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Managing Off-Grid Power Use for Solar Fueled Residences with Smart Appliances, Prices-to-Devices and IoT

Donnelle L. January

University of South Florida

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Managing Off-Grid Power Use for Solar Fueled Residences with Smart Appliances, Prices-to-Devices and IoT

by

Donnelle L. January

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer Engineering
Department of Computer Science and Engineering
College of Engineering
University of South Florida

Major Professor: Ken Christensen, Ph.D.
Srinivas Katkoori, Ph.D.
Yao Liu, Ph.D.

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Dedication

I would like to dedicate my thesis work to God. The Lord Jesus Christ has given me the wisdom, knowledge and continuous strength to pursue my graduate studies. Without Him, this achievement would have not been accomplished. My perseverance throughout my thesis is summed up in one of my favorite Bible verses which is the following: “I can do all things through Christ which strengtheneth me.” – Philippians 4:13

I also dedicate my thesis work to my family. A special acknowledgement and thanks to my parents, Jeffrey January, Sr. and Ana Marie January for giving me the desire and passion to pursue my advanced education, and their never-ending support and encouragement throughout my studies at the University of South Florida. To my siblings: thank you for inspiring me to complete my master’s degree.
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Abstract

Electricity availability has a profound impact in day to day life. Activities such as lighting homes, charging cellphones, and running appliances all depend on electricity use. Around 1 billion people around the world do not have access to electricity, and the majority of these people hail from developing countries in remote areas. Moreover, many of these remote areas lack utility grid access due to the infeasible cost of extending the grid to remote communities. To combat this, various projects on microgrids have been implemented in order to distribute power to these off-grid areas. Nanogrids are defined as “a single domain for voltage, price, reliability, quality, and administration.” These nanogrids are small microgrids that supply electricity to small remote buildings, given a limited electricity supply. Furthermore, nanogrids provide electricity to remote areas in order to increase the livelihood of people living in these unfavorable conditions. In this thesis, a new method is introduced to nanogrids using a locally determined price shared with devices with a goal to match electricity demand to locally generated supply to reduce the number of blackouts while maximizing quality of experience in a nanogrid system.

This thesis provides a review of current rural electrification projects done in developing countries, specifically remote areas in Africa and Asia. A series of algorithms is introduced that sets the price for available electricity use in a household, controlling the power consumption of electrical devices. The topics of Internet of Things (IoT), prices-to-devices and smart appliances are covered in enabling and implementing the proposed algorithms.
A simulation model considers various parameters, including the battery charge and discharge rate, weather forecast, time of day, and time of year with respect to price allocation and power consumption. Simulation results display that the nanogrid paradigm using the controlled price algorithm eliminates the occurrence of blackouts in the rainy season with a reduced battery size (the worst case scenario) as compared to the nanogrid paradigm without price control.

The outcome of this simulation suggests that the distribution of power using price control levels off the electricity demand with supply and allows for smaller battery and smaller solar panels all the while maintaining a high quality of experience. It shows that a remote household using an off-grid system, with control of electricity use through pricing given a limited power supply, can effectively allocate electricity use and match electricity supply with demand. This reduces the occurrence of unwanted blackouts, positively influencing the economical aspect of remote areas with respect to electricity access in developing countries.
Chapter 1: Introduction

1.1 Background

From adjusting one’s air conditioning throughout different times of the year, to keeping the freezer continuously running for food storage, the availability of electricity is crucial in our everyday lives. Approximately 1 billion people in the world have no access to electricity [60]. In the United States alone, roughly 4,118 billion kilowatthours (kWh) of electricity was produced in 2019 [1]. A huge benefit of electricity is clean and reliable lighting. Extending the day through lighting makes is possible to get more tasks done and promotes social and economic growth [10]. Another benefit of electricity is refrigeration. Refrigeration improves our diet and reduces food borne illnesses and enables our miracle drug of antibiotics. For the distribution of power to be possible, an electric grid system is needed. An electric grid, known to most people as the utility grid, is defined as “a network of transmission lines, substations, transformers and more that deliver electricity from the power plant to your home or business” [2]. This distribution network is what allows one to receive electricity.

Non-renewable sources of energy already present an environmental problem due to the large amounts of CO₂ emission polluting the atmosphere. Moreover, sources of electricity generation have also been a topic of discussion in the field of medicine, specifically examining the health effects of using non-renewable sources of energy versus renewable energy. In a study conducted by [5], a comparison was done on the emission of CO₂ versus mortalities from air pollution; it was found that developing countries are at a higher risk of deaths due to these
emissions, concluding that population health will greatly benefit from using non-carbon based renewable sources of generation.

Grid systems that use renewable sources of energy are becoming more prominent. Solar energy as the main source of power has been increasingly popular, particularly in places where most of the population reside in rural areas and where solar energy is abundant, such as India [6]. These types of systems have also been found to produce lower installation and building costs compared to being connected to the utility grid supply in remote areas where communities are islanded from the grid [7]. Remote villages that are connected to the grid show the energy distribution network to be inefficient and unmanageable [7].

Isolated communities may never have access to the utility grid; the cost of extending the utility grid is too great for the benefit gained from receiving power, and renewable sources of energy are now at cost parity to the utility grid power. These places show that having standalone microgrid systems, like the hybrid wind-solar microgrid built in Lençóis Island in Brazil, serve as a great alternative and is reliable, providing good quality as compared to bigger cities connected to the grid [8].

1.1.1 Notion of Service Quality Level

The goal of any electric utility company is to provide reliability of supply to their consumers. This reliability includes having quality of service [9], which measures the overall performance of receiving access to electricity. Any grid system that provides power to its users should provide a high quality of service, whether the user pays for their power to utility companies or receives help from the government. It is to be noted that in this thesis, we refer to quality of service as quality of experience.
1.2 Motivation

1.2.1 A Need for Control – Blackout Versus Controlled Brownout

Today’s world is moving towards using more renewable sources to obtain electricity. With the utility grid, electricity supply matches demand, where the demand will never exceed the supply. For off-grid systems, electricity demand may exceed supply; this is where control mechanisms and policies come are needed. More specifically, areas that utilize off-grid systems have been discovered to have issues with high demand in electricity and low supply. Consumers use more power during peak times, and, as a result, they experience uncontrolled brownouts and even occasional blackouts. In [12], the GridShares project aimed to reduce the occurrence of brownouts in the village of Rukubji, Bhutan. It is comprised of a device that communicates the state of the grid to its users and manages power usage before major brownouts occur. It resulted in a decrease in brownouts of over 92%. Despite the huge success of the project, there were still challenges the software faced; not all users understood the features of GridShare and were still using their loads during timer mode [12]. In this case, electricity supply was less than demand. As a result, there were still some occurrences of blackouts. An approach to the issue of blackouts is to add pricing to the devices being powered. The concept of putting prices to devices is not new [11]. The main idea here is to have the ability to increase price to reduce power demand, which results to a decrease in power use, thus matching supply to demand.

It is important to distinguish the characteristics and lasting effects between brownouts and blackouts. In this thesis, a brownout is referred to as a reduction in power consumption; this means that some devices will still operate but at reduced power. A blackout is characterized by a complete power outage, where there is not enough power to keep any of the devices running. The lasting effects of blackouts are more detrimental than brownouts. When blackouts occur, some devices,
such as refrigerators and freezers, are not able to function which means a lack of food storage and even key medical supplies; this power outage can even become a matter of life or death, like the rolling blackouts experienced in the state of California [63]. Due to this, controlled brownouts are preferred over blackouts.

This thesis argues the idea that having a price-based control mechanism enables better power allocation, power consumption, and power storage in an off-grid system in a single residence. Given limited power supply, a control mechanism would be able to effectively mediate electricity supply and demand, all the while eliminating the occurrence of blackouts with the tradeoff of occasional brownouts.

1.3 Contributions

The main contributions from this thesis are as follows:

- A proposal, design, and simulation model of a method to match electricity demand to supply in a residence powered solely by solar panels with battery storage. The method manages electricity use to prevent residential blackout (out of power case) by use of selective and controlled brownouts of smart appliances in the residence.

- Demonstration of how price can be used as an electricity scarcity index for controlling the electricity use of smart appliances. As electricity availability declines (e.g., as the battery charge declines), price goes up, and devices use less electricity, thus limiting energy demand.

- Application of this new method of controlling electricity use to residences in developing countries. A simulation evaluation of a residence in Cameroon is completed showing a significant reduction in the occurrence of blackouts.
1.4 Organization

The structure of the remaining sections of this thesis is as follows:

- Chapter 2 describes electrification in rural areas and the issues associated with it. Selected local grid projects in Asia and Africa are reviewed. The methods of control with respect to limitations in electricity supply is reviewed.
- Chapter 3 covers the idea of local grids and the notion of price to devices. The emergence of IoT smart appliances, and smart grids are examined. The modeling of local grids is discussed.
- Chapter 4 proposes and develops a new control mechanism for nanogrids with respect to using price for mediating local electricity supply and demand for solar power – defining the design, specifications and process. The layout of supply-level and demand-level of in response to price is described. The use of IoT for communications from supply to demand is described.
- Chapter 5 describes the model used in the simulation of a standalone nanogrid in a rural area. The supply, demand, solar power and price-based control for the model are covered.
- Chapter 6 displays the results of the simulation of the standalone nanogrid, comparing the energy utilization, quality of experience and blackout occurrence between a nanogrid that uses the price control mechanism and a nanogrid that doesn’t.
- Chapter 7 concludes the manuscript and describes potential future work.
Chapter 2: Overview of Rural Electrification in Developing Countries

This part of the thesis reviews the literature associated with rural electrification in developing countries. It reviews the different off-grid projects in various places in Asia and Africa. Most off-grid systems aim to provide power to their users. It is crucial to point out the different features of the off-grid systems and, if successful in obtaining user adoption, the contributing factors that allow the system to prosper.

2.1 Challenges in Rural Electrification

2.1.1 Extending Utility Grid versus Local Renewables

Various projects have been implemented in order to combat the lack of electricity access in off-grid areas [61]. Off-grid systems provide power in remote areas where connection to the utility (electric) grid is infeasible, either due to being too far away from the grid source or surrounding environment conditions that are unfavorable for proper connection to the grid, like the Kingdom of Bhutan [13]. As previously discussed, there are higher costs associated with connecting remote areas to the nearest grid [7],[13]. For these reasons, isolated grids are favored over being connected to the grid for rural locations.

Isolated grids are commonly supported by diesel generators, which require transportation of fuel to remote areas, leading to higher running costs [14]. Renewable energy, such as wind energy and solar energy, serve as an alternative option. Currently, renewable energy technologies are progressively becoming the cheapest solutions for off-grid access to energy [8].
encourages the use of using renewable energy sources in an off-grid system rather than extending the utility grid to remote areas.

2.1.2 Scale of Local Renewables – Building Level

The energy needs of isolated areas greatly differ from places with high populations such as metropolitan areas. Households in rural locations in Sub-Saharan Africa mainly use kerosene for lighting and fuelwood for cooking [16], meaning less use of appliances that require electricity as a source of energy. Rural households do not have a utility grid connection, which contributes to using these type of fuel sources.

For infrastructures that use renewable energy as a fuel source, an important aspect of designing this system is the sizing of the renewable energy. For solar powered systems, the amount of sunlight received in the area is considered for the scaling of the system. A place where high amount of solar radiation is ideal. Components such as the daily load requirement, available energy from the sun, and the power generated by solar panels are taken into consideration.

The economic status of the country plays a role in energy requirements, too. In developed countries with strong economic stability, there is a higher consumption in energy. A typical residence in the United States consumes about 10,000 kWh per year, which is higher than grid-connected rural households in Africa [15].

2.1.3 Supply versus Demand Given Limited Supply

In off-grid areas, electricity supply may not always be met. There may be times when electricity produced by the grid is less than the electricity needed for household members to power their devices, particularly during peak power times. Because of this, not everyone will be able to use their devices when they need to, or they may experience a shutdown of power resulting in a blackout.
In [17], a project was done at an islanded microgrid to electrify a village in Monte Trigo, Cape Verde, where an energy dispenser was introduced to match energy demand with supply given a certain amount of supply. The dispenser displayed the current available energy level and sends a signal to the user to encourage or discourage consumption. It arguably showed to be a success in encouraging consumers to use the available energy supply.

Figure 2.1 shows a configuration derived from the project, assuming direct current (DC) loads [17]. The controller, as the energy dispenser, acts as the control unit, monitoring the rate of energy consumption by the user and the rate of energy being supplied. The project implemented in Monte Trigo sets the premise of this thesis, which aims to match electricity demand given the available supply.

Figure 2.1 Household showing solar panels, batteries, and devices to be powered
2.1.4 Storage of Solar Power for Night Use

In solar powered systems, the energy produced from the solar panels are used during the day when sunlight is present, and extra energy that is not used is stored in batteries for times when there is a lack of sunlight such as cloudy days or during nighttime. Having extra power stored is very beneficial in off-grid systems. It extends the day providing power when there is no sun with artificial lighting, which enables the operation of refrigerators and freezers for food and medicine storage.

2.2 Selected Projects in Asia

The following section reviews off-grid projects in Asia, with the following specifications:

1. The control mechanisms, if any, involved in the operation of the grid.
2. The power supply duration of the grid.
3. The energy storage, if any, of the grid.
4. The occurrence of brownouts or blackouts using the grid. High instances of blackouts are characterized by power outages that occur more than once a month.

2.2.1 Rukubji, Bhutan

The GridShare project was introduced into the village of Rukubji, Bhutan in 2011. The project features a controller, connected to the village’s micro-hydroelectric mini grid, that provides two mechanisms to alleviate brownouts, namely, an indication of the current state of the grid and a control mechanism that cuts power from the house for 30 seconds while using large appliances during voltage drops [12]. The main goal of the system is to reduce the occurrence of brownouts, due to times where the electrical demand of the village is higher than the supply of the mini grid. The hydroelectric grid provides service to 90 households, with a system rated at 40 kW. It delivers electricity to its users to power loads such as lightbulbs, televisions, and electrical appliances, like
rice cookers. The grid does supply power throughout the day but has issues with providing adequate energy supply during times of high energy demand, specifically during morning and evening times, when high-powered kitchen appliances are being used.

Currently, there is no form of energy storage in the system, in which the grid generates excess power, often rejected as heat via a dump load [12]. One effective solution mentioned in the project is to have energy storage, like batteries, which could help alleviate brownouts by having extra energy saved during times of high energy demand. Another solution is to implement a meter and a tariff based on usage of devices, introducing price signaling to reduce energy demand during peak period. The installation of GridShares did provide a control mechanism that limited how much power its users used at specific times, which resulted in a reduction in the occurrence of brownouts in the village. After the installation of the GridShares system, the occurrence and average length of brownouts greatly decreased with over 92% fewer days with major brownouts. The occurrence of blackouts were very few and far in between, which were not recorded.

2.2.2 Ura, Bhutan

Owned and operated by Bhutan Power Corporation (BPC), a micro-hydro grid was installed in the village of Ura, Bhutan. The goal of the grid was to provide electrification to remote communities not connected to the nation’s main grid.

The hydro grid system is rated at 50 kW and provides service to over 158 consumers. The grid supplies power throughout the day but is only limited to the lighting needs of its users. There have been restrictions on users not being able to use other appliances (besides using lightbulbs) while using the grid, but because the restrictions are not thoroughly enforced, users still aimed to use other electrical appliances, such as rice cookers, on the grid. This results in frequent brownouts, which occur when energy demand is high during peak load times [20].
2.2.3 Pokhari Chauri, Nepal

In July 2000, the rural settlement of Pokhari Chauri in Kavre district, central Nepal was provided a Micro-Hydro grid system to fuel the electricity needs of 239 households. It was installed and mainly funded by the United Nations Development Programme-led Rural Energy Development Programme (REDP). The purpose of the grid was to provide reliable power to the settlement’s rural residents overusing candles and kerosene as sources of fuel. The grid features a 22kW Micro-Hydro system and provides electrical service to 239 households. The grid supplies electricity during certain hours of the day, between 4am and 4pm, and 6pm to 11pm [18], achieving a daily power supply duration of 17 hours.

A control mechanism is not set in place; however, a user electricity tariff is implemented in the grid, in the form of micro-loans that users of the grid agree to pay for receiving electricity. No energy storage system was reported for the micro-hydro grid. It was reported that users received reliable service from the grid, and that their energy demand needs were met [19].

2.2.4 Huai Bu, Thailand

The Huai Bu village is one of many projects in Thailand to promote electrification in remote areas, especially places where connection to the grid is not feasible. The micro-hydro system is rated at 25kW, and serves three village hamlets, namely, Huai Bu, Baan Mai, and Sop Laan, totaling 94 households, with 74 households obtaining power from the micro-hydro plant. The hydro system does provide power throughout the day and night, but it does not have any kind of energy storage. In [21], it was found that the hydro system experienced brownouts and blackouts, with even worse blackouts occurring 31% of the time.
2.2.5 Mae Kam Pong, Thailand

Like the Huai Bu village, a micro-hydro grid was built in the rural village of Mae Kam Pong in Tambol Huay Kaeo, Ging Amphur Mae On, Changwat Chiang Mai, roughly 50km from the city of Chiang Mai. It served as a part of a collection of projects to electrify ethnic villages in Thailand.

By a case study done in [21], this micro-hydro project showed to be a successful grid and is Thailand’s longest running off-grid system. The grid’s system is rated at a total of 80kW, stemming from the 20kW installation in 1983, another 20kW added in 1998 as well as an additional 40kW. It supports the electrification of 128 households. Like the Huai Bu system, the hydro system provides continuous power throughout the day and night and does not have any form of energy storage.

An issue that the village micro-hydro system faced was the occurrence of brownouts and blackouts. Like other micro-hydro grid projects done in the different villages in Thailand, the residents of the Mae Kam Pong village faced levels of low voltage and power outages particularly in the evenings. For Mae Kam Pong specifically, it was reported that out of 58 systems, 48 experiences issues with brownouts, and 41 reported problems with blackouts. [21] Argued that the cause of this was due to the increase in appliance use throughout the village, noting that the village was blacked out 9% of the time. A control mechanism was not set in place for the micro-hydro grid, which is a possible reason as to why the village experienced a high energy demand given a low energy supply.

2.2.6 Summary of Projects in Asia

This section summarizes the off-grid projects done in different countries in Asia. It examines whether there is some sort of control mechanism involved in the grid, the energy storage
of the grid, the power supply duration of the grid, and the frequency of brownouts or blackouts.

Table 2.1 shows the comparison of off-grid projects in Asia.

<table>
<thead>
<tr>
<th>Control Mechanism</th>
<th>Power Supply Duration</th>
<th>Energy Storage</th>
<th>Frequency of Brownouts/Blackouts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rukubji, Bhutan [12]</td>
<td>Yes</td>
<td>No</td>
<td>Low instances of brownouts and blackouts</td>
</tr>
<tr>
<td>Ura, Bhutan [20]</td>
<td>No</td>
<td>No</td>
<td>High instances of brownouts and blackouts</td>
</tr>
<tr>
<td>Pokhari Chauri, Nepal [19]</td>
<td>No</td>
<td>No</td>
<td>Low instances of blackouts a year</td>
</tr>
<tr>
<td>Huai Bu, Thailand [21]</td>
<td>No</td>
<td>No</td>
<td>High instances of brownouts and blackouts</td>
</tr>
<tr>
<td>Mae Kam Pong, Thailand [21]</td>
<td>No</td>
<td>No</td>
<td>High instances of brownouts and blackouts</td>
</tr>
</tbody>
</table>

**2.3 Selected Projects in Africa**

The following section reviews off-grid projects in Africa, with the same specifications as the off-grid projects in Asia.

**2.3.1 Monte Trigo, Cape Verde**

The Multiuser Solar Micro-Grid (MSG) Monte Trigo project entered the village of Monte Trigo in February 2012, in the Island of Cape Verde. The project has an energy dispense meter, which implements an algorithm that monitors the electricity consumption of its users and limits the users from using a certain amount of power based on a tariff fee that the user agrees to pay. The main objective of the project was to provide electrification to the village of Monte Trigo, with a 100% renewable energy Multiuser Solar micro-Grid (MSG).
The MSG features a system that rates at 90 kilowatt-hours (kWh) per day. It supplies energy to 60 households, 1 school, 1 kindergarten, 1 medical center, a connection point for telecommunications and TV, 1 hotel for tourists and visitors, and some small commercial shops [17]. The grid provides 24 hours per day of power to its users through a distribution grid. In terms of energy storage, the grid has two lead acid batteries that can store roughly 370 kWh of energy, which is equivalent to approximately 4 days of autonomy in cases of no sunlight.

The project does have a control mechanism based on price (in the form of a tariff). The amount of energy a consumer can use is limited by the tariff they have. As the user consumes energy, the dispense meter tracks the decrease in energy; if the consumption is balanced with the supply, the remaining energy in the storage tank stays constant. When the rate of energy consumption is lower than the rate of energy being supplied, the storage tank fills up, decreases the energy daily allowance, and “rewards” users that save energy by providing extra stored energy (the leftover energy they did not use) for the succeeding days [17]. When the rate of energy consumption is higher than the rate of energy being supplied, the storage tank decreases and eventually becomes empty, and if the consumption is still high after the depletion of the tank, the dispense meter will disconnect the consumption for a short period of time before providing energy to the user again.

The system implements a function that promotes users to take advantage of the surplus of energy at no extra cost on days where there is an abundance of sunlight. There were no reported cases of blackout with the implementation of the energy dispense meter. The project showed a success in balancing the energy supply with demand, adapting the consumers to use energy according to the energy supply set by the agreed tariff.
2.3.2 Osho-Oibor, Kenya

The standalone microgrid in Osho-Oibor, Kenya was installed in 2009. Its system is rated at 10kW wind and solar, and a 10kW diesel generator. The system also has an energy storage, in the form of a battery bank. The grid’s purpose is to provide the community of Osho-Oibor adequate power, with a total of about 22 connections, ranging from private businesses, public institutions, and households. There have been issues with who gets access to power and when, with public institutions given priority and microgrid operators favoring businesses in electricity allocation over households [23].

The system does not have a set control mechanism, although it can be noted that a mini-grid operator switches the power off manually during times of low supply, such as overcast days or days when there is very little wind. During the field study done in [23], it was noted that energy consumption never exceeded 10-15% of the available generation capacity, hinting that the frequency of power outages (blackouts) occurred more often.

2.3.3 Thiba, Kenya

In 2005, the Mini-Hydro grid system was commissioned in Thiba, Kenya. The grid system was installed by GPower, which would eventually cater to 180 households within a 1.6km radius of the grid [19]. The system features a 135kW turbine that fuels the electricity needs of the residents. In this system, there is no control mechanism, and the supply duration of the system does not provide a 24-hour service, limiting the users from only receiving electricity between the hours of 6am to 8pm every day, totaling 14 hours a day. The system does not have a source of energy storage, which likely contributes to not providing 24 hours of service.

During the times of energy distribution from the grid, there is a surplus in energy from the system, allowing households to use appliances high in electricity, such as electric cookers or irons
[19]. It was reported that the users did not receive reliable service from the grid, due to frequent blackouts and brownouts. This was due to frequent power disruptions with maintenance of the system.

2.3.4 Akkan, Morocco

    Like the MSG project in Monte Trigo, an MSG was also implemented in the village of Akkan, Morocco in 2007. The hybrid micro grid also has an energy dispense meter, that keeps track of the energy consumption of the consumers. The hybrid system has a combined rated power of 910W [22], and provides electricity needs to the residents of Akkan.

    The system does have an energy storage, which consists of a battery that allows for up to 4 days on autonomy [22], in case of bad weather conditions. The grid system does have a control mechanism, featuring an energy dispense meter that tracks the user’s energy consumption. This allows for the disconnect of the energy in case the user has a high energy demand given the energy supply. Like Monte Trigo, it was reported that the village does not experience frequent blackouts with the implementation of the energy dispense meter.

2.3.5 Summary of Projects in Africa

    This section compares the off-grid projects done in different countries in Africa. In table 2.2 a comparison of off-grid projects in Africa is displayed. It examines whether there is some sort of control mechanism involved in the grid, the energy storage of the grid, the power supply duration of the grid, and the frequency of brownouts or blackouts. It is to be noted that out of the 4 projects covered, 2 of them are at the residence level, namely the projects in Cape Verde and Morocco. Projects that are at the residence level means that each household receives their own separate electricity supply independent of the electric supply received from other household. For this thesis, we simulate a grid that provides electricity at the residence level.
Table 2.2 Comparison of off-grid projects in Africa

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Mechanism</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Power Supply Duration</td>
<td>24 hours</td>
<td>24 hours</td>
<td>14 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency of Brownouts/Blackouts</td>
<td>No reported cases of blackouts</td>
<td>High instances of blackouts</td>
<td>High instances of brownouts and blackouts</td>
<td>Low instances of blackouts</td>
</tr>
</tbody>
</table>
Chapter 3: Background on Key Technologies

Chapter 3 covers local grids, specifically covering microgrids and nanogrids. It describes the concept of prices to devices and prices to devices on smart appliances. The Internet of Things (IoT) for the possibility of communication in grids is covered, and how the algorithms presented in this thesis depend on this technology to function. Different applications of modeling various local grids are examined.

3.1 Concepts of Local Grids – Microgrids and Nanogrids

Areas disconnected from the utility grid are classified as local grids. A local grid has various sizes that can range from powering a single building (such as a residence) in a designated area to providing power to multiple buildings over a large area. Microgrids and nanogrids are two types of local grid. Microgrids, defined by WG6.22, are “electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded” [3]. These types of grids can function on the grid or exist off the grid as a standalone system. The general scheme of a microgrid can be seen in figure 3.1 [26]; it is to be noted that in the figure, the buildings represent a single residence.

Considered as a smaller version of a microgrid, a nanogrid is defined as “a single domain for voltage, price, reliability, quality, and administration.” [4]. This type of grid provides power distribution to a smaller number of loads, or devices, as compared to microgrids, and typically
works with structures that do not require large amounts of electricity, such as single buildings, small communities, and villages.

Unlike a microgrid, a nanogrid is not connected to the main utility grid. However, nanogrids can be connected to other local grids to provide electrical service to more people. Due to the design of a nanogrid, it is noted that this type of grid shows great potential in areas where people do not have readily access to electricity [25]. Figure 3.2 displays the typical components of a nanogrid [4].

A nanogrid is comprised of an energy source, such as a wind turbine or solar panels, a controller, optional battery storage, loads which are electrical devices, and connection to other grids. The controller functions as the main entity between all the other components and is responsible for functions such as monitoring storage levels, communicating with other grids, distributing power to the loads, and receiving energy from power sources. The loads in a nanogrid can be any electrical device or appliance that draws power from the controller.
Nanogrids can be classified into two types, namely, “managed” and “unmanaged” nanogrids [4]. Unmanaged, or uncontrolled, nanogrids lack communication with load consuming devices on the distribution of power. With a managed, or controlled, nanogrid, communication about power distribution is present. A local price that can be used with nanogrids to communicate to loads the available power is called “price managed” [4]. With price managed nanogrids, the controller can increase or decrease the price of power depending on the available energy from the power source or energy storage and send this price to the loads [27]. The less energy supply the nanogrid has (from the power source or energy storage), the higher the local price, and the more energy supply the nanogrid has, the lower the price. From here, the loads determine whether they are willing to spend the calculated price to receive power. This communication about power and local price to loads can be achieved through the concept of prices to devices, which is described in the subsequent section.

Figure 3.2 Diagram of a nanogrid
3.2 Concept of Prices to Devices

Load consuming devices in a price managed nanogrid receive information from the controller on the current local price for electricity based on the available energy. For this to be possible, devices would need to function as decision making appliances. This approach between the controller and the devices is called “prices to devices” [11]. In this sense, the devices can optimize their operation to satisfy predetermined costs or conditions. Moreover, the term “demand response” provides time and price-dependent variation in demand [11]. For instance, certain devices only function during specific periods throughout the day and adjusts power consumption according to the current price. The objective of demand response is to allow the shifting or curtailing of loads to decrease power consumption during times of constrained energy supply.

Smart grids are defined as “an electrical grid that is able to deliver energy (electricity) in a controlled and smart manner from power generation nodes to active consumers” [46]. These grids can control device power consumption, and either provide or deny power to devices during peak load times. Smart grids have the capability to curtail or reduce power consumption from smart appliances in real-time settings, through automated demand response. The objective of this feature is to reduce peak power to avoid overload of the power network and energy generation capacity [43].

Devices that can function with decreased power are termed as low priority loads [27]. For instance, lightbulbs can still operate without requiring their full power rating, leading to dimmed lights. Devices that operate in this manner can be classified as curtailable loads, which are loads that don’t need their full load demand to operate. Devices that need full power to function are called high priority loads. Freezers or refrigerators need full power continuously to operate, categorizing them as high priority loads. Other devices, such as dishwashers and laundry machines,
can function at any designated time during the day; these devices can be termed as shiftable loads. One important clarification is that priority is a statement of value to the users; the user ultimately decides what devices they consider as high priority or low priority devices, depending on their needs and wants.

To get a better understanding of prices to devices, Figure 3.3 shows the cycle for power control on device function with respect to pricing. The concept behind this is that the devices are given a price for electricity, called “real-time pricing” [62], and make decisions, based on user preference from price, on how much power they consume.

![Diagram of power supply and price signal](image)

**Figure 3.3 Flow of prices to devices for control of power demand**

### 3.3 Overview of Internet of Things (IoT)

The Internet of Things (IoT), coined by Kevin Ashton [35], refers to a “group of infrastructures interconnecting connected objects and allowing their management, data mining and the access to the data they generate” [24]. Devices that interact in IoT includes objects such as TVs, smartphones and smart appliances. In this thesis, machine-to-machine communication (M2M), along with IoT communication protocols, is needed for the full implementation of smart appliances in a nanogrid system with control.
3.3.1 Machine to Machine (M2M) Communication

The main idea behind M2M communication is for the devices to interact with one another on when energy is needed, without involving the consumer. This means the loads (devices) receive price data from the controller and autonomously decide how much power they will consumption. In the survey by [28] on M2M communication in home-based networks, the equipment is connected to a gateway, which, in turn, communicate with other devices for requested power services; the home-based network serves as the M2M communication between the appliances and the building network. In nanogrids, the controller communicates with the local power source or other nanogrids; the interaction between the nanogrid controller, the power source and the devices is referred to as M2M communication.

In this thesis, a price-based control mechanism is implemented in the nanogrid controller, wherein the nanogrid controller monitors power supply and demand, determines the current local price based on multiple factors, sends the price to the devices, and collects information from the battery storage and solar panels on how much energy is distributed to the devices based on the price the devices are willing spend in order to operate.

3.3.2 IoT Communication Protocols

There are various IoT communication protocols that exist, which support communication and the distribution of power between devices. Communication protocols can be grouped into two categories: Low Power Wide Area Network (LPWAN) and short-range network [36]. SigFox and Cellular are LPWAN standard protocols. SigFox is used in wireless technology and can be applied to low energy objects like sensors and M2M communication. Cellular caters to networks that require functionality over longer distances, so local network communication and M2M applications are infeasible for this type of protocol.
Short-range network protocol consists of technologies that allow the connection of smart devices for communication. Examples of this protocol include over Low Power Wireless Personal Area Networks (6LoPWAN), ZigBee. 6LoPWAN is a commonly used IP-based standard internetworking protocol that can communicate and connect with other networks without mediator entities such as translation gateways or proxies. ZigBee is another short-range network protocol which caters to personal area networks that are small, low powered and that require communication over longer distances as compared to 6LoPWAN.

3.3.3 IoT for Communication in Grids

Nanogrid systems require gateways to connect to other nanogrids, in order to communicate about power. Moreover, nanogrid controllers receive information from energy sources on power production, communicate with energy storage on power supply, and relay information to the devices on current energy supply and power consumption. IoT is what allows the interaction of these entities with respect to M2M communication.

For the ability of objects within a nanogrid to effectively interact and communicate with one another, these objects need to act as smart appliances, having wireless communication and monitoring electricity use. Currently, common communication protocols that smart appliances use include ZigBee, Z-Wave, Bluetooth and Wi-Fi [67]. For home-based networks that utilize smart devices, a suitable communication protocol between the controller and devices is ZigBee. Several communication technologies exist in order to facilitate the exchange of data between a nanogrid controller, devices, storage, and gateways.

An energy meter, a device that acts as the main source of communication and data exchange, can be considered as a nanogrid controller. This energy meter monitors all of the devices, receiving information from the devices about power consumption. Because
communicating price in real-time is a crucial factor in proper device consumption, the bandwidth between the controller and devices needs to be taken into consideration. According to [65], for M2M communications, the required bandwidth for devices is between 2 to 5 Mb/s. This bandwidth is what allows for devices to regularly send or receive data, whether it be data about price or power consumption.

Currently, there are a variety of technologies that can support this type of data exchange. Some energy meter products include the Zigbee Smart Energy Wireless Metering Load Switch/Controller and Neurio Home Energy Monitor.

3.3.4 IoT Security in M2M Communication

In [31], Lai and colleagues discusses potential security problems with M2M communications. It was noted that device triggering can be an issue when it comes to devices interacting with a network system. For example, a hacker can put a device in an unwanted state, therefore prompting the device to perform an action that was not intended and waste power, which compromises the systems safety. In the case with the M2M communication in the nanogrid system with a control mechanism, an intruder can trigger a load into using power when it should not be doing so. This can throw off the control mechanisms calculation and cause power loss to other devices, greatly affecting the future power use of the loads, especially high priority loads.

A list of potential security issues in M2M communications is presented in [32], some of which include injection, spoofing, and Denial of Service (DoS). Device triggering, as mentioned previously, is like injection, in which case malicious or unwanted data is introduced to the system which interrupts proper functioning of the system. Spoofing includes the attacker disguising as a user or a network in order to gain access control on certain features of the system, which can potentially throw off the systems processes.
In spoofing, the attacker can disguise themselves as the consumer and increase the price in which they are willing to pay for electricity consumption, which undoubtedly can disrupt what and when power will be distributed to loads. For nanogrid systems, the attacker can mask as the nanogrid controller, which can either give unnecessary energy to the user or deny the user of energy needed, which in this case relates to DoS attacks. DoS attacks refer to preventing certain services to be performed, particularly the services the network provides to the user or devices. For instance, an attacker may insert an invalid input or manipulate messages in the network which causes a device to fail due; this attack can cause harmful secondary effects to the network, which may also result in other devices malfunctioning and failing in the network. A real-life device was examined in [64], wherein a Philips Hue Connected bulb accepts commands from a user app using ZigBee-Light Link protocol; in this example, an eavesdropper can gather device information, gain control of the device, and reduce device use or prevent the device from operating.

Security issues with M2M communications have been addressed, and certain architectures have been implemented in order to combat this challenge. A M2M communication protocol for smart grids was introduced in [33]. This protocol entails relaying the security of data between devices using intermediary nodes, wherein the data collectors do not have access to the content while verifying the information’s integrity, all using cryptographic algorithms with shared keys. In [34], a review is done the application of Key Policy ABE (KP-ABE) that uses KP-ABE to securely allow communication between a smart grids control center to specific users in the system through encrypted messages. For the realm of security in nanogrid systems using smart appliances, a similar policy can be established in order to maintain data integrity between the nanogrid controller and the devices. The techniques presented could fix the security problems mentioned.
earlier; with the example of the ZigBee connected bulb, the eavesdropper would not be able to retrieve information from the device, thus not being able to compromise the device’s operation.

3.4 Emergence of Smart Appliances

A smart appliance is defined as “an appliance that includes the intelligence and communications to enable automatic or remote control based on user preferences or external signals from a utility or third-party energy service provider.” [37]. These appliances can be things like refrigerators, dishwashers, coffee makers, ovens, etc. and are able to interact with external entities such as nanogrids. Moreover, smart appliances (or devices) can be modified based on the consumer’s wants. In nanogrid systems, these devices can communicate with both the user on how much price they are willing to spend to run specific devices and the nanogrid controller on how much power to give based on the price.

Smart appliances have also been found to be ideal complements to renewable sources of energy, such as solar power, due to the inherent variability in supply [29]. Examples of smart appliances include Philips Hue lightbulbs and Whirlpool dishwashers. The costs associated with smart appliances depend on the brand, model and features; in general, smart devices cost about 30 to 50 percent more money than their traditional counterparts [68]. For instance, conventional dishwashers typically range from $400 to $700 while smart dishwashers can range from $650 to $1,600 [66].

Smart grids are defined as “an electrical grid that is able to deliver energy (electricity) in a controlled and smart manner from power generation notes to active consumers” [46]. These grids can control device power consumption, and either provide or deny power to devices during peak load times.
3.4.1 Ability to Curb or Reduce Power Use in Real-time

Smart grids have the capability to curtail or reduce power consumption from smart appliances in real-time settings, through automated demand response. The objective of this feature is to reduce peak power to avoid overload of the power network and energy generation capacity [43]. There are approaches that help facilitate this real-time power reduction through applications like Nonintrusive Appliance Load Monitoring (NALM) [44] and RECognition of electrical Appliances and Profiling in real-time (RECAP) [45]. In the interest of this study, smart appliances can reduce their power consumption on overcast days where the presence of sunlight is reduced, or in cases where energy storage is limited. The importance of implementing the control methods from this thesis is to help facilitate smart appliances in autonomously adjusting their power consumption without the need for consumer interaction, based on price signals received from the grid.

3.4.2 Ability to Delay Power Use

In addition to curbing or reducing power use, smart appliances can delay power use, especially during peak load times, and smart grids help facilitate this action like task scheduling, all through the concept of demand response. To have a better understanding, demand response is defined as “a tariff or program established to motivate changes in electric use by end-use customers, in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardized” [47]; this demand response is associated with appliances that can perform load shifting, like dishwashers turning on at a specified time or delaying the operation of laundry machines. There have been demand response programs and schemes in smart grids that show how smart appliances can curb or reduce power use, and delay (or reschedule) power use in
real-time as needed [48]. This load modification is achieved by the energy providers sending control signals which reduce and shut down appliances in homes, particularly during peak load times and times when there are limitations in energy generation.

3.5 Modeling of Local Grids

Many local grid projects have been studied, evaluated, and analyzed in finding the best design given the technical and financial limitations for the respective grid system. In order to analyze the performance of these projects, the design of the local grids need to be modeled. There are various software applications that help achieve this analysis, especially renewable energy systems.

3.5.1 Hybrid Optimization Model for Electric Renewables (HOMER)

HOMER, created by the National Renewable Energy Laboratory in the United States, is a free software application that is designed for evaluating the technical and financial factors into the design of a microgrid system, ranging from standalone grids to on-grid systems [30]. It compares costs of installation, operation, and maintenance of the modeled grid systems. HOMER allows its consumers, typically grid system designers, to explore numerous technology options based on the availability of energy resources. There have been many simulation models done on local grid systems using HOMER [38], [39], [40].

3.5.2 Improved Hybrid Optimization by Genetic Algorithms (IHOGA)

Developed by the Electrical Engineering Department at the University of Zaragoza (in Spain), IHOGA is a software tool that is used for optimization in the simulation of hybrid renewable systems for electrical energy generation [30]. The main goal of IHOGA is to find the cheapest cost in systems for optimization as well as reducing other variables, such as the emission of carbon dioxide or unmet load demand.
3.5.3 RETScreen

Developed by the Government of Canada, RETScreen is a software application designed for the evaluation and analysis of renewable, energy efficient projects [30]. It supports both the technical and economic aspect of designing such projects and can range from capabilities such as supporting different configurations of the system to analyze the financial aspect of a system. The most current version of RETScreen is RETScreen Expert, which was made available to the public in 2016 [41].

3.5.4 Other Tools and Approaches

Other software tools for the analysis and evaluation of renewable local grid projects include applications such as Hybrid2, IPSYS, SOLSIM, AREA, and many others [42]. The main objective of these types of software is to determine the most efficient and effective way of implementing a grid system given various settings, configurations and parameters. In this thesis, it is important to note that the nanogrid system considered is hypothetically pre-designed, and that the algorithms proposed are implemented in such a system.
Chapter 4: Design of Nanogrid with Price-Based Control Mechanism of Demand

The proposed price-based control mechanism is described in this chapter, detailing the process of the method and the different metrics associated in measuring the performance of the method. The use of IoT for communications in order to implement the control mechanism is covered.

4.1 Goal of Achieving Best Possible Quality of Experience

Given a finite supply of energy, it is important to effectively utilize how the energy is being used, which means balancing between providing dependable energy versus storing up energy when necessary. This scenario of having reliable electricity over having enough energy presents a trade-off when considering how much energy should be used and when the energy should be used.

In this thesis, we argue that reducing electricity consumption (referred to as brownouts) is preferred over complete power outages (blackouts) when there is a high electricity demand and a limited electricity supply. In this thesis, it is important to define a brownout versus a blackout when measuring the performance of the nanogrid model under study. A brownout occurs when a device operates at a reduced power rating. A blackout occurs when a high priority load is unable to operate with the given power supply or when no power is available.

Because we are considering an independent residence in off-grid rural Cameroon where electricity supply is limited, we deem the proposed control mechanism appropriate in order to obtain the best level of quality of service. For this thesis, we refer to quality of service as quality of experience, which is defined in the subsequent sections.
4.2 Using Price as a Supply-level Signal

Certain devices have a high priority when it comes to energy demand. For instance, refrigerators need a specific amount of power to operate at all times during the day. The refrigerator will fail when either no power or insufficient power is supplied to it. Other devices, like lightbulbs, have the capability to function at reduced power supply. Lightbulbs operating at reduced power are distinguished by dimness. With electrified households in rural locations receiving limited supply, having some kind of control would help in matching energy supply with demand; people would be prompted to spend more money to operate devices that have a higher priority than devices that don’t have as significant of an impact. For this reason, using price as an index of electricity scarcity allows for better distribution of power to high priority and low priority devices. In this setting, implementing control using price would identify trade-offs that can be made with device consumption.

4.3 System Parameters and Performance Metrics

It is important to detail the system parameters for the system under study, which is detailed below:

1. Full Load Demand \( (Full\_load) \) – A device operating at 100% power (in W).
2. Minimum Load Demand \( (Min\_load) \) – The adjusted power demand when the full load demand cannot be satisfied. The minimum load demand for a high priority load is the same as the full load demand (in W).

   For a high priority load: \( Min\_load = Full\_load \)

   For a low priority load: \( 0 < Min\_load < Full\_load \)
3. Satisfied Load Demand \( (Sat\_load) \) – The satisfied power demand from the device (in W).
4. Unsatisfied Load Demand \( (Unsat\_load) \) – The unsatisfied power demand from the device (in W).

5. Power Wasted \( (Power\_wasted) \) – The leftover power once the devices are fully satisfied and the energy storage is full (in W).

6. Daily Weather \( (Weather) \) – The type of weather, the amount of sunshine received, experienced throughout the day (in float).

7. Local Energy Price \( (Energy\_price) \) – A variable in the system that specifies the price as an index of electricity scarcity (in dollars per Wm).

The performance metrics, the measurements of performance of the nanogrid under the study, are described below:

1. Quality of Experience \( (QoE) \) – Denotes the percentage of power consumption the devices are operating at. It is calculated from the following:

\[
QoE = \frac{Sat\_load}{Full\_load} \times 100
\]

2. Energy Utilization – The amount of energy used throughout the whole day given the amount of energy received during that day. It is important to note that the battery size of the system gives us a deeper insight into energy utilization, which is covered in the experiments chapter. Energy utilization is dependent on the type of season; the less solar energy received throughout the season, the lower the overall energy utilization would be in order to prevent a blackout from occurring given the battery size. It is measured below:

\[
\text{Energy Utilization} = \frac{\text{Energy consumed for the whole day (in Wh)}}{\text{Solar energy received for the whole day (in Wh)}} \times 100
\]

3. Loss of Power – This occurs when there is an unsatisfied power demand from the high priority load at any given time during the day. This is noted as a blackout occurrence.
4.4 Design of Supply-level Price Signaling

When considering price signaling to mediate and control power consumption, it is important to detail the supply side of power distribution. Figure 4.1 displays the function view of a nanogrid with IoT based price signaling for demand control, where the controller and the devices are located within the residence. The four algorithms run within the price signal component, which is incorporated within the nanogrid controller and communicates to the devices about price.

![Diagram of a nanogrid with IoT based price signaling for demand control](image)

The energy price is calculated at each algorithm, wherein the algorithms run in the nanogrid controller itself. The controller gets input from the battery level, battery charge and discharge rate, the time of day and weather forecast. From these inputs the algorithm starts from setting the current energy price based on the current battery level threshold. From there, it sets the energy price, then passes the energy price to the next algorithm that takes into account the charge and discharge rate between the solar panels charging the battery and the devices discharging the battery and alters the energy price accordingly. The same process is followed for the algorithms setting the energy price based on time of day and the next day’s weather forecast. Once the final energy price gets calculated, it is communicated to the devices.
The first algorithm looks at the current battery level threshold and shown in figure 4.2. The constants HIGH_THREASH and LOW_THREASH represent the parameters for getting the battery level thresholds. MAX_PRICE and MIN_PRICE are determined by the local power price value, and the variables battery_charge and energy_price represent the current battery charge level and the calculated energy price, respectively. The variable adj_eng represents the modified energy price when the battery level is in between the low threshold and high threshold, and is calculated used the following formula:

\[
adj_{\text{eng}} = \text{MIN\_PRICE} + \frac{(\text{MAX\_PRICE} - \text{MIN\_PRICE}) \times (\text{battery\_charge} - \text{LOW\_THRESH})}{\text{HIGH\_THRESH} - \text{LOW\_THRESH}}
\]

<table>
<thead>
<tr>
<th>Algorithm for setting energy price based on battery level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constants:</strong></td>
</tr>
<tr>
<td>HIGH_THREASH //High battery charge level threshold (percentage of charge)</td>
</tr>
<tr>
<td>LOW_THREASH //Low battery charge level threshold (percentage of charge)</td>
</tr>
<tr>
<td>MAX_PRICE //Maximum energy price (dollars per Wm)</td>
</tr>
<tr>
<td>MIN_PRICE //Minimum energy price (dollars per Wm)</td>
</tr>
<tr>
<td><strong>Variables:</strong></td>
</tr>
<tr>
<td>battery_charge //Current battery charge level (percentage)</td>
</tr>
<tr>
<td>energy_price //Energy price (dollars per Wm)</td>
</tr>
<tr>
<td>adj_eng //Adjusted energy price (dollars per Wm)</td>
</tr>
<tr>
<td><strong>do forever</strong></td>
</tr>
<tr>
<td>for (every minute)</td>
</tr>
<tr>
<td>if (battery_charge &gt; HIGH_THREASH)</td>
</tr>
<tr>
<td>energy_price = MIN_PRICE</td>
</tr>
<tr>
<td>else if (battery_charge &lt; LOW_THREASH)</td>
</tr>
<tr>
<td>energy_price = MAX_PRICE</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>energy_price = adj_eng</td>
</tr>
<tr>
<td>send energy_price to charge and discharge rate algorithm</td>
</tr>
</tbody>
</table>

Figure 4.2 Algorithm for setting price based on battery level

The algorithm sets the energy price by traversing through a series of check points, based on the battery charge level. Once the energy price is determined, it gets sent to the next algorithm that updates the energy price using the charge and discharge rate values.
Once the energy price is received from the first algorithm, the second algorithm takes into account the difference between the charge rate of the solar panels providing power and the discharge rate of the devices consuming power. The three constants ADJUST_CHARGE, ADJUST_MIDDLE, and ADJUST_DISCHARGE are the adjustment factors of the energy price. The constants POSITIVE_RATE and NEGATIVE_RATE represent the thresholds for measuring the variable charge_difference. The variable charge_difference is the difference between the solar panels providing power (if any) and the devices consuming power. The energy_price variable gets updated based on the charge and discharge rate, which then gets sent to the algorithm that looks at the time of day. The algorithm can be seen in figure 4.3.

<table>
<thead>
<tr>
<th>Algorithm for setting energy price based on charge and discharge rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constants:</strong></td>
</tr>
<tr>
<td>ADJUST_CHARGE //Adjustment factor for charge difference is positive (float)</td>
</tr>
<tr>
<td>ADJUST_MIDDLE //Adjustment factor for charge difference is in between positive and negative (float)</td>
</tr>
<tr>
<td>ADJUST_DISCHARGE //Adjustment factor for charge difference is negative (float)</td>
</tr>
<tr>
<td>POSITIVE_RATE //Threshold for positive charge difference (float--a number greater than 0)</td>
</tr>
<tr>
<td>NEGATIVE_RATE //Threshold for negative charge difference (float--a number less than 0)</td>
</tr>
<tr>
<td><strong>Variables:</strong></td>
</tr>
<tr>
<td>charge_difference //Current battery charge difference (in W)</td>
</tr>
<tr>
<td>energy_price //Energy price received from battery algorithm (in dollars per Wm)</td>
</tr>
<tr>
<td><strong>do forever</strong></td>
</tr>
<tr>
<td><strong>for</strong> (every minute)</td>
</tr>
<tr>
<td><strong>if</strong> (charge_difference &gt; POSITIVE_RATE)</td>
</tr>
<tr>
<td>energy_price = energy_price * ADJUST_CHARGE</td>
</tr>
<tr>
<td><strong>else if</strong> (charge_difference &lt; NEGATIVE_RATE)</td>
</tr>
<tr>
<td>energy_price = energy_price * ADJUST_DISCHARGE</td>
</tr>
<tr>
<td><strong>else</strong></td>
</tr>
<tr>
<td>energy_price = energy_price * ADJUST_MIDDLE</td>
</tr>
<tr>
<td><strong>send</strong> energy_price to time of day algorithm</td>
</tr>
</tbody>
</table>

Figure 4.3 Algorithm for setting price based on charge and discharge rate
The third algorithm takes into account the instantaneous time of day in updating the energy price. The constants HIGH_RATE and LOW_RATE display the adjustment factor for the energy price, reserving HIGH_RATE for updating the energy price when there is no sunlight (nighttime) and LOW_RATE for updating the energy price during the daytime when sunlight is present. The constants SUN_UP and SUN_DOWN represent the time when the first appearance of the sun and the last appearance of the sun occur during the day, respectively. Like the first two algorithms, the energy price gets updated once again based on the adjustment factors for the current time during the day through the variable time_of_day, which then gets sent to the fourth algorithm. The algorithm can be seen in figure 4.4.

```
Algorithm for setting energy price based on time of day

Constants:
- HIGH_RATE //Adjustment factor for high price rate during the night (in float)
- LOW_RATE //Adjustment factor for low price rate during the day (in float)
- SUN_UP //Time between sunrise and sunset (in minutes)
- SUN_DOWN //Time between sunset and sunrise (in minutes)

Variables:
- time_of_day //Current time of day (in minutes)
- energy_price //Energy price received from charge algorithm (in dollars per Wm)

do forever
    for (every minute)
        if ((time_of_day >= SUN_UP) AND (time_of_day <= SUN_DOWN))
            energy_price = energy_price * LOW_RATE
        else if ((time_of_day < SUN_UP) OR (time_of_day > SUN_DOWN))
            energy_price = energy_price * HIGH_RATE
        send energy_price to next day weather algorithm
```

Figure 4.4 Algorithm for setting price based on time of day

The last algorithm in setting the energy price at the supply side updates the energy price by looking at the next day’s weather forecast. The constants CLOUDY_RATE and SUNNY_RATE represent the adjustment factors based on whether the next day is forecasted to be a day with mostly overcast (cloudy day) or a day with clear skies (sunny day), while the constants CLOUDY_DAY and SUNNY_DAY represent the forecasted day. The weather variable represents the weather
forecast for the next day; this variable is received from the internet through IoT, which gets sent to the nanogrid controller. The energy_price then gets calculated one last time before being sent to the devices for price signaling. The algorithm is shown in figure 4.5.

<table>
<thead>
<tr>
<th>Algorithm for setting energy price based on next day’s weather forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constants:</td>
</tr>
<tr>
<td>CLOUDY_RATE //Adjustment factor for price rate during cloudy days (in float)</td>
</tr>
<tr>
<td>SUNNY_RATE //Adjustment factor for price rate during sunny days (in float)</td>
</tr>
<tr>
<td>CLOUDY_DAY //Cloud Day (in float)</td>
</tr>
<tr>
<td>SUNNY_DAY //Sunny Day (in float)</td>
</tr>
<tr>
<td>Variables:</td>
</tr>
<tr>
<td>weather //Weather condition (float – forecast for the next day’s weather)</td>
</tr>
<tr>
<td>energy_price //Energy price received from time of day algorithm (in dollars per Win)</td>
</tr>
<tr>
<td>do forever</td>
</tr>
<tr>
<td>for (every minute)</td>
</tr>
<tr>
<td>if (weather = SUNNY_DAY)</td>
</tr>
<tr>
<td>energy_price = energy_price * SUNNY_RATE</td>
</tr>
<tr>
<td>else if (weather = CLOUDY_DAY)</td>
</tr>
<tr>
<td>energy_price = energy_price * CLOUDY_RATE</td>
</tr>
<tr>
<td>send energy_price to all devices</td>
</tr>
</tbody>
</table>

Figure 4.5 Algorithm for setting price based on next day’s weather forecast

4.5 Design of Device-level Response to Price Signaling

Once the energy price from the supply level algorithms is determined, it gets sent to the devices. From here, the devices, as smart appliances, will adjust their power consumption based on the energy price calculated from the four energy supply algorithms. For high priority loads such as the freezer, it is under the assumption that it will pay MAX_PRICE price to continuously operate at 100% power. The algorithm for this device response can be seen in figure 4.6, where the algorithm runs within the device itself. The constant MAX_EXPEND represents the maximum energy expenditure that the device can use, and the FULL_ENERGY constant represents the full power demand for the device. The variable energy_demand represents the actual amount of power the device will be consuming. The variable mod_energy represents the modified energy
expenditure when the energy demand is greater than the maximum energy price set by the user for the device, and is calculated using the following formula:

\[
\text{mod\_energy} = \frac{\text{MAX\_EXPEND}}{\text{energy\_price}}
\]

**Algorithm for setting power use at demand side in response to price signal**

**Constants:**
- MAX\_EXPEND //Maximum energy expenditure (dollars per Wm)
- FULL\_ENERGY //Full energy demand for this device (Wm)

**Variables:**
- energy\_demand //Energy demand (Wm)
- energy\_price //Energy price received from price algorithm (dollars per Wm)
- mod\_energy //Modified energy demand (in float)

**do forever**

**for** (every minute)

**if** (energy\_price < MAX\_EXPEND)

- energy\_price = FULL\_ENERGY

**else**

- energy\_price = FULL\_ENERGY * mod\_energy

**adjust** device to consume energy\_demand from battery (or other power source)

Figure 4.6 Algorithm for setting power use at demand side in response to price signal

It is to be noted that once the control mechanism, through the series of algorithms above, communicates price data to the devices, the devices will respond to the price data in the short term by reducing QoE accordingly (controlled brownout) to prevent QoE = 0 (which constitutes a blackout) from occurring in the long term, where short term represents minutes or hours and long term represents days. The control mechanism has a policy that sets key internal parameters, represented by the constants in the algorithms, that do not change; these constants are determined in an ad hoc manner, where only a human (or a future self-adjusting algorithm) changes these values. In this thesis, the constants are preset to values between 0.0 and 1.3, with the exception of the constants in the next day’s weather forecast algorithm where the constants are modified according to the season.
To get a better understanding of how the nanogrid controller communicates between the devices, figure 4.7 shows the communication between the controller and devices. The algorithms run in the controller, which determine the local price; this local price gets sent to the devices, which the devices automatically, by running an algorithm, decide how much power to use and adjust power consumption accordingly.

![Diagram](image)

**Figure 4.7 Communication between nanogrid controller and devices**

### 4.6 Use of IoT for Communications from Supply to Device

In order to implement the price-based control mechanism, the application of IoT technology is needed. Communicating information about price to the devices is what allows real-time adjustments of power to be possible. In the communication from the nanogrid controller to the devices, ZigBee technology can be used to exchange data about price. In communicating price and power data, real-time estimates of power consumption are required to make continuous proper adjustments of price. ZigBee provides this capability through the application of sensors and actuators with the use of smart meters. The sensors and actuators allow the monitoring of power consumption in smart appliances. The power consumption of these appliances gets sent to the main control center, in this case the nanogrid controller, which then get fed into the algorithms along
with the battery level storage, the charging received from the solar panels, the current time of day, and the next day weather forecast. From here, the price will be calculated then sent to the appliances; based on the price received, the devices will decide whether they fully operate, adjust their power consumption or turn off.
Chapter 5: Model of Price-Based Control Mechanism of Demand

This chapter discusses the modeling used in applying the price-based control algorithms in a standalone nanogrid system in a developing country. It describes the system under study, the assumptions about the environment and the parameters of the model. The factors, factor levels and response variables are detailed. Then, the properties of solar power are described, outlining daily weather and monthly profiles of solar radiation in different seasons. The sizing of solar panels and batteries is described.

5.1 Demand-side Simulation Model of a Typical Household in a Developing Country

The system under study consists of typical residential building found in the capital city of Yaoundé, Cameroon [49]. The household examined serves as a proxy for a rural location in Cameroon. It contains detail about the appliances that are contained in the dwelling, specifically, the power rating of the appliances and the typical hourly power consumption of the appliances. We were unable to acquire weather pattern data from the city of Yaoundé; however, the city of Douala, Cameroon [51] contains weather patterns that closely resemble the weather patterns found in Yaoundé, which is the chosen model of solar power used in this study.

5.1.1 Appliances and Load Consuming Devices

The household in the study comprises 8 load consuming devices, namely, a 170W freezer, two televisions rated at 100W and 130W, respectively, a 75W lightbulb, a 36W fluorescent lightbulb, a 115W fan, a 2W Telephone charger and a 60W laptop charger [50].
5.1.2 Power Use by Time-of-Day

The power consumption of appliances varies throughout different times of the day. Loads like the freezer, require continuous power use throughout the day. Other loads, like lightbulbs and televisions, operate at different times throughout the day. Figure 5.1 displays the power use of a typical household experienced throughout the day (12am to 11pm) [50].

There are certain assumptions that are made in the system under study with respect to the power consumption of the devices in response to the price-based control algorithms. High priority loads, function at either 100% power or 0% power, and need continuous power throughout the day. Low priority loads, like lightbulbs, can be curtailed, capable of functioning at less than 10% power; in this case, the lightbulbs would be dimmed due to the reduction in power; take note: the fluorescent light only needs 2W to operate, thus we deemed it appropriate to function at either 100% power or 0% power. Table 5.1 details the power consumption of the devices, identifying the curtailable devices.

![Figure 5.1 Power use by time of day for typical household](image)
Table 5.1 Power specification of devices under study

<table>
<thead>
<tr>
<th>Device</th>
<th>Power rating (W)</th>
<th>Duration of use throughout the day (hrs)</th>
<th>Curtailable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezer</td>
<td>170W</td>
<td>24</td>
<td>No</td>
</tr>
<tr>
<td>Television</td>
<td>100W</td>
<td>6</td>
<td>Yes – 100%, 90% or 0% power</td>
</tr>
<tr>
<td>Television</td>
<td>130W</td>
<td>5</td>
<td>Yes - 100%, 90% or 0% power</td>
</tr>
<tr>
<td>Lightbulb</td>
<td>75W</td>
<td>6</td>
<td>Yes - 100%, 75%, 50% or 0% power</td>
</tr>
<tr>
<td>Laptop</td>
<td>60W</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>Telephone charger</td>
<td>2W</td>
<td>7</td>
<td>Yes – 100%, 75% or 0% power</td>
</tr>
<tr>
<td>Fan</td>
<td>115W</td>
<td>9</td>
<td>No</td>
</tr>
<tr>
<td>Fluorescent lightbulb</td>
<td>36W</td>
<td>1</td>
<td>No</td>
</tr>
</tbody>
</table>

5.1.3 Model of Solar Power

The solar power of any given location varies greatly and is dependent on factors such as the time of day, the type of weather, and the season of the year. In general, the amount of solar energy increases between sunrise and sunset, with the most amount of solar power received in the afternoon hours. There is no power generated during the night, when there is no presence of the sun.

5.1.3.1 Effects of Time-of-Day, Daily Weather and Time-of-Year

The amount of solar power also depends on the type of weather experienced throughout the day. In Cameroon, there are five daily cycles experienced throughout each season of the year, varying from very illuminated (sunny) days to overcast days (cloudy). In the system under study, two daily weather patterns were considered – a cloudy day and a sunny day. A cloudy day is characterized by high percentage of clouds, associated with a higher percentage of precipitation
(rain) and a decrease in solar power. A sunny day is characterized by an increase in solar power, clear skies, and very illuminated. Both types of weather can be seen in figure 5.2.

![Figure 5.2 Solar power supply as function of daily weather](image)

Different seasons experience various amounts of solar power, depending on the type and occurrence of daily weather. In this study, an “ideal” season is introduced, where the solar power of sunny days was sized accordingly in order to meet the daily load requirement for all the devices in the household to function at 100% power. The ideal season is characterized by 30 sunny days experienced throughout the month. In Douala, Cameroon, four seasons can be observed, namely, the dry season, two intermediate seasons, and the rainy season. The dry season, December-January-February, is characterized by longer sunshine duration, and less than 5 days a month of rainy (cloudy) days. The two intermediate seasons, March-April-May and October-November are characterized by a decrease in sunshine duration, and less amount of sunny days compared to the dry season. The rainy season, June-July-August-September, is characterized by less sunshine duration, a higher percentage of clouds associated with high precipitation (rain), and greater than 20 days a month of rainy days [51].
For the purposes of this study, the two intermediate seasons experienced in Douala, Cameroon were combined as one season due to the similar amount of solar power received throughout both seasons. Figure 5.3, figure 5.4, figure 5.5 and figure 5.6 display the solar power supply received throughout the four seasons.

5.2 Supply-side Simulation Model of a Typical Household in a Developing Country

In a solar powered nanogrid system, there are two methods of energy supply, namely, the energy produced by solar panels that are used throughout the day and the storage of energy in the
batteries in times when solar power is unavailable, like during nighttime or when there is no solar radiation received during the day.

5.2.1 Sizing and Cost of Solar Panels

Proper sizing of solar panels is crucial in providing the most stable and effective power generation in solar powered nanogrids. There are various factors to take into consideration when getting the appropriate solar panel size. To make things simple, we will make certain assumptions when determining the size of solar panels. It is important to take note that the sizing of solar panels

---

**Figure 5.5 Solar power supply during intermediate season**

**Figure 5.6 Solar power supply during rainy season**
in this case is intended for an off-grid system, meaning the energy demand from the devices are completely dependent upon the energy supply from both the solar panels and battery storage. Moreover, we assume that the daily electricity consumption is constant throughout the year, regardless of seasonal conditions. It’s important to consider the average peak sun hours (PSH) experienced throughout the day, with the worst case PSH used (during the season with the least amount of peak sun hours). The energy production from solar panels decrease, due a number of losses, such as energy conversion loss (conv. loss), losses due to temperature, soiling, voltage drop, and other losses [53]. The equation for solar panel sizing is as follows [53]:

\[
\text{Output} = \frac{\text{daily load consumption}}{\text{PSH} \times \text{battery efficiency} \times \text{conv. loss} \times \text{other losses}}
\]

In calculating the solar panel size given a 7.06kWh daily consumption, with 4 peak sun hours, a battery with an efficiency of 80%, a conversion loss of 98%, and other losses of 90%, we get the following solar panel size: Solar panel size = 7.06 ÷ (4 * 0.8 * .98 * 0.9), which equals a solar PV array size of 2.5kW (2,500W). Given this array size, we divide this number by the rating of a solar PV module. Standard solar panels are rated between 230W and 275W [52], so we will assume our model to be rated at 250W, which means that the total number of 250W solar PV panels we need to for prospering sizing equals the following:

Number of solar panels = 2,500W ÷ 250W = 10 solar panels

This means that we will need 10 250W solar panels to fully power a household with a 7.06kWh daily load consumption. Given the average solar panel cost in Florida to be $2.65/W [57], we calculate the cost of the off-grid system to be ($2.65/W) * 2,500W = $6,625.

5.2.2 Sizing and Cost of Batteries

In standalone grids, there are three common types of batteries used in home energy storage systems, namely, saltwater, lithium ion and lead acid batteries [54]. Lithium ion and lead acid
batteries are more common types of energy storage among the three. It has been found that lithium ion batteries have higher efficiency, longer lifetimes, and lower costs over a longer period of time [55], [56]. However, lead acid batteries are more common in off-grid systems due to initial lower cost and reliability [54]; for this reason, lead acid batteries were sized in the system under study. In this study, we consider lead acid batteries in the sizing and cost of the battery storage in the nanogrid system due to the generally high costs associated with purchasing batteries. When sizing a battery for an off-grid system, certain things need to be taken into account, which include the battery efficiency, the number of black days (overcast days), the efficiency of the inverter and the depth of discharge [59]. The equation for proper battery sizing is as follows:

\[
\text{Battery bank} = \frac{\text{black days} \times \text{daily load consumption}}{\text{battery efficiency} \times \text{depth of discharge} \times \text{inverter efficiency}}
\]

With 4 black days, a daily load consumption of 7.06kWh, a battery efficiency of 80%, a depth of discharge of 80%, and an inverter efficiency of 90%, we yield a battery size of approximately 49 kWh. For the sizing of the battery based on the calculated 49kWh, we will assume the battery has a 100% efficiency and depth of discharge rating. In order to meet the 49kWh battery size, 4 500Ah 24V lead acid batteries need to be purchased. Each set of batteries cost about $1,800 [58], giving us a total of $1,800 \times 4 = $7,200 in cost for battery storage.

In addition to the initial cost of the batteries, the lifespan and operational costs need to be taken into consideration. The average lifetime for typical solar batteries are 5 – 15 years, depending on the type of batteries used; there are no associated operational costs to maintain the batteries. For solar panels, the average lifespan is about 25 to 30 years; the operational costs of solar panels include the upkeeping of solar panels. For a 2.5kW solar PV system, we calculate the costs to be approximately $600.
It is assumed that the government, in an effort to increase the country’s electrification rate and boost the economy, would carry the costs for the solar panels and battery storage in order to meet the needs of households in remote locations. It should be noted that batteries make up a large amount of the expenses when designing a grid system. The price-based control algorithm aims to show that by its implementation, the battery size can be reduced, allowing huge savings.

### 5.3 Model of Price-Based Control Mechanism of Demand

Figure 5.7 displays the model of the implemented price-based control mechanism in a nanogrid system in a household in a developing country. The series of control algorithms within the nanogrid controller provide real-time energy price based on the available energy supply, the minimum and maximum price, the charge and discharge rate of the devices with respect to the solar panels, the certain time of day, and the next day weather forecast. With this real-time energy price, the nanogrid controller sends the information to the devices, where the devices, based on user preference, consume 100% power when the price is low, curtail their power if the price is within a certain threshold, or shut off their power if the price is too high. It is important to note that for the system under study, the freezer (high priority load) is essentially paying the maximum calculated price to keep food storage at optimum. This behavior is due to the effects of the freezer compared to the other devices; the effects of shutting off the freezer power is more detrimental versus temporarily shutting off the power of the other devices.
Figure 5.7 A nanogrid with price-based control mechanism in a household
Chapter 6: Simulation Experiments for Price-Based Control Mechanism of Demand

Chapter 6 details the simulation model used in implementing the price-based control mechanism driven nanogrid in a household in a developing country. The assumptions and formulas of the model are discussed, along with the design of the experiments and results from the experiments.

6.1 Developing the Simulation Model

A simulation model is built, formed from the system under study, to run and analyze results on the performance of a nanogrid system with and without the implementation of the control mechanism. As indicated earlier in table 5.1, the system under study comprises one 170W freezer, two televisions with power ratings of 100W and 130W, one 75W LED lightbulb, one 36W fluorescent lightbulb, a 115W fan, a 2W telephone charger, and a 60W laptop. 10 250W solar panels serve as the power source and 4 500Ah 24V lead-acid batteries serve as the energy storage in the nanogrid.

6.2 Design of Experiments

In order to evaluate the performance of the proposed control mechanism and apply it, it is imperative to detail the factors and factor levels. The factors include the control mechanism, the type of season, the battery size, the battery level threshold, the charge and discharge rate of the devices, the charge and discharge rate threshold, the time of day, and the next day weather forecast. The factors and factor levels are detailed below:
• Control Mechanism: Specifies whether the nanogrid system is implemented with the price-based control mechanism or not. This factor has two levels – yes and no.
• Type of Season: Defines the type of season experienced throughout the year. There are four levels for this – ideal, dry, intermediate, and rainy.
• Battery Size: Defines that battery size the nanogrid system has. The two battery sizes are fixed according to two factor levels – 1x and 2x. It is important to note that the specific battery sizes were calculated based on only the number of black days the nanogrid system would need to supply energy; more specifically, the black days for the city of Yaoundé, Cameroon was considered [59]. 2x represents 4.57 black days and 1x represents 2.29 black days. Moreover, all fixed battery sizes start at 100% battery level at the start of the season.
• Battery Level Threshold: Defines the battery charge level, which is composed of two levels – low threshold battery level and high threshold battery level.
• Charge and Discharge Rate Threshold: Specifies the charge difference which encompasses the solar panels providing power (charging) versus the devices using power (discharging). The thresholds have two levels, namely, the negative rate and the positive rate.
• Charge and Discharge Rate Adjustment Threshold: Specifies the adjustment made based on the charge and discharge rate threshold. This consists of three levels – low rate, medium rate, and high rate.
• Time of Day: Specifies the adjustment factor based on the time of day, containing two factors, namely, morning and evening.
• Next Day Weather Forecast: Defines the adjustment factor based on the next day’s weather. There are two levels – sunny rate and cloudy rate. The two levels are adjusted by the user based on the type of season.
As covered earlier, the constants (factors) are preset to certain values, with the exception of the next day’s weather forecast which is changed (by the user) during different seasons. The values were generated from simple experiments, which consists of setting all the factors to a small range of set values (0.0 to 1.3), then altering the next day’s weather factor to achieve an instance of no blackouts for each season. The values for the adjustment factors are as follows:

- Battery level adjustment factor – low = minimum price, medium = adjusted price, high = maximum price
- Charge and discharge rate adjustment factor – low = 0.4, medium = 0.7, high = 1.0
- Time of day adjustment factor – morning = 0.4, evening = 0.9
- Next day’s weather adjustment factor – Ideal season: cloudy rate = 0.15, sunny rate = 0.1. Dry season: cloudy rate = 0.22, sunny rate = 0.21. Intermediate season: cloudy rate = 0.35, sunny rate = 0.3. Rainy season: cloudy rate = 1.3, sunny rate = 0.78

6.2.1 Battery Sizing Experiment

In this experiment, we examine the behavior of the system based on the battery size. The energy utilization, quality of experience, loss of power (blackout) and total energy wasted (kWh) are observed, for two battery sizes, namely, 1x and 2x. The battery sizing experiment allows us to evaluate and compare the performance of the nanogrid system with and without the control mechanism. Table 6.1 summarizes the testing performed for the battery sizes in the rainy season for the uncontrolled and controlled nanogrid.

6.2.2 Season Effects Experiment

This experiment has been tested to examine the system over 1 month (30 days) for four different types of seasons. The energy utilization, quality of experience, loss of power (blackout) and total energy wasted (kWh) are observed for the ideal season, dry season, intermediate season
and rainy season. It is to be noted that the ideal season is characterized by sunny days every day of the month, which means that the devices will always operate at 100% power because the electricity supply matches the demand. Table 6.2 details the effects of the different seasons used for testing in the system.

Table 6.1 Battery sizing for rainy season

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery Size (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Rainy</td>
<td>2x</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Rainy</td>
<td>2x</td>
</tr>
</tbody>
</table>

Table 6.2 Season effects for ideal, dry, intermediate and rainy season

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Ideal</td>
<td>1x</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Ideal</td>
<td>1x</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Dry</td>
<td>1x</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Dry</td>
<td>1x</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>Intermediate</td>
<td>1x</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Intermediate</td>
<td>1x</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
</tr>
</tbody>
</table>
6.3 Results from Experiments

In this section, we measure the performance of the system based on the performance metrics previously outlined. We present the results from energy utilization, QoE with battery level, and the occurrence of blackouts.

6.3.1 Energy Utilization

Table 6.3 summarizes the energy utilization of the system based on battery size. For the battery sizing experiment, the energy utilization for the nanogrid without control is higher compared to the nanogrid with the control mechanism enabled. Table 6.4 displays the energy utilization of the system based on the different seasons. We observe that the energy utilization for the nanogrid without control is higher compared to the nanogrid with control for the dry season, intermediate season and rainy season.

<table>
<thead>
<tr>
<th>Table 6.3 Energy utilization from battery sizing experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment number</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
Table 6.4 Energy utilization from season effects experiment

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
<th>Energy Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Ideal</td>
<td>1x</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Ideal</td>
<td>1x</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Dry</td>
<td>1x</td>
<td>98%</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Dry</td>
<td>1x</td>
<td>96%</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>Intermediate</td>
<td>1x</td>
<td>92%</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Intermediate</td>
<td>1x</td>
<td>88%</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
<td>91%</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
<td>89%</td>
</tr>
</tbody>
</table>

6.3.2 Quality of Experience (QoE) and Battery Level

Table 6.5 summarizes the QoE from the battery sizing experiment. We see that the QoE for the battery size in the nanogrid without control is significantly lower than the nanogrid with control, with a reduction of 51% and 37% with battery sizes of 1x and 2x, respectively. Moreover, we note that the QoE with the control mechanism enabled has a difference of only 3% with the two battery sizes; it can be argued that the same QoE with both battery sizes can be achieved.

Table 6.6 displays the QoE from the season effects experiment. We observe that the QoE for the intermediate and rainy seasons are greatly lower in the nanogrid without control versus with control, with differences of 40% in the intermediate season and 51% in the rainy season.

Figure 6.1, figure 6.2, figure 6.3 and figure 6.4 show the results from the battery sizing experiment that compares the QoE and battery level in the rainy season. It can be observed that the QoE in the nanogrid without control becomes zero after 3 days and 8 days for battery sizes of
1x and 2x, respectively; this is due to the loss of power experienced on those days. For the nanogrid with control, the QoE remains at a relatively steady state through the season without a blackout occurring at any time for both the battery sizes.

Table 6.5 QoE from battery sizing experiment

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
<th>Quality of Experience (QoE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
<td>61%</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Rainy</td>
<td>2x</td>
<td>27%</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Rainy</td>
<td>2x</td>
<td>64%</td>
</tr>
</tbody>
</table>

Table 6.6 QoE from season effects experiment

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
<th>Quality of Experience (QoE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Ideal</td>
<td>1x</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Ideal</td>
<td>1x</td>
<td>100%</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Dry</td>
<td>1x</td>
<td>90%</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Dry</td>
<td>1x</td>
<td>90%</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>Intermediate</td>
<td>1x</td>
<td>40%</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Intermediate</td>
<td>1x</td>
<td>80%</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
<td>10%</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
<td>61%</td>
</tr>
</tbody>
</table>
We observe in figure 6.5, figure 6.6, figure 6.7 and figure 6.8 the effects of the different seasons showing the effective control of devices in the nanogrid with control compared to the nanogrid without control. In the nanogrid with control, the QoE and battery level never hits 0% for both the dry and intermediate season, versus the nanogrid without control that has a QoE of 0% whenever the battery level hits 0% for the day.

6.3.3 Occurrence of Blackouts

Table 6.7 summarizes the occurrence of blackouts with respect to the battery sizing experiment for the rainy reason, which is over a period of 30 days. It is noted that we identify the rainy season as the worst case scenario due to the least amount of solar power received for the month. We observe no occurrence of blackouts for the nanogrid with control.

Table 6.8 displays the occurrence of blackouts with respect to the season effects experiment for the four different seasons. For the nanogrid with control, a blackout occurrence of 0 days for all four seasons is achieved. The nanogrid without control experiences a blackout for the dry, intermediate and rainy season.

6.3.4 Discussion of Results

The results from the experiments gives us an understanding of how the nanogrid performs in different settings. It can be observed that the nanogrid system performs differently between the nanogrid with the control mechanism and the nanogrid without the control mechanism. As outlined previously, the battery size has an effect on the energy utilization given the type of season. In analyzing the energy utilization, the nanogrid with the control mechanism implemented has a slightly lower energy utilization compared to the nanogrid without control. This is due to goal of the control mechanism to save up enough electricity supply in order to always satisfy the minimum
load (the load requirement from the freezer); this is to prevent a blackout from occurring at any time during the whole day given the battery size.

Figure 6.1 Results of QoE and battery level with battery size = 1x – Uncontrolled nanogrid

Figure 6.2 Results of QoE and battery level with battery size = 1x – Controlled nanogrid
It is seen that the nanogrid without control exhibits a lower QoE than the nanogrid with control for the intermediate and rainy seasons. For an uncontrolled nanogrid, the QoE is either at
100% (all devices powering at full load demand) or 0% (unsatisfied load demand from the freezer) for any given day; the uncontrolled nanogrid never saves energy to store for overcast days. For a

![Graph](image)

**Figure 6.5** Results of QoE and battery level during dry season – Uncontrolled nanogrid

![Graph](image)

**Figure 6.6** Results of QoE and battery level during dry season – Controlled nanogrid
controlled nanogrid, the QoE never goes below 58% for any given day; the load requirement from the freezer will always be satisfied, and the other devices will lower their power consumption as
the local price increases in response to power scarcity index. The nanogrid with control looks at a series of factors that help determine whether energy should be stored up for the next day.

Table 6.7 Blackout occurrence from battery sizing experiment

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
<th>Blackout (out of 30 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
<td>27</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Rainy</td>
<td>2x</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Rainy</td>
<td>2x</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.8 Blackout occurrence from season effects experiment

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Control Mechanism</th>
<th>Season</th>
<th>Battery size (fixed)</th>
<th>Blackout (out of 30 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Ideal</td>
<td>1x</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Ideal</td>
<td>1x</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Dry</td>
<td>1x</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Dry</td>
<td>1x</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>Intermediate</td>
<td>1x</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>Intermediate</td>
<td>1x</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>Rainy</td>
<td>1x</td>
<td>27</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>Rainy</td>
<td>1x</td>
<td>0</td>
</tr>
</tbody>
</table>

It is to be noted that the QoE for the nanogrid with control is roughly the same with different battery sizes without comprising the occurrence of blackouts. We argue that because of this similar
QoE, a smaller battery size and a smaller solar panel size can be purchased, therefore allowing huge savings in spending costs associated with solar panels for energy production and batteries for energy storage. This means that in a real installation, the government, who would carry the costs in building a solar-powered grid for a rural household in a developing country with economic constraints, would be spending approximately 20% less money on these costs. Given limited electricity supply, reduction in power (brownout) is favored over complete loss of power (blackout).
Chapter 7: Conclusions and Future Research Directions

Enabling electrification plays an important role in the livelihood of people. Like Cameroon with a rural electrification rate of just 17%, other developing countries face the issue of providing dependable power to people in rural locations. For a single residence with available solar power and battery storage in a developing country, a price-based nanogrid distribution of electricity within the residence offers a potential remedy in supplying power, operating as standalone entities for producing energy to allow for better quality of life.

This thesis is focused on a price-based control mechanism for a nanogrid system. Off-grid projects were presented, analyzed and evaluated on the frequency of controlled brownouts and uncontrolled blackouts, particularly identifying if there was any kind of control mechanism implemented. The proposed control mechanism calculates energy price based on user priority with how much money they are willing to spend in order to operate their devices.

A simulation evaluation of a residence in a developing country implementing the proposed method was presented, showing results that with incorporating a price-based control mechanism, there was a 100% reduction in the occurrence of complete power outage (blackouts) during all three types of seasons experienced throughout the year. The proposed price-based control mechanism shows great potential in reducing the occurrence of blackouts and can be effective in mediating energy supply with demand given a limited power supply. Moreover, with the implementation of the control mechanism, the battery size, which comprises a huge part of the costs associated with off-grid systems, can be reduced in order to meet similar quality of service,
and the smaller battery size still achieved 100% reduction in the occurrence of blackouts. The QoE decreased without the control mechanism for the intermediate and rainy seasons, with a 25% and 40% reduction in QoE with battery sizes 2x and 1x in the intermediate season, respectively, and a 37% and 51% reduction in QoE with battery sizes 2x and 1x in the rainy season, respectively. An increase in the QoE without the control mechanism occurred during the dry season, with a 1% increase in QoE with a battery size of 2x; this decrease is due to the goal of preventing blackouts using the control mechanism.

With the proposed control mechanism, a trade-off occurs from the reduced power consumption from the loads (brownouts) throughout the day compared to power outages (blackouts) occurring. Given the technical and economical constraints of a standalone system in a developing country, we argue that the occurrence of brownouts is favored over the occurrence of blackouts.

Future research directions include:

- Testing the price-base control mechanism in real-time and studying the results.
- Can a price-based nanogrid for a solar fueled residence self-tune its internal parameters to provide optimal performance across all seasons of a year?
- How do shiftable loads affect power consumption and energy price?
- How can multiple residences share power between nanogrid systems?
- How does increasing the time period between updates to price affect price oscillation, QoE, and the occurrence of blackouts?
References


