I = I_{\mathrm{ph}} - I_{\mathrm{o}} \left(\exp\left(q \frac{V + IR_{\mathrm{s}}}{N_{\mathrm{cs}} \gamma k T_{\mathrm{c}}} \right) - 1 \right) - \frac{V + IR_{\mathrm{s}}}{R_{\mathrm{sh}}} , \tag{1}$$

where I is the current supplied by the module, V the voltage over the terminals of the module, I_{ph} the photocurrent, I_{o} inverse saturation current, R_{s} series resistance, R_{sh}

shunt resistance, q the elementary charge, k the Boltzmann constant, $\gamma \in [1, 2]$ the diode quality factor, N_{cs} the number of cells in series and T_{c} the effective temperature of the cells. In the one-diode model, the photocurrent I_{ph} is assumed to be directly proportional to the irradiance falling on the PV cell. It also depends slightly on the temperature. Diode reverse saturation current I_{o} depends on temperature and energy gap of the cell material [42].

In PVSyst, a battery model of moderate sophistication has been chosen. According to the manual, the model requires relatively little input from the user—mainly the type of technology, voltage and nominal capacity. On the other hand, the model is described as sufficiently detailed, especially regarding voltage behaviour at the end of charge and discharge. The model is valid only for lead-acid batteries, as they are common in PV systems.

The battery model is described by the equation

$$U_{\mathrm{batt}} = U_0 + \alpha \mathrm{SOC} + \beta (T_{\mathrm{bat}} - T_{\mathrm{ref}} + R_{\mathrm{i}}) I_{\mathrm{batt}} \ , \tag{2}$$

where U_{batt} is the voltage over a battery element, U_0 intercept of the open circuit voltage linear part at SOC = 0, SOC the state of charge, α the slope of the open-circuit line (a material constant), T_{batt} temperature of the battery, T_{ref} reference temperature, β temperature coefficient, R_{i} internal resistance and I_{batt} battery current (positive meaning charge and negative meaning discharge).

The basic equation (2) does not work at deep discharges and at the end of charge. Therefore a corretion is applied. When the state of charge (SOC) falls under 30%, the voltage starts to fall quadratically regardless of the current.

At the end of charge, electrolyte dissociation (also know as *gassing*) starts to happen. In PVSyst it is assumed that this phenomen induces an excess voltage. The current wasted in gassing depends exponentially on this excess voltage. The end of charge is determined as the point where the gassing current matches the charging current.

The state of charge is rarely chosen as a basic variable as it is not accessible by direct measurements. However, by balancing charging and discharging currents, a reasonable estimate for the state of charge can be obtained. One has to take into account the fact that electrochemical conversion is not perfect, thus lowering the so called *coulombic efficiency*, which is specified as 97% in PVSyst. Furthermore, some *self-discharge* happens in a battery. It is strongly dependant on temperature, age and type of the battery. However, in PVSyst only the temperature-dependence is taken into account. The dependence is exponential and doubles for every 10-degree increase in temperature. The reference temperature of 20 °C is specified.

Nominal capacity of a battery is not a well defined quantity. In practice, it is measured by charging the the battery full and then discharging it completely assuming that we can define the point of full charge and complete discharge. The three most important factors affecting capacity are age, discharge rate and temperature. In PVSyst age is not taken into account.

Usually manufacturers define nominal capacity with a 10-hour discharge, i.e. discharge current is a tenth of the capacity. However, usually in photovoltaic systems, currents are significantly lower. This can increase the actual capacity up to 150% of the nominal capacity. In PVSyst this is taken into account by weighing the decrease in SOC by the nominal capacity corresponding to the discharging current. This correction needs to be applied also when charging the battery. Therefore, PVSyst saves an average capacity of subsequent discharge steps, in order to apply it to the next charging period. Battery capacity decreases as a function of battery temperature. For temperature dependence, PVSyst uses a predetermined profile.

The battery model in PVSyst has some obvious shortcomings. For example, the temperature dependence is linear (see eq. 2) in all operating conditions. Internal resistance is assumed to be constant. Also polarisation effects are ignored. However, it is sufficiently sophisticated for PV system simulation.

Different consumption profiles can be described in PVSyst. One can assume an unlimited load (i.e. grid connected power plant), constant load, monthly averages, seasonally varying daily profiles, probability based profiles etc. Furthermore, one can also import a year-spanning profile in hourly or in daily values.

PVSyst combines the information from the PV module, batteries and consumption. At all times, consumption, production and net change in energy storage have to match:

$$P = C + S_{\text{net}} \ . \tag{3}$$

Even though PVSyst is not designed to model microgrids, it can be used to model them by taking into account the losses in microgrid.

5.1.2 RETScreen

RETScreen is an Excel-based software made by the governmental Natural Resources Canada for evaluating the feasibility of renewable energy, energy efficiency and co-generation projects. The software is provided by the government of Canada free of charge. It is aimed for decision-makers and professionals for evaluating whether an energy project makes financial sense. [51]

The RETScreen analysis contains five steps: energy, costs, emissions, financial analysis and sensitivity or risk analysis. First, the load and network to be satisfied is defined. Second, the energy model, i.e. how the power is produced, is described. This is followed by cost analysis, which can be made in varying detail. After that, one can perform emission analysis based on the alternatives the project has. Lastly, financial and risk analysis is presented, in which the user can define various parameters and assumptions.

The financial analysis provides the user various results to aid the decision making of a project's financial viability. These include internal rate of return (IRR), payback period and NPV.

IRR of an investment is the discount rate at which the NPV of the investment equals zero. In other words, it is the discount rate at which the investor ends up with same amount or more value after the project. An investment can be considered acceptable if the IRR of the investment is higher than the minimum acceptable rate of return or the cost of capital (these might not be equal). A high enough IRR does not quarantee the viability of a project, but is an indicator.

NPV is the sum of present values of individual cash flows. NPV provides a simple tool for evaluating a project. If the NPV is negative, the project is most likely not economically feasible as it draws more money than it produces. If NPV is positive, the project might be feasible. NPV is defined as

$$\text{NPV} = \sum_{t=0}^{N} \frac{R_t}{1+r^t} \ , \tag{4}$$

where R_t is the net cash flow during timestep t and N the total number on timesteps.

Payback period is the time that a project takes to reach break-even point. It does not take into account the time value of money, which is it's greatest limitation. However, it is popular due to it's simplicity.

The ability to calculate LCOE has been implemented in Retscreen. LCOE offers a way for comparing different methods of producing electricity, taking into account all cost over the lifetime. It is defined with the equation

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \ , \tag{5}$$

where I_t is investment expenditures during timestep t, M_t the operations and maintenance expenditures during timestep t, F_t the fuel expenditures during timestep t, E_t the electricity generated during timestep t, r the discount rate and n the projected lifetime of the system, in units of t. It should be noted that the assumptions made during estimation of the lifetime of the system n and discount rate r can have a significant impact on the LCOE [7].

5.2 Grid model

In order to estimate the voltage behaviour in a microgrid, a grid model needs to be constructed. Fortunately, for a DC grid this is relatively straightforward.

Let us first consider a simple DC circuit consisting of an ideal voltage source, two (resistive) loads and the wirings between them. Let us also set a (known) finite resistance for the wires between the components. This situation is depicted in the Figure 6. We are interested in the voltages across the loads.

We begin by noting that the right side of the circuit can be replaced with a simpler equivalent circuit: we can combine the wires and the rightmost load with a single resistor R^*. Now, for the resistance of the equivalent circuit, the following equation applies.

$$R^* = 2R_2 + R_{2,\text{load}} \tag{6}$$

Let us then apply Kirchhoff's circuit laws [56] to the circuit. Kirchhoff voltage law together with Ohm's law [56] yields us a set of two equations:

$$\begin{cases} E - 2R_1 I_1 - R^* I_2 = 0 \\ E - 2R_1 I_1 - R_{1,\text{load}} I_{1,\text{load}} = 0 \ , \end{cases} \tag{7}$$

where I_1 is the current passing through the resistor R_1, I_2 the current passing through the equivalent circuit with the resistor R^*. Kirchhoff's current law states in this case that

$$I_1 = I_{1,\text{load}} + I_2 \ . \tag{8}$$

Combining equations (7, 8) and after some algebra we have the equation for voltage across the first load:

$$U_{1,\text{load}} = R_{1,\text{load}} I_{1,\text{load}} = \frac{ER^*}{R^* + 4R_1} \ . \tag{9}$$

Now it is quite straightforward to generalise equation (9) for any number of loads, i.e. nodes. We replace all the quantities referring to the first node (i.e. the quantities of the form x_1) to quantities referring to the ith node and replace $E \hookrightarrow U_{i-1}$ and $R^* \hookrightarrow R_i^*$. This way we arrive to an iterative solution for $U_{i,\text{load}}$ (eq. 12).

Now, let us look the situation at node i. This is depicted in Figure 7. We want to create an equivalent circuit of the rest of the circuit to the right, meaning nodes $i+1, i+2, i+3, ..., n$. In order to do this, we have to start at the end of the circuit, at node n (Fig. 8). As was said above, the resistance of the equivalent circuit for resistors past the node n is given by equation (6). Now the resistance of the equivalent circuit for nodes n and $n-1$ is

$$R_{n-1}^* = 2R_{n-1} + \frac{1}{\frac{1}{R_{n-1,\text{load}}} + \frac{1}{R_n^*}} \ . \tag{10}$$

By applying equation (10) repeatedly we can obtain the equivalent resistance of the circuit from node i onwards:

$$R_i^* = 2R_i + \frac{1}{\frac{1}{R_{i,\text{load}}} + \frac{1}{R_{i+1}^*}} \ . \tag{11}$$

This result can be applied to generalise equation (9). For the voltage U_i across node i we have

$$U_i = \frac{U_{i-1} R_i^*}{R_i^* + 4R_i} \ , \tag{12}$$

where R_i^* is given by equation (11). It is important to note that both equations (11, 12) are iterative and that the iterations run in different directions. This means that we have to first apply equation (11) to obtain all the resistances and only then can be apply equation (12).

Now, in a typical microgrid application, we do not know the resistances of the loads. However, we know the power the user wants to get out of a device. Therefore, we can use equation (13) to calculate the resistance of the loads from the power of loads.

$$R_{i,\text{load}} = \frac{U_{\text{nom}}^2}{P_i} \ , \tag{13}$$

where U_{nom}^2 is the nominal voltage across the load and P_i the power consumed at node i. For nodes with production instead of consumption (typical in microgrids), we can just flip the sign of P_i.

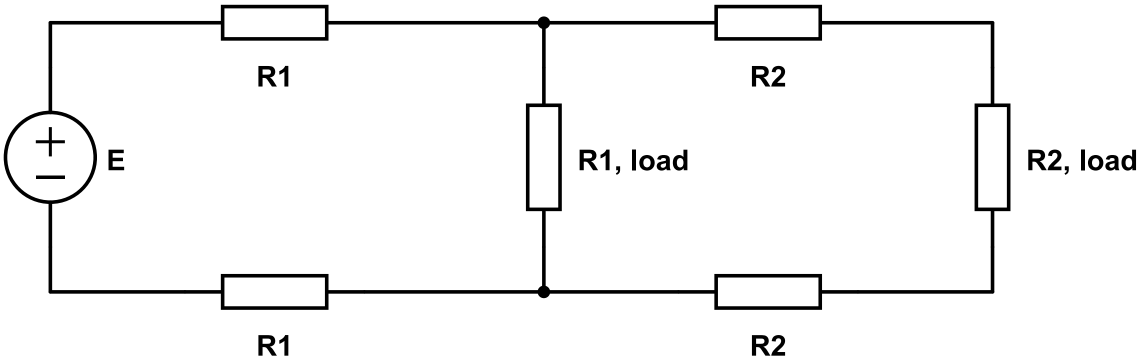


Figure 6: A circuit consisting of an ideal voltage source (source voltage E), two resistive loads with resistances $R_{1,\text{load}}$ and $R_{2,\text{load}}$ and wirings between them having known resistances.

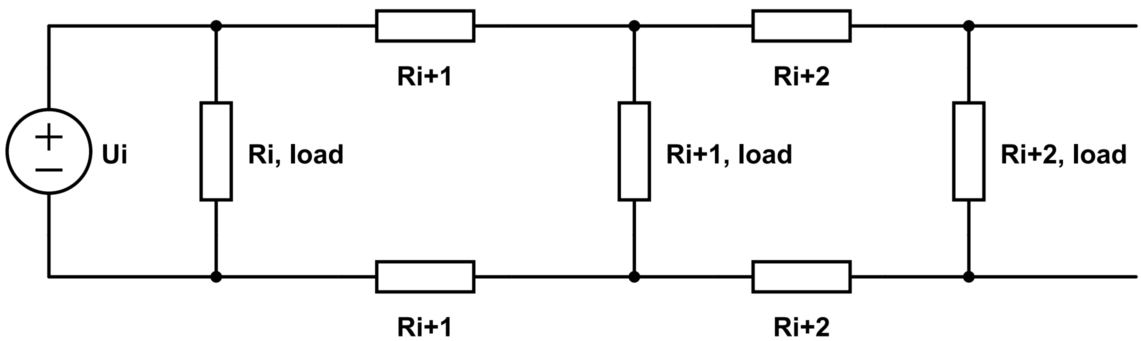


Figure 7: A circuit consisting of n nodes depicted around node i.

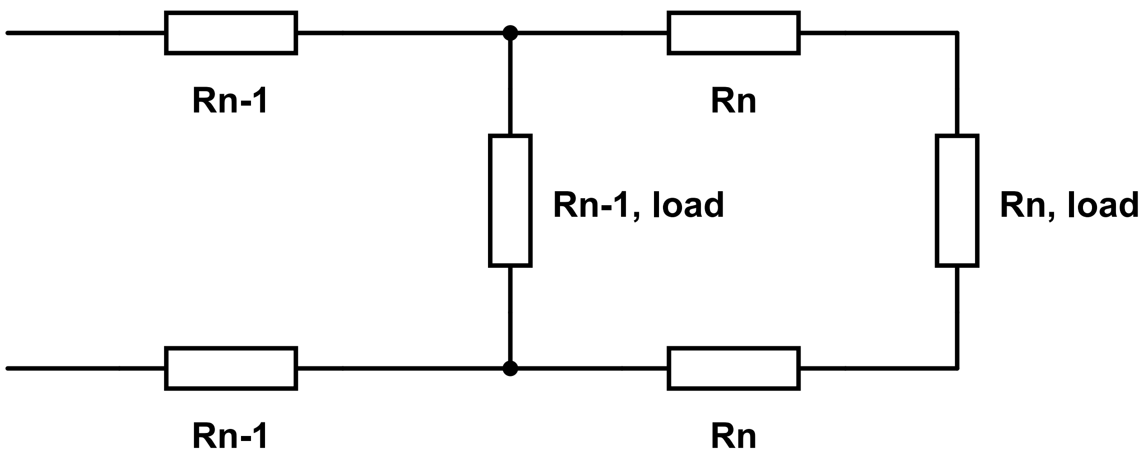


Figure 8: A circuit consisting of n nodes depicted around node n.

6 Results

In this work, we investigated solar powered microgrid installation in India and Finland with the aim of finding an optimal size for the microgrid. We will first describe the Indian microgrids in section 6.1 and then the Finnish microgrids in section 6.2. The analysis is threefold: technical simulations are made with PVSyst, grid analysis using the grid model described earlier and economic analysis using Retscreen.

6.1 Solar microgrids in India

The Indian microgrid cases were modeled based on the microgrids that Boond Ltd. (see sections 2.3.3 and 4.5) operates in rural Uttar Pradesh, India. However, in order to find the optimal size, large parameter variations were made. In the end the cases were quite dissimilar to the Boond microgrids.

6.1.1 Simulations with PVSyst

The simulations made with PVSyst were done to establish the technical feasibility of the microgrid electricity production, storage and consumption. As it is not possible to model grid effects in PVSyst, therefore, they were modeled using a separate grid model. This simplification was justified as from the production point of view the DC grid only adds ohmic wiring losses to the system.

PVSyst simulation parameters were set so as to represent the Boond microgrids as accurately as possible. PVSyst database did not have any meteorological data from Uttar Pradesh, so the location of the microgrid was set to New Delhi, India (28.6° N, 77.2° E), which has a quite similar climate as rural Uttar Pradesh. The solar incident energy profile in New Delhi is shown in Figure 10. The available solar energy varies from 7 kWh/m^2/d in March-April to 5 kWh/m^2/d in July. Surface albedo was set to 0.2, as this value represents the rural installation environment (according to PVSyst).

The simulated system consisted of a varying amount of PV panels, batteries and consumption. The solar panels were set to a 30° constant tilt and faced South. Generic polycrystalline silicon solar panels were chosen from the PVSyst product database. They had an efficiency 10.8% at STC. Generic 12-volt vented plated lead-acid batteries were chosen. They were organised to a battery bank of 8 batteries in series resulting in a system voltage of 96 volts. The consumption was defined as a daily profile that was constant throughout the year. The profile is presented in Figure 9. The consumption was varied by normalising the average daily consumption to different values. It turned out that the shape of the profile did not have an effect on the operation of the microgrid, only the average daily consumption did. The main simulation parameters are listed in Table 3.

The reference case contained 1200 W_p of PV capacity, 160 Ah battery storage and 8 kWh/day consumption. This resulted in a yearly solar fraction of 69.6%. This means that around one third of the time, power was not available for consumption. Monthly solar fraction is shown in Figure 11. From the figure we can see that the

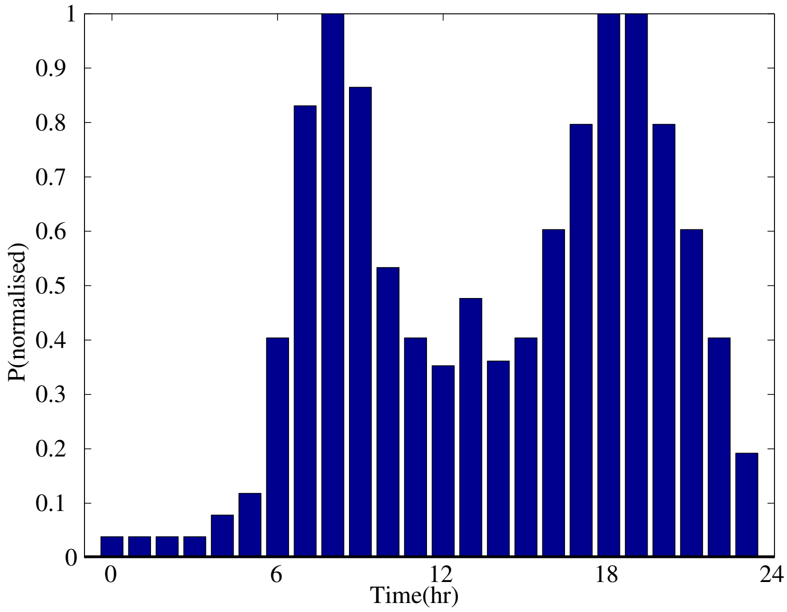


Figure 9: The normalised daily power consumption profile used in the Indian case simulations.

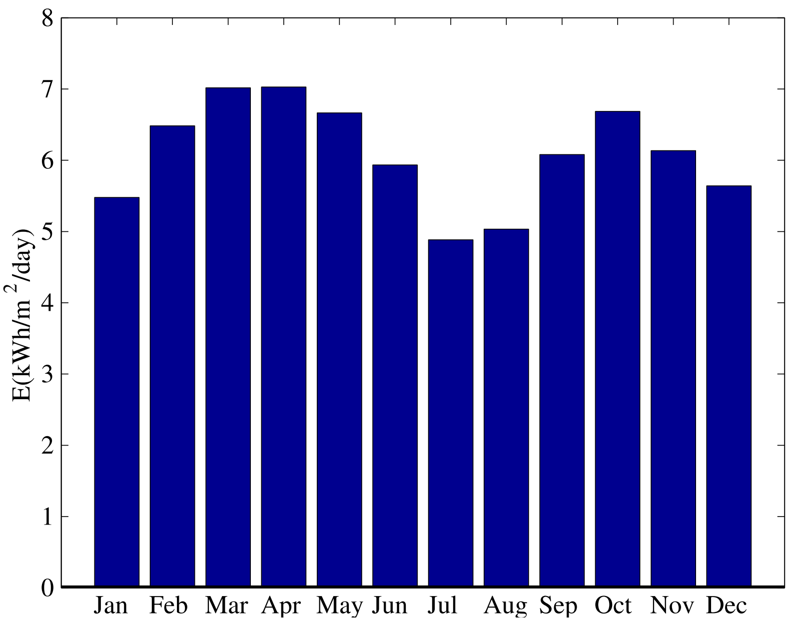


Figure 10: The daily average solar incident energy falling on the tilted PV panels over the year in New Delhi, India.

Table 3: Typical parameters for the Indian microgrid installation in PVSyst simulations, kept constant between simulations. Parameters marked with * were varied.

Parameter	Value
Location	New Delhi, India (28.6° N, 77.2° E)
Surface Albedo	0.2
Panel orientation	30° tilt, South
Panel type	$60W_p$ Si-poly
Panel efficiency	10.8% at STC
Wiring and network losses	0.3 % at STC
System voltage	96V
Regulator	Generic MPPT converter
Battery type	12V vented plate lead-acid
PV peak power	1200 W_p*
Battery size	160 Ah*
Consumption	8 kWh/day*

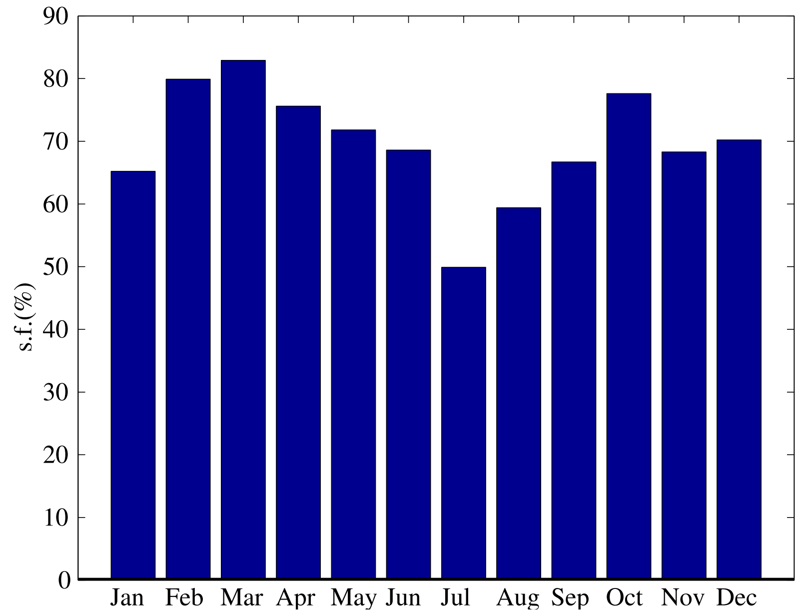


Figure 11: Monthly average of solar fraction for the Indian reference case.

solar fraction ranges from 83% in March to 50% in July. One should note that the solar fraction profile is mostly similar as the solar incident energy profile in Figure 10. The average battery SOC was near the low limit, at 48%. Excess or unused energy was very low, around 1 kWh/year.

In the sensitivity analysis, the varied parameters included PV array peak power, average daily consumption and battery bank size. The results from these can be seen in Figures 12, 13 and 14, respectively.

As we can see from Figure 12a, the solar fraction (the amount of consumption covered by PV produced electricity) increases linearly with increasing PV peak power until a saturation level is reached. This saturation means that all or almost all consumption is covered by PV power. The position of the saturation and the slope of the linear part of the curve depend on the amount of consumption. A higher consumption causes the saturation level to shift to a higher peak power and a more gradual slope.

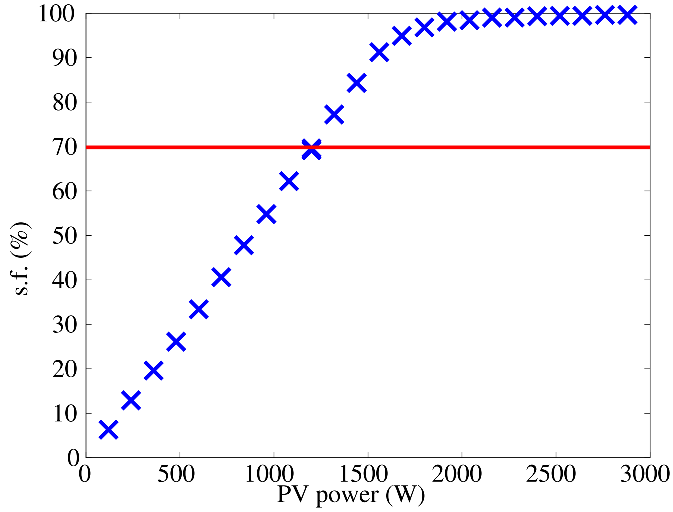
Figure 12b shows the average state of charge of the battery in the microgrid. At low PV power there is not enough electricity in the grid to fulfill the consumption and the state of charge remains at or around the safety limit of the state of charge (50%). Increasing PV power increases the average state of charge. Near the safety limit (around 1500 W_p in the figure), the change is rapid. Increasing the PV power further increases the state of charge, but more gradually.

Increasing average daily consumption decreases solar fraction, as we can see from Figure 13a. Doubling the consumption reduces the solar fraction to a half, tripling the consumption drop the solar fraction to a third. This is quite expected as the solar fraction is defined as the fraction of consumption covered by PV electricity, and the production does not increase.

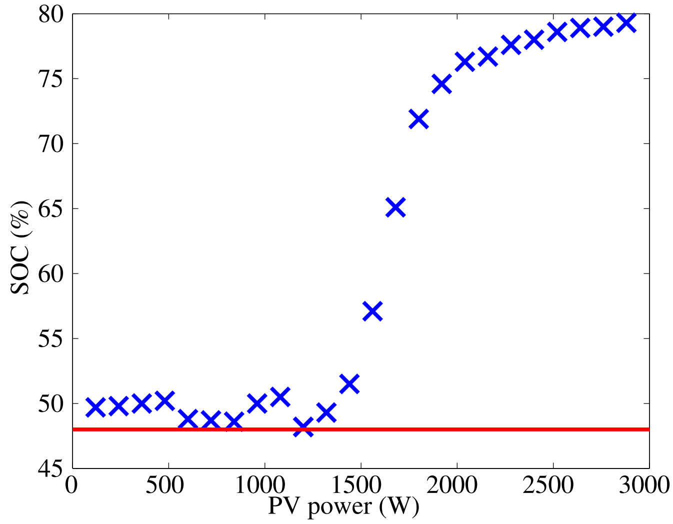
Average state of charge is decreased by increasing consumption, as one could expect. The change is steepest around 5 kWh/day in this case. Increasing consumption further causes the average state of charge to hit the safety limit for batteries (50%).

Solar fraction and average state of charge do not correlate very strongly with battery bank size. Battery size does not have any effect on solar fraction, as we can see from the Figure 14a. The changes in the figure can be attributed to statistical fluctuations. Increasing battery size decreases average state of charge, albeit slowly and somewhat randomly. This behaviour is clear from Figure 14b and stems from the fact that at greater battery sizes, there is not enough PV power to charge the batteries fully.

As these simulations were made for a specific microgrid, the results cannot be—quantitatively—applied to other microgrids. For example, one cannot certainly say the correct amount of PV power for a microgrid with a consumption of 800 kWh/day and a battery size of 1600 Ah (ten times higher than in these simulations). And this was not the aim of this work. However, one can qualitatively apply these results to other microgrid installations.

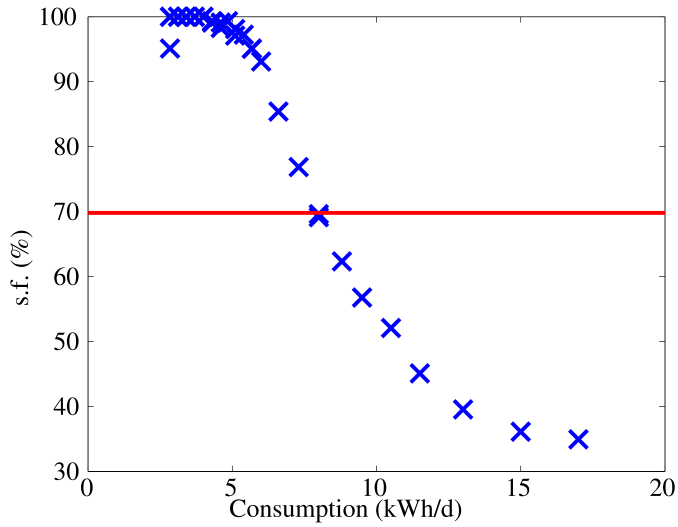


(a) Solar fraction (s.f.) as a function of PV peak power.

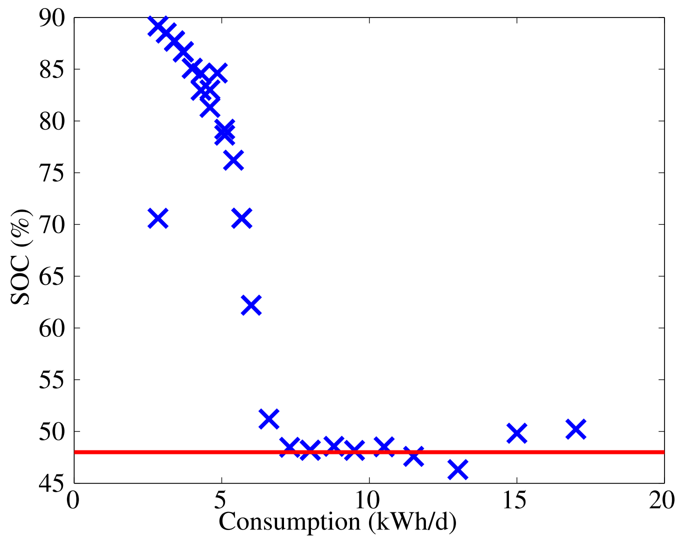


(b) Average state of charge of the battery as a function of PV peak power.

Figure 12: Solar fraction and average state of charge when varying the PV peak power. In these simulations, average daily consumption was set to 8 kWh/day and battery size to 160 Ah. The red line shows the solar fraction and average SOC in the reference case.

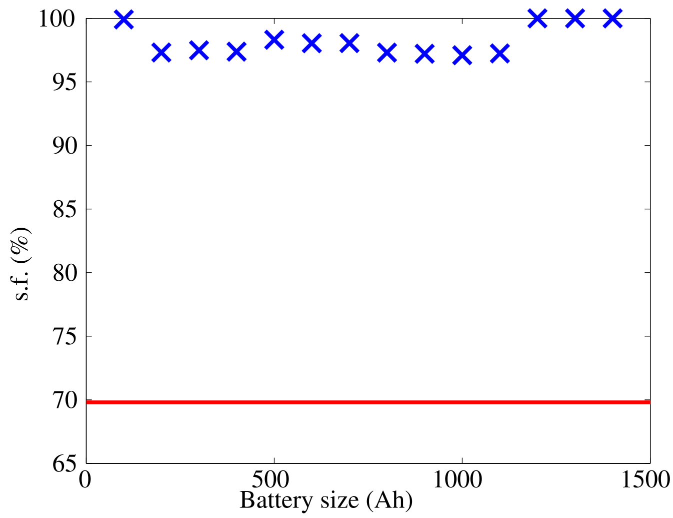


(a) Solar fraction (s.f.) as a function of average daily consumption.

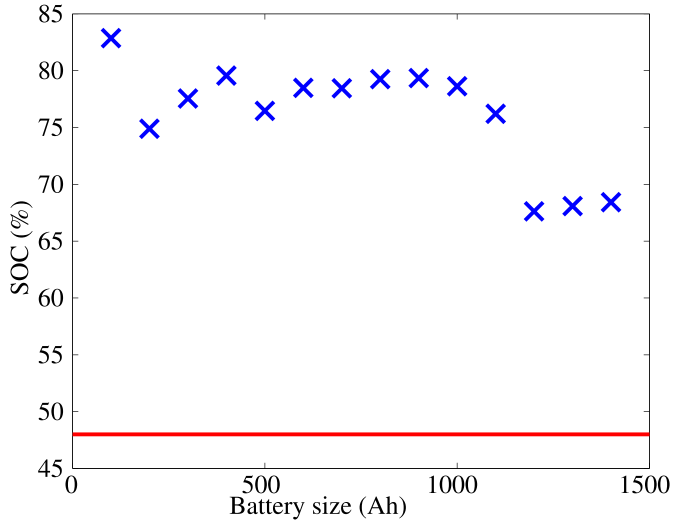


(b) Average state of charge of the battery as a function of average daily consumption.

Figure 13: Solar fraction and average state of charge when varying the average daily consumption. In these simulations, PV power was set to 1200 W_p and battery size to 160 Ah. The red line shows the solar fraction and average SOC in the reference case.



(a) Solar fraction (s.f.) as a function of battery capacity.



(b) Average state of charge of the battery as a function of battery capacity.

Figure 14: Solar fraction and average state of charge when varying battery size. In these simulations, average daily consumption was set to 8 kWh/day and PV peak power to 1800 W_p. The red line shows the solar fraction and average SOC in the reference case.

6.1.2 Grid analysis

For estimating the wiring requirements in a microgrid, the grid model described in section 5.2 was used. We modeled a single linear DC microgrid consisting of 10 consumption nodes and a single production node. The power consumption was divided evenly between the consumer nodes. The system voltage was set to 96V. The maximum voltage drop was set to 10%, i.e. the voltage should not drop below 86.4 volts in any node. A number of different gauge wires were modeled. Copper wiring with a resistivity of 0.0188 $\Omega mm^2/m$ was used. The Figure 15 shows the maximum amount of total power consumption that can be present in a microgrid. As we can see from the Figure 15, the maximum power drops very quickly with increasing internodal distance (i.e., longer wires between consumption points). Changing the wire gauge to a greater one allows more power to be transferred. The cost of the wiring is directly proportional to the cross-sectional area.

In order to relate the power values in Figure 15 to something more concrete, let us assume a microgrid constructed with 4 mm^2 copper wire consisting of 10 households with a combined power consumption of around 1 kW. Let us also assume that the households are pretty close each other, say 10 meters. This would be enough for the wire to handle. Every household could use 100 watts of power, enough to fulfill the lightning (made with LEDs) and mobile phone charging needs of the household by a wide margin.

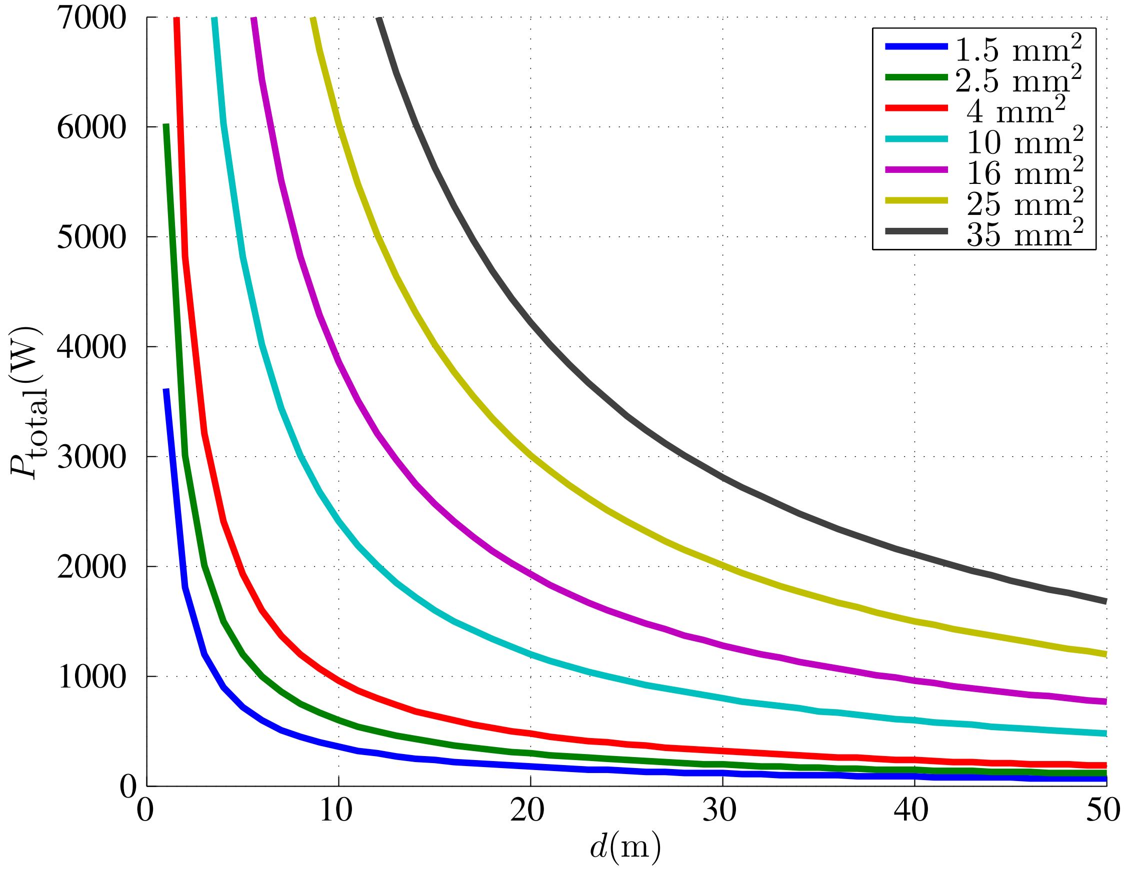


Figure 15: Maximum transferrable power in a microgrid consisting of 10 nodes containing consumption as a function of internode distance d. The different graphs refer to the cross-sectional area of the wires used. The maximum is defined as the power at which the voltage drop does not exceed 10%.

6.1.3 Economic analysis

The economic feasibility of the microgrid installations was investigated with Retscreen. The main parameters were kept as similar as possible with the technical simulations made with PVSyst. The location of the microgrid was chosen to be Amausi, Lucknow, Uttar Pradesh, India as reliable meteorological data was available in Retscreen database from Chaudhary Charan Singh International Airport situated in Amausi, Lucknow. As microgrids in India are installed to supplement or substitute kerosene lightning, the base case power system was set to be kerosene. The kerosene consumption was set to reflect actual consumption based on studies [53, 31]

The proposed case power system consisted of PV panels, a battery bank and consumption. The panels were similar as in the technical simulations, with an efficiency of 10.8% at STC. The panels were tilted 30 The panels were tilted 30° tilt and faced South. connected to a MPPT-controller and overall losses in the system were set to 5%. This resulted in a capacity factor of about 19%. The battery bank had a voltage of 96 volts and a capacity of around 4 kWh (about 40 Ah). The power consumption profile is flat because Retscreen does not provide means to define it. A more complete list of parameters is presented in Table 4.

The reference system had 0.74 kW_p of PV capacity, 2.1 kWh/day of consumption and a battery size of 40 Ah. Kerosene price was set to 0.2 Eur/l, O&M cost to 4% of initial cost, inflation to 5% and debt ratio to 50%. This resulted in an LCOE of 0.42 Eur/kWh and an IRR of 8%.

In sensitivity analysis, the varied parameters were kerosene price, daily average consumption, inflation, debt ratio, interest rate, PV array power, PV price and operations and maintenance costs. The change in consumption can reflect two kinds of changes in microgrid: an increase in the number of households part of the microgrid, or an increase in the amount of consumption of each household. Therefore, a small increase of 0.36 Eur/Wh in wiring costs was made for each increase in average consumption. This was in accordance with the numbers Boond Ltd. provided.

Figure 16 shows the internal rate of return (IRR) (see section 5.1.2) of the microgrid installation as a function of kerosene price. The IRR ranges from -5% at 0.1 Eur/l to about 25% at 0.4 Eur/litre. The feasibility limit of 5% IRR is crossed around 0.17 Eur/litre. As we can see, the price of kerosene has a considerable effect on the economic feasibility of the microgrid: the higher the price, the better the investment in a microgrid is.

Figure 17 shows the changes in economic feasibility with changing overall average daily consumption. Other things equal, the IRR ranges from -5% at 1 kWh/day to about 13% at 2.8 kWh/day. The feasibility limit is crossed around 1.7 kWh/day. These values correspond to 10 households or 50 Wh per household, 28 households or 280 Wh per household and 17 households or 170 Wh per household, respectively. LCOE ranges from 1.1 Eur/kWh around 0.5 kWh/day to about 0.38 Eur/kWh at 2.8 kWh/day. Overall, the greater the consumption, the higher the IRR and lower the levelised cost of electricity (LCOE).

Operations and maintenance costs constitute almost a half of the annual costs associated with a microgrid installation (the other half being debt payments). Fig-

Table 4: Parameters for the Indian microgrid installations in Retscreen simulations, kept constant between simulations. Parameters marked with * were varied.

Parameter	Value
Location	Amausi, Lucknow, India
Panel orientation	30° tilt, South
Panel efficiency	10.8% at STC
Total losses	5 % at STC
System voltage	96V
Regulator	MPPT converter
Base case power system	Kerosene
Kerosene consumption	5.2 l/household/month
Debt term	10 years
Project life	25 years
Kerosene price	0.2 Eur/l*
Households	20*
Daily average consumption	100 Wh per household*
Inflation	5%*
Debt ratio	50%*
Debt interest rate	2% above inflation rate
PV array power	0.74 kW_p*
PV price	2000 Eur/kW*
O&M	4% of initial costs*
Wiring cost	0.36 Eur/Wh

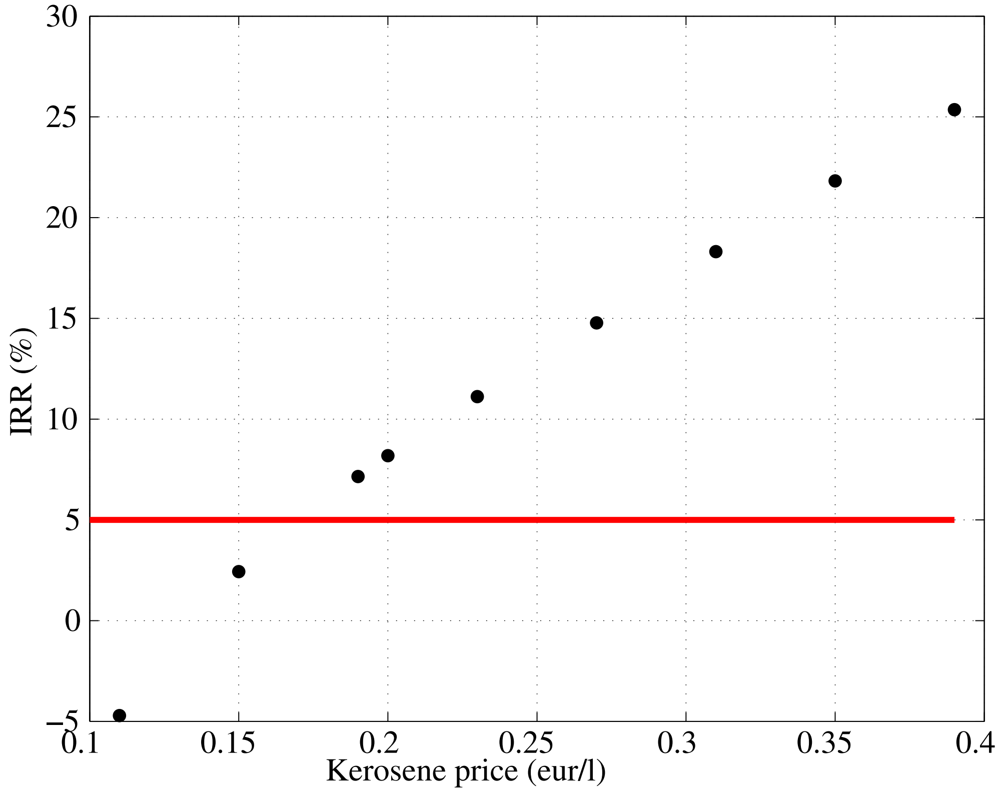
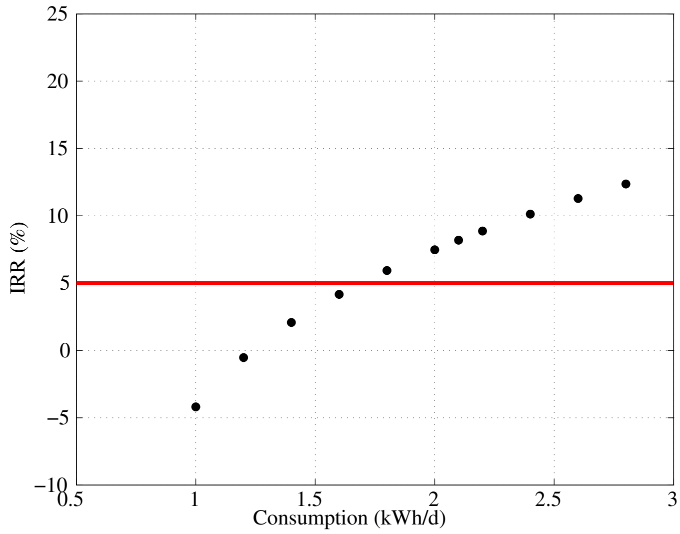
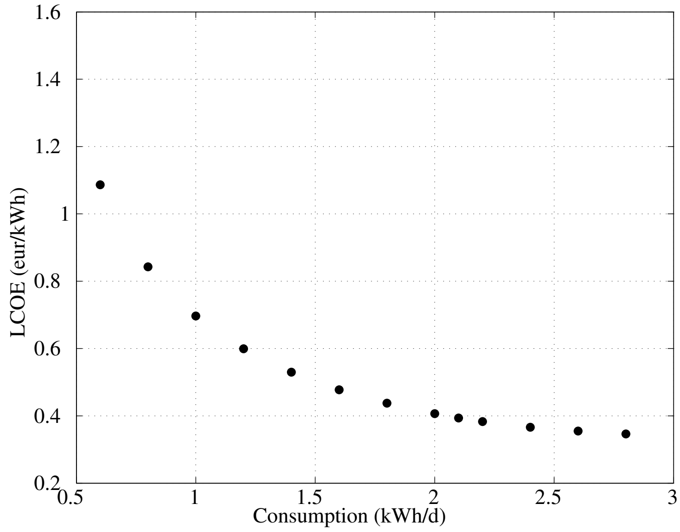


Figure 16: IRR of a microgrid installation in India as a function of kerosene price. 5% IRR can in this case be taken as an economic feasibility limit.

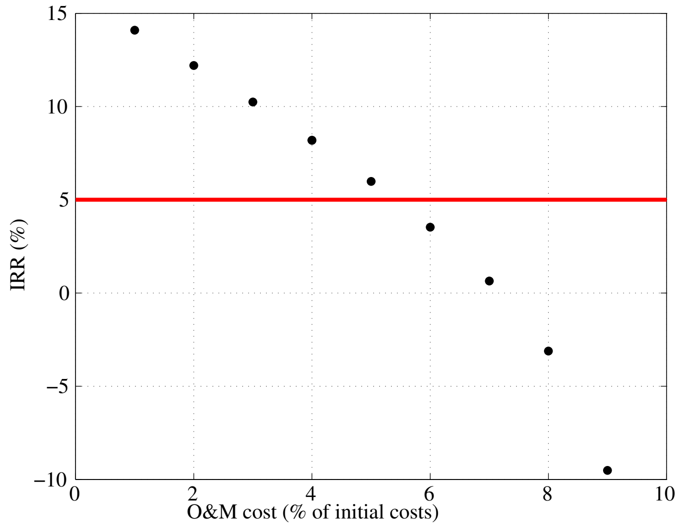


(a) IRR of a microgrid installation in India as a function of the total daily consumption in the microgrid. 5% IRR can in this case be taken as an economic feasibility limit.

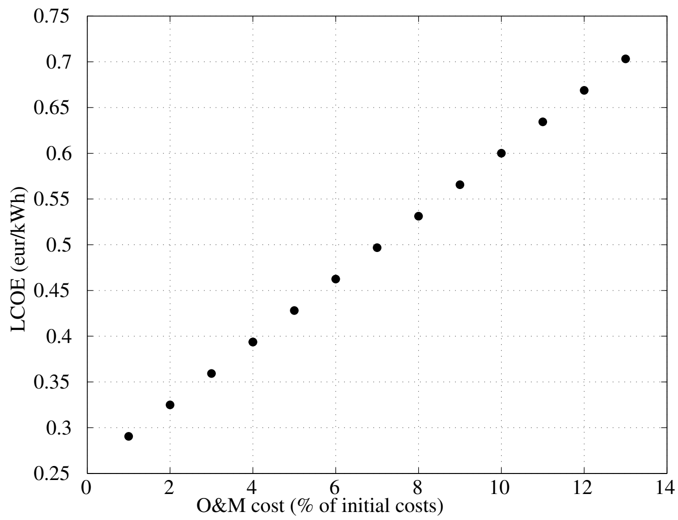


(b) LCOE of a microgrid installation in India as a function of the total daily consumption in the microgrid.

Figure 17: Parameters for deciding the economic feasibility of a microgrid installation in India as a function of daily average consumption in the microgrid. A change in daily average consumption can reflect a change in the number of households or the amount of consumption per household.



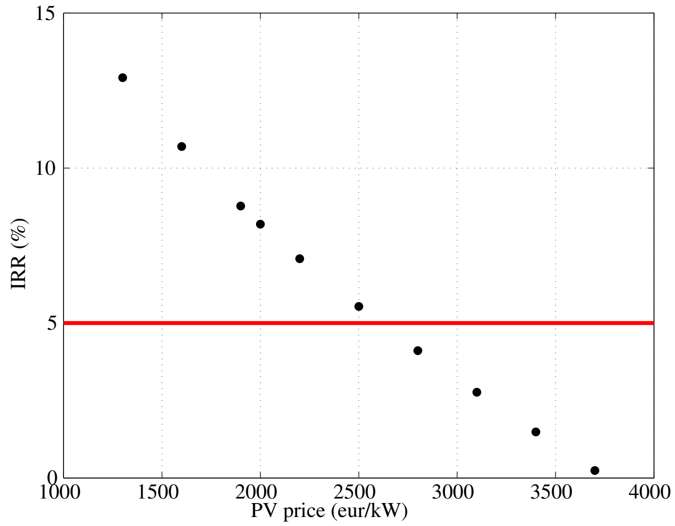
(a) IRR of a microgrid installation in India as a function of the operation and maintenance costs of the microgrid. 5% IRR can in this case be taken as an economic feasibility limit.



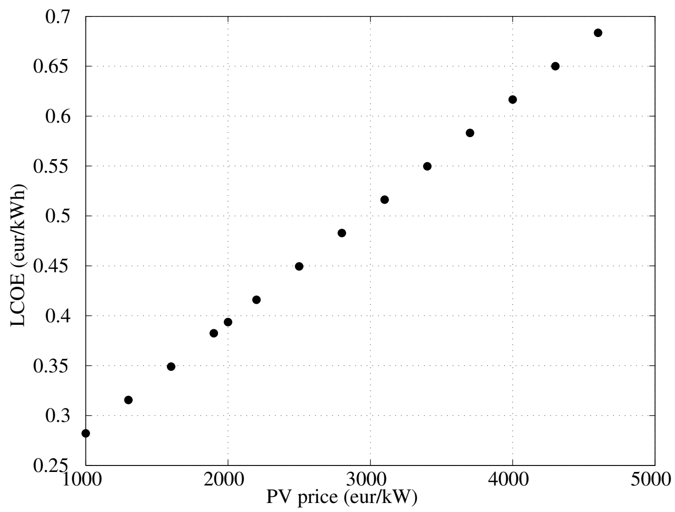
(b) LCOE of a microgrid installation in India as a function of the operation and maintenance costs of the microgrid.

Figure 18: Parameters for deciding the economic feasibility of a microgrid installation in India as a function of maintenance cost of the microgrid.

ure 18 shows IRR and LCOE as a function of operation and maintenance costs. As is expectable, increasing O&M costs lower the economic feasibility of the installation. IRR ranges from 15% at 1.5 % of initial costs to -10% at 9% of initial costs. The feasibility limit is situated around 5% of initial costs. The LCOE relation of O&M costs is linear, ranging from 0.3 Eur/kWh at 1.5 % of initial costs to 0.6 Eur/kWh at 10% of initial costs.



(a) IRR of a microgrid installation in India as a function of PV peak capacity price. 5% IRR can in this case be taken as an economic feasibility limit.

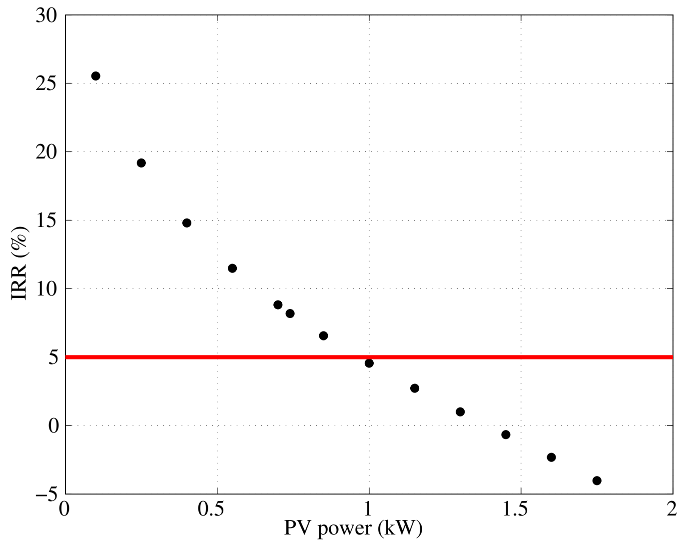


(b) LCOE of a microgrid installation in India as a function of PV peak capacity price.

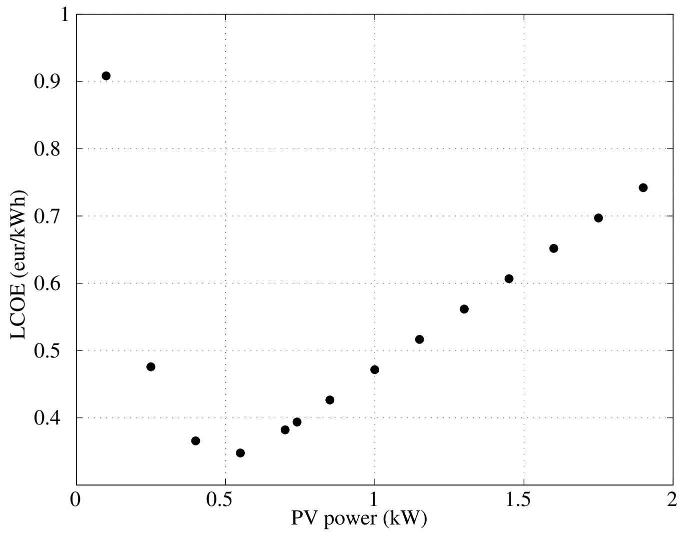
Figure 19: Parameters for deciding the economic feasibility of a microgrid installation in India as a function of PV peak capacity price.

Prices of photovoltaic panels has decreased very rapidly in the last years. Cost of the panels make the bulk of the initial costs of a solar powered microgrid. Figure 19 shows the effect of PV price on the economic feasibility. The results are mostly similar to the operations and maintenance costs. The feasibility limit is crossed around 2600 Eur/kW (see Fig. 19a).

Figure 20 shows the feasibility of the microgrid installation as a function of installed PV panel peak power. The IRR ranges from 25% at 0.1 kW to -5% around 1.7 kW. The feasibility limit is quite low, at around 1 kW. LCOE ranges from 0.35



(a) IRR of a microgrid installation in India as a function of the total installed PV production in the microgrid. 5% IRR can in this case be taken as an economic feasibility limit.



(b) LCOE of a microgrid installation in India as a function of the total installed PV production in the microgrid.

Figure 20: Parameters for deciding the economic feasibility of a microgrid installation in India as a function of the total installed PV production in the microgird.

Eur/kWh at 0.5 kW to 0.9 Eur/kWh at 0.1 kW. LCOE shows interesting behaviour at peak power under 0.5 kW. In this region, all the consumption in the microgrid is not met and any increase in PV power leads to a substantial increase in the feasibility of the system.

Debt ratio has a smaller effect on the feasibility. Increasing debt ratio increased both the IRR and LCOE, which sends a contradictory message: financing the installation with debt made it more profitable in financial terms but also drove the price of the produced electricity higher. Inflation has a similar effect as debt ratio. Higher inflation (resulting in a higher fuel price escalation rate) led the installation to be more profitable financially but at the same time increased the price of electricity.

The results above show that operating a microgrid in rural Uttar Pradesh, India would most likely be economically and technically feasible. In most probable conditions, the IRR would be higher than the inflation rate and the LCOE around 0.4 Eur/kWh. If the microgrid project would also be inclusive for the users (villagers), would use local labor (being thus socially sustainable) and would fullfil the other energy frugal criteria (section 2.2) it could be labeled as energy frugal.

6.2 Solar microgrids in Finland

The Finnish microgrid cases were based on the approach that the microgrids should disturb the macrogrid as little as possible. Therefore, the cases were designed so that the microgrids would not inject any power to the macrogrid.

We simulated two different cases: a bigger microgrid with around 500 kW of PV capacity and average yearly consumption around 11 GWh and a smaller one with around 50 kw of PV capacity and average yearly consumption around 400 MWh. The bigger case represents a microgrid serving a city block, office building or a shopping center and the smaller case a microgrid consisting of individual townhouses or an apartment complex. Otherwise the cases were identical.

Both cases use grid electricity as base case power system. The proposed case power system consisted of solar panels, the required inverter (for AC loads) and consumption. Proposed case uses grid electricity as backup power system. The main parameters for Retscreen calculations are shown in Table 5. The PV panels had a capacity factor of 12.6 %, which is a result of the orientation, tilt and efficiency of the system. Both the cases had a solar fraction of about 10%. The daily average solar radiation profile is shown in Figure 21. It varies from 5.7 kWh/m^2/d in June to 0.8 kWh/m^2/d in December-January.

For the case with the bigger microgrid, consumption was defined as a flat profile with a yearly consumption of 11075 MWh. The required peak load that the system has to satisfy was set to 2150 kW. The average load was 1250 kW. This consumption equals roughly the consumption of a mid-size shopping center (with around 10 million visitors) or a 500-employee office building [23].

For the case with the smaller microgrid, yearly consumption was set to 443 MWh, peak load to 85 kW and average load to 50 kW. This is equal to the electricity consumption of around 20 townhouses or an apartment complex consisting of around 150 to 200 apartments.

The energy storage option of a microgrid was not included in this part of the study, as it is not possible to implement that in Retscreen. However, if it were to be implemented, it would increase the costs of the microgrid and drive the feasibility down.

The reference system for both cases had system parameters as described in Table 5. This resulted in an LCOE of 0.11 Eur/kWh and an IRR of 2.9%, for both cases.

The results from the sensitivity analysis are shown in Figures 22, 23 and 24. As we can see from the figures, the two different cases produce qualitatively similar results. Figure 22 shows the economic feasibility of microgrid installation in Finland for the two cases as a function of grid electricity price. The IRR ranges from -5% at 0.07 Eur/kWh to 45% at 0.35 Eur/kWh. The economic feasibility limit of 2% is passed at just below 0.1 Eur/kWh. It should be noted here that the electricity price refers to the consumer price (including taxes and transmission fees), not the wholesale price.

Figure 23 shows the economic feasibility of a microgrid installation as a function of operation and maintenance costs of the microgrid. The results are qualitatively

Table 5: Parameters for the Finnish microgrid installations in Retscreen simulations, kept constant between simulations. Parameters marked with * were varied.

Parameter	Value
Location	Helsinki-Vantaa Airport, Finland
Panel orientation	45° tilt, South
Panel efficiency	14.7% at STC
Total losses	1 % at STC
Inverter efficiency	97.5%
Base case power system	Grid electricity
Debt term	10 years
Project life	25 years
Grid electricity price	0.1 Eur/kWh*
Yearly electricity consumption	11075 MWh* / 443 MWh*
Inflation	2%*
Debt ratio	50%*
Debt interest rate	1% above inflation rate
PV array power	1000 kW* / 50 kW*
PV price	1300 Eur/kW*
O&M	4% of initial costs*

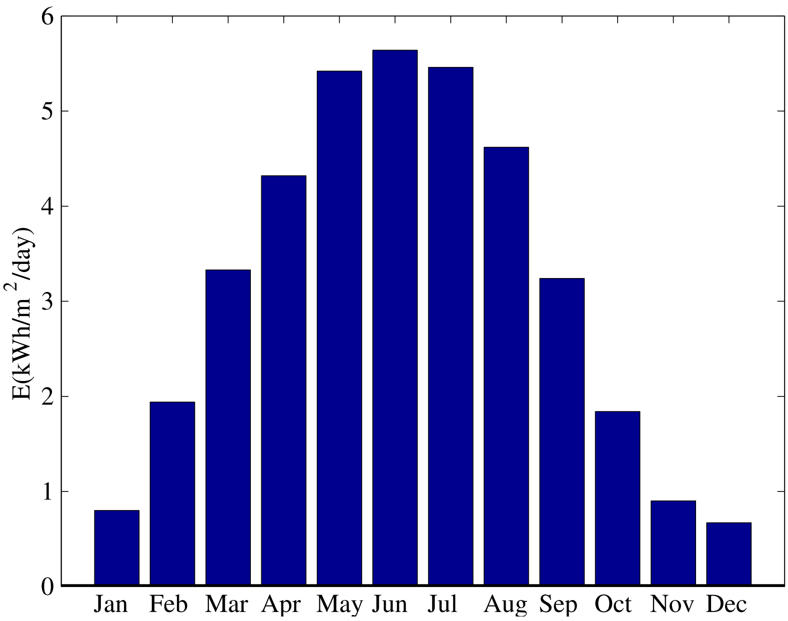
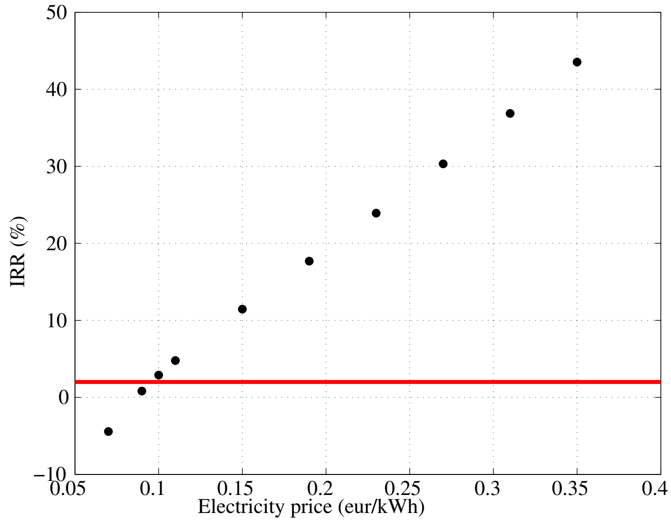
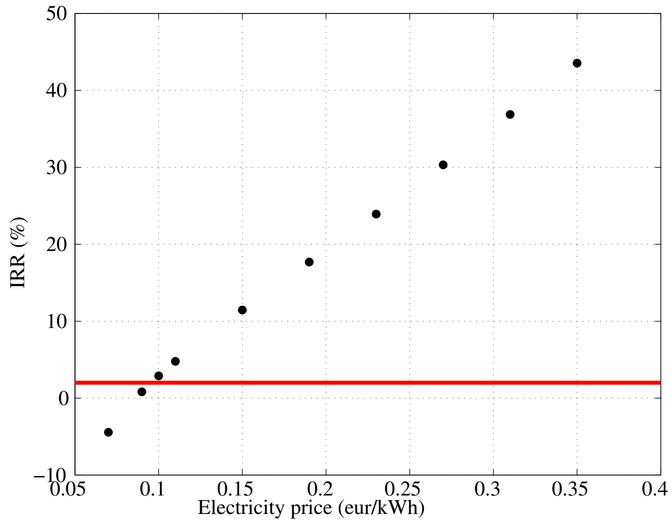


Figure 21: The daily average solar incident energy profile over the year in Helsinki-Vantaa Airport, Finland.

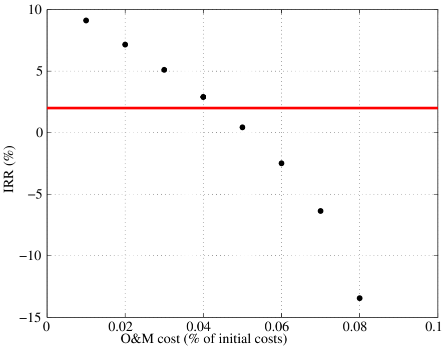


(a) IRR of a bigger microgrid installation in Finland as a function of electricity price.

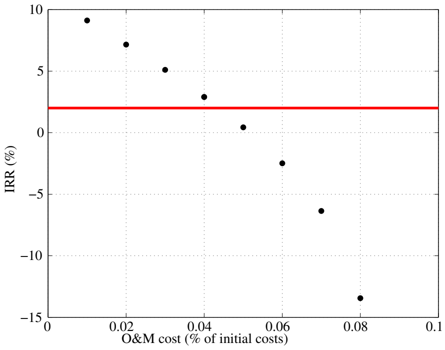


(b) IRR of a smaller microgrid installation in Finland as a function of electricity price.

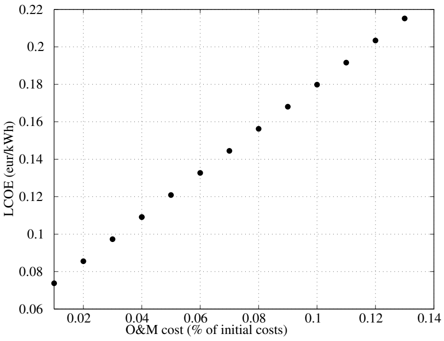
Figure 22: The economic feasibility of the microgrid installation cases in Finland as a function of electricity price. Note that this electricity price refers to the price paid by the consuming user, not the wholesale price. Therefore, it includes taxes and transmission fees. 2% IRR can in this case be taken as an economic feasibility limit.



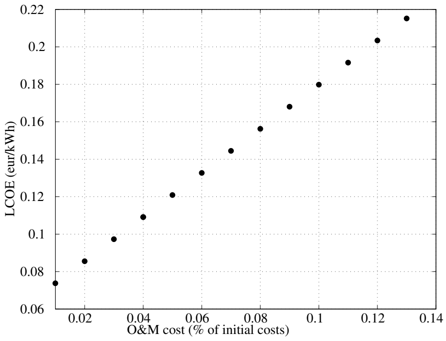
(a) IRR of a bigger microgrid installation in Finland as a function of the operation and maintenance costs of the microgrid.



(b) IRR of a smaller microgrid installation in Finland as a function of the operation and maintenance costs of the microgrid.



(c) LCOE of a bigger microgrid installation in Finland as a function of the operation and maintenance costs of the microgrid.



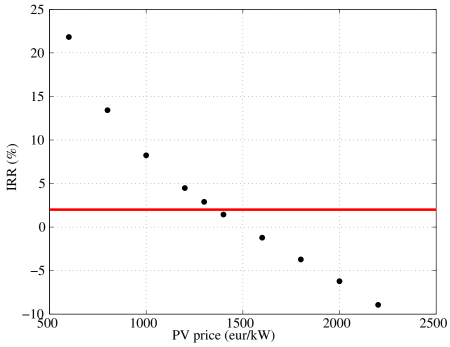
(d) LCOE of a smaller microgrid installation in Finland as a function of the operation and maintenance costs of the microgrid.

Figure 23: Economic feasibility of microgrid installations in Finland as a function of operation and maintenance costs. 2% IRR can in this case be taken as an economic feasibility limit.

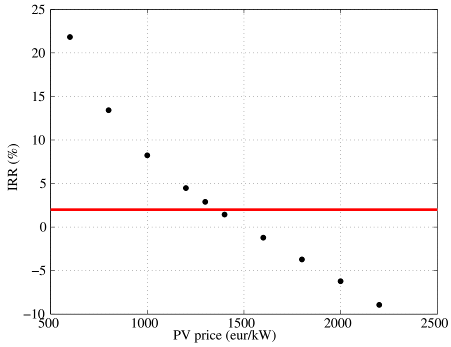
similar between the smaller and bigger microgrids. The IRR ranges from 10% at 1% to -15% at 8% of the installation cost. The feasibility limit of 2% is crossed at 4% of the installation cost. Figures 23c and 23d show that the LCOE depends linearly on O&M costs. It ranges from 0.08 Eur/kWh at 1% of the installation cost to 0.22 Eur/kWh at 13% of the installation cost.

The economic feasibility as a function of PV peak capacity price is shown in Figure 24. The results are qualitatively similar between the two cases. IRR ranges from 23% at 600 Eur/kW to -10% at 2200 Eur/kW. The feasibility limit is crossed at around 1300 Eur/kW. LCOE depends linearly on PV price. It ranges from 0.04 Eur/kWh at 600 Eur/kW to 0.24 Eur/kWh at 2800 Eur/kW.

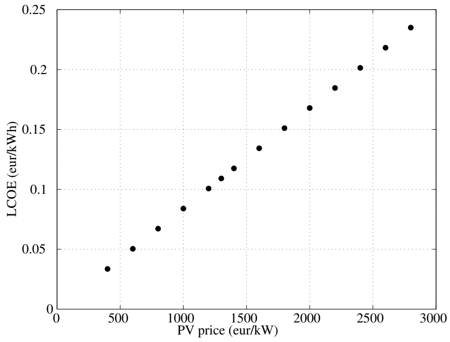
The economic analysis above reveals that the price of the electricity produced with a PV microgrid is competitive compared to grid electricity price in the most probable conditions. The LCOE for microgrid produced electricity is 0.109 Eur/kWh



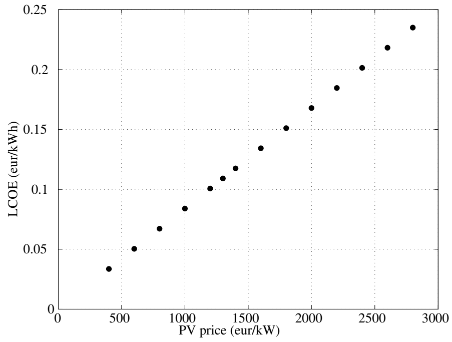
(a) IRR of a bigger microgrid installation in Finland as a function of PV peak capacity price.



(b) IRR of a smaller microgrid installation in Finland as a function of PV peak capacity price.



(c) LCOE of a bigger microgrid installation in Finland as a function of PV peak capacity price.



(d) LCOE of a smaller microgrid installation in Finland as a function of PV peak capacity price.

Figure 24: Economic feasibility of microgrid installations in Finland as a function of PV peak capacity price. 2% IRR can in this case be taken as an economic feasibility limit.

and (macro)grid electricity costs around or above 0.1 Eur/kWh. In most cases, the IRR would also be above inflation rate and the project thus economically feasible.

7 Summary of results

In this section, the results presented in section 6 are analysed. Based on this analysis, conclusions are drawn and described.

Based on the PVSyst simulation results from the Indian microgrid installations (section 6.1) we can say that the sizing of a microgrid is very situation dependent. Generally, increasing the amount of PV capacity increases the solar fraction, but it also increases the amount of unused (i.e. lost) energy. Increasing the consumption has the opposite effect. Battery size does not have a significant effect on microgrid operation as long as there is enough PV capacity to satisfy the consumption. It was also found that the daily consumption profile did not have a significant effect on the operation of the microgrid.

However, one can not provide a universal solution that would work everywhere. The sizing depends on what one wants to optimize. Say one wants to have a high solar fraction. Then it would be wise to have an excess of PV capacity. Or if one wants to minimize the unused energy but still provide enough power for consumption. Then it would be wise to have a large battery and just enough PV capacity. In any case, one should use PVSyst or a similar program for sizing a microgrid as they are readily available.

If one takes the economic feasibility as the goal, economic analysis of the Indian microgrid cases provides some means for deciding an optimal size for a microgrid. Increasing the ratio of consumption to the installed PV capacity leads to lower levelised cost of electricity (LCOE) and higher internal rate of return (IRR), which means that the microgrid is more feasible. However, this comes with the cost that power is not always available. In our analysis, the unavailability of power did not have an opportunity cost. The Indian reference case had an LCOE of 0.42 Eur/kWh and an IRR of 8%, meaning that the case is economically feasible.

The cost of alternative power sources, in the Indian case kerosine and in the Finnish case grid electricity, plays a significant role in the feasibility of a microgrid. As the price and cost of the alternative increases, the microgrid becomes more appealing solution. In India the price of kerosine is fixed by heavy subsidies and therefore not very volatile or sensitive to oil markets. Thus it would be wise to reduce the subsidy on kerosine, therefore increasing the feasibility of renewable energy microgrids and reducing government expenses.

The economic analysis of the Finnish cases reveals that the price of the electricity produced with a PV microgrid is competitive compared to grid electricity price. The LCOE for microgrid produced electricity is around 0.109 Eur/kWh and (macro)grid electricity costs around or above 0.1 Eur/kWh. The reference case shows this too; the IRR of the case is 2.9%, meaning that the investment would be feasible.

In developed countries such as Finland the investment in a microgrid is justified only if the uninterruptible power supply (UPS) feature of the microgrid is essential. This could be the case in a military application, hospital or some rural area. However, an investment in a microgrid without energy storage would be feasible even in other cases, such as a shopping center, apartment complex or a small neighbourhood. However, does this count as a true microgrid, remains an open question.

Grid analysis of the Indian cases show that for a certain transferred power the production and consumption should be situated as near as possible in order to minimise the wiring losses. Increasing the distance between the two requires greater wire gauges for the same amount of transferred power and thus costs more.

The amount of available solar electricity depends on the location and climate of the microgrid installation and also on the tilt of the solar panels. In India, the monsoon rains last from June to September, reducing the available solar radiation (Fig. 10). Furthermore, in our case, the panels were tilted 30° in order to have a smoother solar energy profile. One could have the panels completely horizontal and thus maximise the amount of solar energy during June solstice, but it would reduce the power available during winter. In Finland, due to it's more northernly location, the available solar electricity profile varies more throughout the year (Fig. 21). During the winter, very little solar power is available. Therefore, it would be wise to have other distributed energy resources (DERs) in the microgrid also.

To conclude, microgrids in developing countries act as affordable energy solutions alleviating (energy) poverty, true to the energy frugal ideology. In developed countries they can be used to increase the reliability of the power grid, but at a relatively high price as energy storage is expensive. However, they can be used to increase renewable energy penetration at a competetive price.

8 Conclusions

In this work, solar powered microgrids were investigated as an application of energy frugality. First the concept of energy frugality was defined. Secondly, a short literature review of solar power and microgrids was presented. Thirdly, the results of the analysis were presented and conclusions drawn.

Energy frugality means solving the energy needs of the poor by frugal innovations. Energy frugal solutions are are inclusive, affordable and sustainable. Microgrids are small electricity networks that include both local production and consumption. They also have the ability to disconnect and reconnect to the macrogrid.

Microgrid cases with different parameters and locations were analysed. The tools included PVSyst for technical simulations, simple DC grid model for grid analysis and Retscreen for economic feasibility study.

The optimal size for a microgrid depends on the target one wants to achieve. For example, if one wants to have a high solar fraction, it is wise to have excess PV capacity in the microgrid. However, economic feasibility analysis suggest that increasing the ratio of consumption to production would increase the economic feasibility of a microgrid. It was also found that the cost of the alternative power system for a microgrid plays a significant role in the feasibility of a microgrid.

It was found that the energy produced with solar powered microgrid is competitively priced compared to other available options: kerosene in rural India and grid electricity in Finland.

Based on this work, we can say that in developing countries microgrids contribute to reducing energy poverty as true energy frugal innovations. In developed countries microgrids can increase the reliability of the power grid, but the price is high. However, they can still increase the amount of renewable energy production at a price that can compete with grid electricity, in other words, it has reached grid parity.

In future studies one should increase the sophistication of the grid model and model a microgrid as a system. This might show phenomena that cannot be grasped by simpler models. One could also include an opportunity cost for the unavailability of power. A possible improvement could also be to introduce other energy sources into the microgrid.

References

[1] Meragao power website. `http://meragaopower.com/`, Cited 1.8.2014.

[2] Sähkomarkkinalaki 588/2013. Law about electricity markets, Finnish law.

[3] *Military Microgrids Market Potential*. Red Mountain Insights, 2013.

[4] Thomas Bialek. SDG&E Borrego Springs microgrid demonstration project. In *2012 Smart Grid Program Peer Review Meeting*, 2012.

[5] Thomas Bialek. Borrego Springs microgrid demonstration project - final project report. (CEC-500-2014-067), 2013.

[6] Boond.net. Boond website. `http://www.boond.net/`, Cited 1.8.2014.

[7] K. Branker, M.J.M. Pathak, and J.M. Pearce. A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews*, 15(9):4470 – 4482, 2011.

[8] Benjamín A Carreras, DE Newman, and Ian Dobson. Does size matter? *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 24(2):023104, 2014.

[9] Richard Chang. Tata nano: The world's cheapest car. *The New York Times, January*, 2008.

[10] Clayton Christensen. *The innovator's dilemma: when new technologies cause great firms to fail*. Harvard Business Review Press, 2013.

[11] Ms Ira Martina Drupady et al. *Energy access, poverty, and development: the governance of small-scale renewable energy in developing Asia*. Ashgate Publishing, Ltd., 2013.

[12] John A Duffie and William A Beckman. *Solar engineering of thermal processes*, volume 3. Wiley New York, 1980.

[13] Katharine Earley. Shaking off the energy crisis: how far can kinetic deliver on its promises? *The Guardian*, June 2014.

[14] Miriam Golden and Brian Min. Theft and loss of electricity in an Indian state. *International Growth Centre, London School of Economics and Political Science*, 2012.

[15] Biswarup Gooptu. Solar energy startups out to power rural india with cost-effective and less toxic solutions. *The Economic Times*, 10 2013.

[16] Jaap Gordijn and Hans Akkermans. Business models for distributed generation in a liberalized market environment. *Electric Power Systems Research*, 77(9):1178–1188, 2007.

[17] IEA. World energy outlook 2011.

[18] IEA. World Energy Outlook 2013. http://dx.doi.org/10.1787/weo-2013-en.

[19] Pierre Ineichen, RR Perez, RD Seal, EL Maxwell, and A Zalenka. Dynamic global-to-direct irradiance conversion models. *Ashrae Transactions*, 98(1):354–369, 1992.

[20] Gust Startup Funding & Investing. Gust: Boond engineering development. `https://gust.com/companies/boond_engineering_development_p_ltd_`, Cited 1.8.2014.

[21] Kelli L Joseph. The politics of power: electricity reform in India. *Energy Policy*, 38(1):503–511, 2010.

[22] S. Kale. *Electrifying India: Regional Political Economies of Development*. Stanford University Press, 2014.

[23] Nissinen Kari, Möttönen Veli, Niemi Renita, Nenonen Suvi, and Alho Johanna. Kauppakeskusten kestävän käytettävyyden arviointi. (VTT Technology 44), 2012.

[24] Luke Keller. Design for this century december 15th, 2011 a liter of hope. 2011.

[25] Shahidur R Khandker, Douglas F Barnes, and Hussain A Samad. Energy poverty in rural and urban India: are the energy poor also income poor? 2010.

[26] Toni Kylkisalo and Raili Alanen. Tasajännite taajaman sähkönjakelussa ja mikroverkoissa. Technical report, VTT working papers 78. Available: http://www. vtt. fi/inf/pdf/workingpapers-/2007, 2007.

[27] Hannu Jaakko Laaksonen. Protection principles for future microgrids. *Power Electronics, IEEE Transactions on*, 25(12):2910–2918, 2010.

[28] Robert H Lasseter. Microgrids. In *Power Engineering Society Winter Meeting, 2002. IEEE*, volume 1, pages 305–308. IEEE, 2002.

[29] Benjamin YH Liu and Richard C Jordan. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar energy*, 4(3):1–19, 1960.

[30] Arindam Maitra, Ben York, Haresh Kamath, Tom Key, and Vikas Singhvi. Microgrids: A primer. 2013.

[31] Preeti Malhotra, IH Rehman, Preety Bhandari, R Khanna, and R Upreti. Rural energy data sources and estimations in India, 2002.

[32] Tata Motors. Tata nano europe, for future launch in international markets, displayed at 79 th geneva motor show, 2009.

[33] Tariq Muneer, Muhammad Asif, and Saima Munawwar. Sustainable production of solar electricity with particular reference to the indian economy. *Renewable and Sustainable Energy Reviews*, 9(5):444 – 473, 2005.

[34] Jayaseelan Naidoo. An Infinite Vision: The Story of Aravind Eye Hospital. http://www.huffingtonpost.com/jayaseelan-naidoo/an-infinite-vision-the-st_b_1511540.html.

[35] Ashling O'Connor. Tata Nano–world's cheapest new car is unveiled in India. *Times Online*, 2008.

[36] Official Statistics of Finland (OSF). Energy supply and consumption [e-publication], 2013. http://tilastokeskus.fi/til/ehk/index_en.html, Helsinki: Statistics Finland [referred: 21.11.2014].

[37] Official Statistics of Finland (OSF). Production of electricity and heat [e-publication], 2013. http://tilastokeskus.fi/til/salatuo/index_en.html, Helsinki: Statistics Finland [referred: 21.11.2014].

[38] Government of India. Jawaharlal Nehru National Solar Mission. http://www.mnre.gov.in/file-manager/UserFiles/mission_document_JNNSM.pdf, Cited 1.8.2014.

[39] Coimbatore Krishna Prahalad. *The Fortune at the Bottom of the Pyramid*. Pearson Education India, 2006.

[40] European Commission press release. Energising europe: A real market with secure supply, 2007. http://europa.eu/rapid/press-release_IP-07-1361_en.htm, Cited 3.1.2015.

[41] Navi Radjou, Jaideep Prabhu, and Simone Ahuja. *Jugaad innovation: Think frugal, be flexible, generate breakthrough growth*. John Wiley & Sons, 2012.

[42] PVSyst SA. PVSyst help. http://files.pvsyst.com/help/index.html, Cited 8.2.2015.

[43] AA Salam, A Mohamed, and MA Hannan. Technical challenges on microgrids. *ARPN Journal of engineering and applied sciences*, 3(6):64–69, 2008.

[44] Pasi Salonen, Tero Kaipia, Pasi Nuutinen, Pasi Peltoniemi, Jarmo Partanen, et al. An lvdc distribution system concept. In *Nordic Workshop on Power and Industrial Electronics (NORPIE/2008), June 9-11, 2008, Espoo, Finland*. Helsinki University of Technology, 2008.

[45] Ernst Friedrich Schumacher. *Small is beautiful: A study of economics as if people mattered*. Random House, 1993.

[46] Tassilo Schuster and Dirk Holtbrügge. Tata nano: The car for the bottom-of-the-pyramid. In *Fallstudien zum Internationalen Management*, pages 83–102. Springer, 2011.

[47] Gireesh Shrimali and Sunali Rohra. India's solar mission: A review. *Renewable and Sustainable Energy Reviews*, 16(8):6317–6332, 2012.

[48] Solanki Chetan Singh. *Solar photovoltaics: fundamentals, technologies and applications*. PHI Learning Pvt. Ltd., 2011.

[49] California Energy Commission & California Public Utilities Commission State of California. Go solar california! - incentive eligible photovoltaic modules in compliance with SB1 guidelines, 2014. `http://www.gosolarcalifornia.ca.gov/equipment/pv_modules.php`, Accessed 9.7.2014.

[50] Thomas F Stocker, Dahe Qin, Gian-Kasper Plattner, M Tignor, Simon K Allen, Judith Boschung, Alexander Nauels, Yu Xia, Vincent Bex, and Pauline M Midgley. Climate change 2013: The physical science basis. *Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5)(Cambridge Univ Press, New York)*, 2013.

[51] Didier Thevenard, Gregory Leng, and Sylvain Martel. The retscreen model for assessing potential pv projects. In *Photovoltaic Specialists Conference, 2000. Conference Record of the Twenty-Eighth IEEE*, pages 1626–1629. IEEE, 2000.

[52] Aalto University. NewGlobal Website. `http://newglobal.aalto.fi/`, Cited 21.2.2015.

[53] Johannes Urpelainen and Semee Yoon. Solar home systems for rural India: Survey evidence on awareness and willingness to pay from Uttar Pradesh. *Energy for Sustainable Development*, 24:70–78, 2015.

[54] Christopher Villarreal and David Erickson. Microgrids: A regulatory perspective. Technical report, California Public Utilities Commission, 2014.

[55] A Wooldridge. First break all the rules: The charms of frugal innovation. *Economist*, 2010.

[56] H.D. Young and R.A. Freedman. *Sears and Zemansky's University Physics*. Addison-Wesley series in physics. Addison-Wesley, 2000.

[57] Marco Zeschky, Bastian Widenmayer, and Oliver Gassmann. Frugal innovation in emerging markets. *Research-Technology Management*, 54(4):38–45, 2011.