Organically Grown Microgrids: the Development and Simulation of a Solar Home System-based Microgrid

by

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Abstract

The United Nations has declared 2012 the “International Year of Sustainable Energy for All”. A substantial portion of the world’s population (some 1.3 billion people) currently live without electricity and development efforts to reach them are progressing relatively slowly. This thesis follows the development of a technology which can enable community owned and operated microgrids to emerge based solely on the local supply and demand of that community.

Although this thesis ends with the technical analysis of a DC/DC converter, there is a significant amount of background to cover in order to properly understand the context in which it will be used.

After providing an introduction into typical rural electrification efforts and pointing out some of the shortcomings of these projects, this thesis introduces some cutting edge efforts which combine solar home system technology with cellular technology and discusses the benefits of such a marriage of technology.

Next, the research proposes some tweaks to this novel technology and provides a high-level economic demonstration of the spread of solar home systems in a community based on these modifications. It then takes this concept even further and proposes the addition of a DC/DC converter which could turn these individual solar home systems into a proper microgrid.

This thesis elaborates on the development process of simulating such a microgrid in PSCAD, including the individual components of a solar home system and the specific task of designing the converter which would form the backbone of the proposed microgrid. The final simulations and analyses demonstrate a microgrid that is both technically and economically feasible for developing world applications.

Acknowledgements

Developing this concept has been a dream of mine for a number of years. I could not have gotten this far without the constant backdrop of support I have received along the journey.

Words cannot express the appreciation I would like to extend to Dr. Mehrdad Kazerani. I would like to thank him for seeing potential in this dream and his huge help in completing this research. It has been wonderful to draw on his knowledge and working with him has very much been a pleasure.

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Carla, the love of my life, thank you for encouraging and enabling me to pursue this dream, I wouldn't have got here without you! You are an incredible blessing to me, our kids, and so many others!

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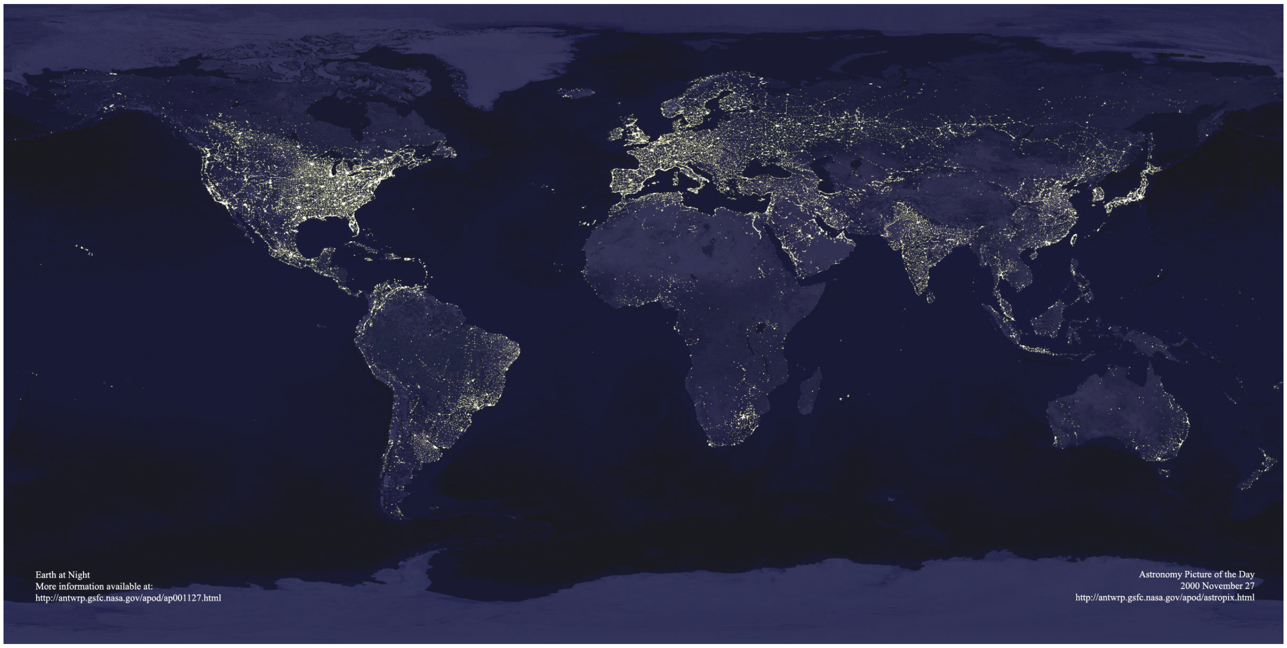
And to the Almighty, for guiding me along, every step of the way.

Dedication

This research is dedicated to those who will benefit from having electricity.



“Earth at Night” photo credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/NGDC, DMSP Digital Archive. `http://apod.nasa.gov/apod/image/0011/earthlights2_dmsp_big.jpg`

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Chapter 1

Introduction

This year, 2012, is the International Year of Sustainable Energy for All [1]. In his vision statement for the year, [2], Secretary General Ban Ki-moon, outlines the incredible benefits of electricity. He also laments the vast numbers of people who still do not have electricity. He outlines how providing electricity is foundational to achieving many of the Millennium Development Goals, even though electricity itself is not mentioned. But whether it is providing decent employment for young people, achieving primary education for all children, or reducing CO_2 emissions, electricity can be found at the core of many of the goals.

Unfortunately, current attempts at reaching the 1.3 billion people [2] who currently live without electricity are progressing very slowly. The main challenges of extending the electrical grid to without electricity (mainly in Africa and south-east Asia) are summarized in the International Energy Agency's 2010 report.

> "Rural electrification is defined here as the process by which access to electricity is provided to households or villages located in the isolated or remote areas of a country. Remote or rural regions lacking electricity supply are often characterised by well identified challenges. They may lie at a reasonable distance from national or regional electricity grids (remote villages in the Amazon), may be difficult to access (far from urban centres with a difficult terrain such as large rivers or jungles), or may suffer harsh climatic conditions that render electrification through grid extension a perilous task. Rural communities are also often highly dispersed with a low population density and characterized by a low level of education, low load density generally concentrated at evening peak hours, and low revenues. Adding to these challenges, the rural poor without access to electricity either spend relatively large amounts of their scarce

> financial resources on energy, or a disproportionate amount of time collecting firewood."[3]

The Secretary General expands on these challenges in his vision statement by listing a number of barriers that need to be overcome [2]:

1. Path dependence where existing policies favour status quo solutions.
2. Financial obstacles caused by high initial costs of clean energy technologies.
3. Pricing policies that diminish returns on capital and impede private investment.
4. Business models that worked well for establishing national grids but are not applicable in rural areas.

This research covers the existing attempts at rural electrification in the developing world. Then, by working with the ideas present in a few of these attempts, it provides economic and technical demonstrations of how a community-based microgrid made up of individual solar home systems can emerge and function. This microgrid grows without needing to follow the whims and financial abilities of entities outside the community. This research presents a disruptive technology that, in this author's opinion, addresses the barriers to rural electrification in a way that no current technology or business model is able to match.

Chapter 2 provides some background to the various topics needed to cover this subject. First, it reviews the components required for a solar home system. Then, it reviews some of the vast literature surrounding rural electrification efforts and attempts to demonstrate that most endeavours fall far short of their goals.

Chapter 3 highlights a number of very recent projects that, in this author's opinion, are steps in the right direction. The chapter then discusses some of their shortcomings and suggests how the technology could be tweaked to better meet the goals of rural electrification. This is followed with an economic demonstration of this modified technology. It shows how rural electrification could occur, based solely on funds from within the community already being spent on kerosene. The chapter then presents another addition to the technology which turns the standalone solar home systems that grew out of the economic simulation into a full-fledge microgrid. The chapter ends with a brief survey of current research and technology that may prove applicable to this additional technology.

Chapter 4 guides the reader through the technical design of a microgrid based on multiple solar home systems, i.e. a solar neighbourhood. It covers the development of the component models needed to simulate a solar home system as well as the development of the novel technology required to connect the solar home systems into a microgrid.

Chapter 5 analyses the technical results that came from simulating this community based solar neighbourhood. It demonstrates that such a technology is both technically and economically feasible.

Finally, Chapter 6 provides some conclusions to this research. Acknowledging that this work is a first attempt at a paradigm shift for rural electrification, it also reviews some the future work that should be undertaken in developing these concepts further.

Chapter 2

Background and Literature Review

This chapter provides an overview of the components required for off-grid electrical systems, as well as a literature review of how these components are put to work in typical projects in the developing world.

2.1 Components of Standalone Electrical Systems

Before launching into the more interesting discussion of rural electrification efforts in the field, it is important to understand the basic elements that are used in solar home system (SHS) projects. Although there are other sources of electricity, such as wind or diesel generator, solar is by far the most popular because it is clean, easy to install, and relatively maintenance free.

2.1.1 Photovoltaics

Solar energy comes from exploiting the energy in photons received from the sun. As the photons strike a surface they can pass their energy to electrons. Photovoltaic (PV) cells are constructed such that the electrons are not easily able to return to their rest energy directly and are forced through a circuit, providing energy. These cells are strung together in series and in parallel to form a PV module. The final output of voltage and current of a typical module are displayed in figure 2.1. These curves vary greatly based on numerous factors including the type of PV technology employed, the quality of materials used, and construction techniques.

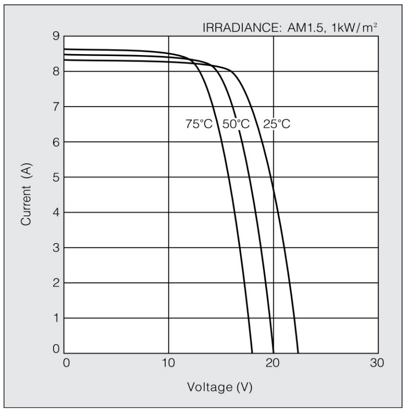

Figure 2.1: IV characteristic curves for the Kyocera KD135SC 135W Solar Module.

Fundamental to this discussion is the fact PV modules usually represent over 40% of the total cost of an SHS. Therefore, it is important to improve the efficiency and productivity of these panels as much as possible.

2.1.2 Maximum Power Point Tracker

Rather than holding its voltage constant and varying current based on the load (like a battery), both the voltage and current of a PV panel vary according to its IV characteristic curve and the load attached as per the fundamental formula $V = IR$. By inspection of figure 2.1, one can see that if the load resistance is very large the circuit will operate at a high voltage but very low current; therefore very little power will be produced. Similarly, if the load resistance is very small, the current through the circuit will be quite large but the voltage will be negligible, again resulting in very little power being produced. Almost all loads require a fixed voltage; so, a battery is used to provide a constant voltage as well as to provide power when the panel is not generating power. If the panel were connected directly to the battery, it would be forced to always operate at the battery voltage. However, the power produced at this point may not be the highest amount of power available from the panel at the given insolation and temperature.

Therefore, it is standard for all SHSs, except very small systems, to include a DC/DC converter which reflects the battery voltage as the voltage corresponding to the maximum power point at the terminals of the PV panel at an moment of time. In this way, the panel is always operating near it maximum power point.

2.1.3 Charge Controller and Battery

The requirement of a battery separates renewable standalone systems from both generator-based, standalone systems and grid connected systems. The battery is a non-linear device; among other things, the terminal voltage is affected by the ambient temperature, whether it is being charged or discharged, its state of charge and even its age. State of charge, or SoC, is a measure of the amount of energy stored in the battery usually measured as a percentage of the maximum capacity of the battery. Knowing the SoC of a battery or battery bank is crucial for charging and operating the system and keeping the battery at it optimal health. (For the overall health of the battery it is critical neither to drain it too low nor overcharge it.)

For this reason, SHSs usually include some sort of charge control monitor. This device prevents the batteries from being drained too low or overcharged. They also control the rate of charging of the battery. For example, if a battery charge is quite low, it can be charged at quite a high rate, i.e., a large current can be injected into the battery without any ill effects. As the SoC of the battery nears full, the charge control will continue charging the battery but at a slower rate. Finally, when the battery is fully charged, the charge controller will simply provide enough power to overcome the internal self-discharge of the battery. (This is shown visually in figure 2.2.) Physically, this functionality is usually incorporated into the MPPT.

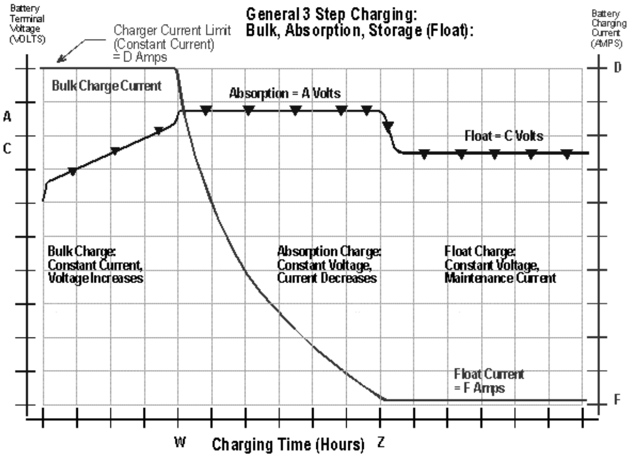

Figure 2.2: Generalized three-stage charging profile for a lead acid battery. [4]

For almost any application it is of critical importance to know how much energy remains in the system and yet it is quite difficult to measure this quantity precisely. Most systems either rely on predefined curves relating SoC to terminal voltage or simply track the amount of power flowing into and out of the battery to estimate the SoC at a given moment. The former depends on the battery type having been characterized ahead of time and the battery in use actually following the observed behaviour. The later depends on having a good understanding of the battery characteristics as well as knowing the initial SoC of the battery.

2.1.4 Load

Fundamentally, the load is the driving factor behind any power system, large or small. In SHSs, the load usually consists of lights, cell-phone chargers, possibly a radio or TV, small refrigerators, and even laptops and desktop computers. Many of these items require AC voltages and therefore an inverter, which can be considered as part of the load. It is required as well to convert 12V, DC from the battery to 120V (or 240V), AC for the load.

Each of these loads has some key characteristics that need to be known when designing the SHS. The peak power, in Watts, of the load needs to be understood as well as the times when it is used throughout the day or week. These two characteristics can be combined to give the profile of the load. For example, a 14W fluorescent lamp may be used from 5AM to 7AM and then again from 7PM to 10PM. From this data the load profile says that the system will have a 14W load from 5 to 7AM and again from 7 to 10PM. It also says that the bulb draws a total of 70WHr (14W x (2+3)Hr) from the system. When the load profiles for all the loads in a system are added together, it gives the peak load on the system as well as the total WHr requirement for the system.[1]

2.1.5 System Sizing

Understanding the total load and the load profile is the first step in designing a system. When the total WHr of the load are divided by the system voltage the result is the AHr required for the system. Continuing the example given previously, if an SHS uses two 14W bulbs each, for 5 hours every day, then the total daily load is 140WHr (2 x 14W x 5Hr). Assuming a system voltage of 12V, the system requires approximately 12AHr (140WHr / 12V) of battery storage. (For comparison, standard lead-acid battery sizes range up

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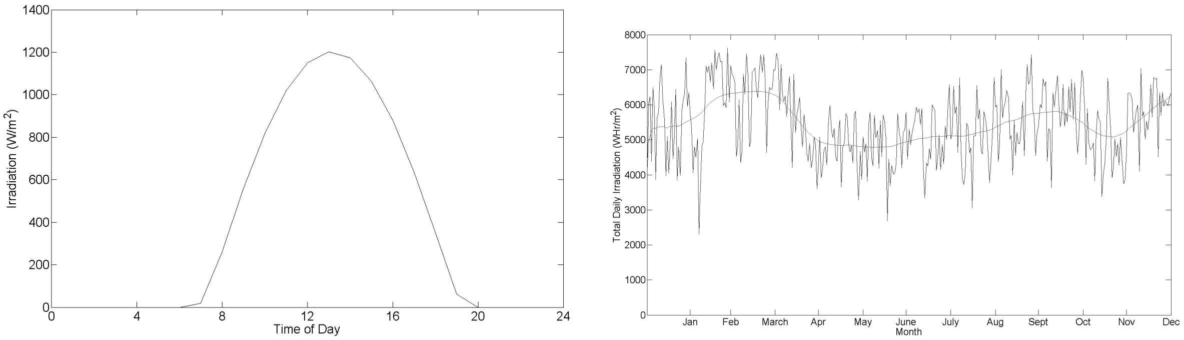
[1] The "coulomb" is the official unit of electric charge, defined as 1 Amp-second. Therefore, an Amp-Hour (AHr) is equal to 3600 coulombs. The batteries used in SHSs are usually rated in AHr and, using the system voltage, this is easily converted into Watt-Hours (WHr). In keeping up with SHS literature, this paper references "AHr" and "WHr".

to 200AHr; 12AHr is a very small battery.) In this case, a single 12V, 12AHr battery is sufficient but two 12V, 6AHr batteries wired in parallel would also work.

The final step is to calculate the amount of generation needed. For PV-based systems, this requires a good understanding of the total amount of energy available over the course of a day. This is done by recording the insolation (a measurement of the amount of irradiation) levels over the course of each day for a year or more. Sample insolation curves are shown in figure 2.3. The minimum of the annual average insolation is, in this case, roughly 5000WHr/m^2 (in May). This means that, as a worst case scenario, the area will receive the equivalent of 5 hours of sunlight at 1000W/m^2. (1000W/m^2 is a standard level of insolation at which panels are rated). Therefore, a 14W panel will produce 70WHr of energy. Since the previous example requires 140WHr, the SHS will need two 14W panels or one 28W panel.



(a) Hourly levels on March 22, 2001.

(b) Daily levels for 2001.

Figure 2.3: Insolation data for Narok, Kenya. Data from [5]

These values need to be adjusted to account for a number of factors. For example, to maintain the batteries in good health, the usable capacity of each battery is usually 50% - 80% of its rated capacity. System sizes are also often scaled up to account for very overcast days. (From figure 2.3(b), it is obvious that although the minimum average might be around 5kWHr/m^2, in reality, some days dip below 2.5kWHr/m^2.) As well, there are inefficiencies and losses in the system due to the wiring, MPPT, inverter and the battery bank. Each calculation should be scaled appropriately to account for these losses of energy resulting in a higher number of required batteries and panels. All of these factors increase the reliability of the system but also greatly increase the final cost.

In summary, the balance of system components for an SHS usually include a PV panel, an MPPT (or simple charge controller), a battery, and loads including inverters. The system is sized based on the load requirements. This often includes scaling factors to cover worst case scenarios for load requirements or generation amounts.

2.2 Current Efforts in Rural Electrification

As alluded to in the Introduction, rural electrification efforts vary significantly in their goals and complexity. This section provides the reader with a backdrop to the world of development work and electrification projects in general. The scope of development efforts dedicated to providing electricity is staggering but these schemes can generally be lumped into two categories: (i) individual systems which include solar powered flash-lights all the way up to solar home systems, and (ii) micro-grid systems which are generally much smaller versions of national grids. There is little overlap between these categories.

2.2.1 Solar Home Systems

Individual systems, such as SHSs and portable solar powered lights, are generally focused on providing lighting and supplanting kerosene as a lighting source. As the cost for PV technology has fallen, these systems have grown immensely popular in the past decade. For example, Zara Solar in Mwanza, Tanzania has sold thousands of systems to individuals around the region [6]. These very small systems use 14W panels and 25AHr to 50AHr batteries to provide about three hours of light to the homes. Similarly, Solar Energy Foundation has distributed thousands of systems in Ethiopia [7], and Kenya is a world leader in SHSs [8].

[9] typifies the efforts for standalone systems. Following the general procedure presented in 2.1.5, the author measures and estimates the various relevant parameters, such as solar insolation, battery efficiency and lifetime, load requirements, and costs. These are combined into a formula which finds the optimal, from a cost perspective, size and configuration of a system which can provide electricity for a single house.

There are literally hundreds of different organizations dedicated to providing (either in a for-profit or not-for-profit model) lighting and power in this manner. The Sirona Haiti/IEEE Rural Electricity Project [10] is another good example. This project has both a technically and economically interesting model where a central, PV-based charging station is used to charge up to forty customized batteries. (The technology also accommodates other charging mechanisms such as wind or even bicycle-based generators to charge the batteries.) The end user then brings these batteries to their house and plugs them in to provide power, mostly for lighting, in the house. The end-users each pay a monthly subscription fee for the use of the battery. The entire scheme is summarized in figure 2.4.

Figure 2.4: A diagram from the Sirona Cares literature illustrating their rural electrification project in Haiti. ©2012 Sirona Cares

The advantage of these systems is non-technical and cannot be understated; the definition of ownership and responsibility is quite clear. Subsidies aside, one person or household purchases the system; they are the ones set to benefit from the system and are the only ones affected if the system is not working. Even in the Sirona Cares model, one person is responsible for the base charging station and batteries.

The main disadvantage of these systems are the high initial capital costs. Even very small systems, which are useful only for lighting, can cost over $150 [11], an unattainable amount for the target population. Additionally, unless the systems are quite large, the size of allowable loads are limited. Thus, the final economic benefit for these systems to both the individual and to the region is difficult to measure. [12]

For these reasons, many projects opt for microgrid systems to provide electricity to multiple households or whole communities. These systems not only provide light to the recipients but also have sufficient capacity to drive other loads such as fridges, wood saws, and computers which support improved health care and economies.

2.2.2 Microgrids

Microgrids, representing the other end of the spectrum, are, in some ways, simply very scaled down versions of standard, national grids. [13] is one such example of a microgrid endeavour. Analysing a farm in Zimbabwe which is looking to get electricity, the paper uses the Homer software package to study the best combination of solar and biogas generation to service the aggregate load of the whole community. (As it turns out, the conclusion is that biogas alone, without any PV installation, would provide the most cost effective method of servicing the farm and village.) [14], [15], and [16] are other, very similar, examples of designing microgrids for villages in South Africa, Bangladesh, and Uganda, respectively. There are hundreds of other similar projects around the world from northern communities in Canada to remote communities in the Pacific Ocean. (Even in developed countries, microgrids are being touted as an economic and technical solution to many of the problems facing the current infrastructure [17].)

Unfortunately, the capital required for these projects is significant, especially for PV-based microgrids which this research focus's on;p far too much for the local communities that the projects are meant to serve. These schemes are either heavily dependent on outside donations or have unique circumstances where a local entity is able to bear the brunt of the capital and operation and maintenance costs. Since these systems serve many people, the economics of ownership are not as clear cut as with the individual systems, and so the economics required to run the microgrid is layered on top of the technical infrastructure. This means that when these efforts are successful, the results are rarely scalable or repeatable.

2.3 Critique of Current Solutions

Obviously, increasing numbers of people in the developing world *are* getting access to electricity, albeit slowly, and enjoying an improvement in their quality of life. However, many of these projects have only been “limited successes”, as they are often euphemized. The successful ones usually have very specific contexts, or were only successes in certain ways but not all (e.g., access to electricity was increased but total costs were ignored), or were temporal (e.g., the micro-grid was running successfully at the end of the project, but the report failed to include information about the project after a certain time).

Of the many papers discussing the unique challenges of rural electrification using SHSs, [18] has the best summary of why these projects tend to fail. The paper states, "...the barriers to SHS in [Papua New Guinea] are neither technical nor social, but seamlessly mangled to include technological, economic, political, and social barriers." Although the research is specific to Papua New Guinea, the lessons learned are applicable to other contexts. The lack of high-quality panels and other system components, as well as harsh environments and poor maintenance, combine to make up the technical obstacles observed. The economic obstacles are lack of access to capital for SHSs and poverty in general. The paper summarizes the political obstacles, which include poor capacity within the government, the electricity provider and aid organizations as well as interference by individuals to serve their own needs. Finally, the societal challenges boil down to a lack of understanding about SHSs.

The conclusion of [18] is that SHSs *are* a viable option for the few who can afford the systems, who understand how to maintain them, and whose electrical consumption is within reason. But for many others, there are economic, social, and technical reasons why SHSs are not a viable means to access electricity.

This is reiterated in [12] which states, "In summary, the economic case for investments in [renewable energy] is proven, provided technical problems in service provision are adequately addressed. But, the evidence base for the links between [renewable energy] and poverty remains thin. Improved evaluation tools - of the sort already adopted in some recent projects are needed to build the case that RE should be a priority for a poverty - oriented lending institution."

One final paper surveying the success of SHS projects in El-Salvador [19] demonstrates that both the NGO/donor-driven model to promote SHSs and market-driven models have shortcomings. It concludes,

> Results of a comparative analysis support several conclusions. (1) For small NGOs, the promotion of markets is appealing because of the potential for financial sustainability; yet a reliance on markets may also heighten complexity and increase opportunities for failure. (2) In implementation of market-based projects, all stakeholders, including potential consumers, private-sector service providers, and the staff of NGOs acting as project managers, will face pressures to modify and adapt their attitudes and behaviors. **(3) Alternative models for small-scale projects that integrate market-based and donor-based design features deserve consideration.**" *(Emphasis added)*

On the other hand, microgrids also have their challenges. A review of microgrid projects (such as those reported in [20] and [16]) and even full grid expansion projects (such as those reported on in [21] and [22]) provides some insight into the incredible range of challenges that these endeavours face. Significantly higher capital costs, political wrangling, increased technical complexity and complicated revenue recovery mechanisms make these projects even more untenable. [23] summarizes the challenges to include low population density which leads to high capital and operating costs, limited ability to pay leading to low demand and rates of cost recovery, and political interference. (Other reports to formally iterate these challenges include the International Energy Agency's 2010 report [3] and [24].)

2.4 Economics and Energy

It is obvious by this point that economics are one of the foundational reasons why many of these projects are un-scalable or un-sustainable. The un-scalable projects have unique situations were a local entity is able to absorb most of the cost of the project. The un-sustainable projects usually do not integrate sufficient economic feedback into the operations and as such the infrastructure ends up failing over time. Most development projects such as Solar Energy Foundation (SEF), Solar Electric Light Fund (SELF), as well as [25] and [20] all are reliant on outside donor funding. Their local economic model is not sustainable. Even the Sirona Cares project in Haiti ([10]), despite its high-level business plan at being self-sufficient, has a long way to go before it is economically viable on its own merits. The foundational assumption in all these cases is that the end users cannot afford the full cost of electricity and therefore in order to provide them with electricity it must be subsidized.

As it turns out, this is not necessarily the case. As shown in [6] and [25], the poorest people in the world tend to pay much higher rates for energy than others. So, although the daily expenditure on energy is relatively small, it represents a significant portion of these peoples budget. Moreover, this inequality is compounded by the poor quality of this energy, i.e., when used for lighting, much of the energy in kerosene is wasted as heat.

As an example, the cost of kerosene in 2010 in rural Tanzania was about 1500 Tanzanian shillings (approximately $1 per litre.[2]) When used for lighting in the ubiquitous hurricane lantern, a litre of kerosene lasts about four hours with a brightness of approximately 100 lumens, to be generous. Very roughly, this is equivalent to a 2W fluorescent bulb. Therefore, this energy is costing about 12.5¢ per WHr or $125 per kWHr (as compared to less than 20¢ /kWHr in most of North America). As a point of interest, the smallest 12V, DC fluorescent lights available are around 9W and put off over 500 lumens of light. [26]

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[2] Interestingly, the price of kerosene in the same rural town has risen to over 2300TZS, or $1.35 at the current exchange rate, as of March of 2012.

Another way of looking at this situation is from the total expenditure viewpoint. For example, if a household spends even only 20¢ to 30¢ per day on kerosene, this adds up to between $70 and $100 per year.[3] Therefore these relatively small amounts add up quickly and represent a significant portion of the cost of a small SHS, which could eliminate these costs altogether. The stumbling block is that a lump sum of even $100 is usually unattainable for these people.

This perspective was popularized by the late economist, C.K. Prahalad. He touted the viewpoint that rather than view the poor (often referred to as the "bottom of the [economic] pyramid") as in need of donations and subsidies, entrepreneurs need to view this sector as a vast, relatively untapped market of consumers and producers. [27] He encouraged companies to begin designing and marketing products specifically for this market. As people gain a new perspective on development work this viewpoint is gaining momentum [28] [29]. [4]

2.5 Chapter Summary

This chapter has reviewed the components required in PV based rural electrification schemes as well as reviewed how these components are utilized in development projects in the developing world. It also provided a basic analysis of the cost of energy for populations in the developing world. Without new technologies and business models, the majority of people who do not have access to electricity will continue to be left in the dark, spending large amounts of their income on kerosene and dirty energy.

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[3] This data was gathered in Mugumu, Tanzania in 2010.

[4] Some caution needs to be taken when presenting this perspective. Although it is attractive to conventional economic perspectives it is not without its opponents such as [30] which says, "...transforming the poor into protoconsumers of [transnational corporations] products and services cannot address the structural drivers of their circumstances and will lead to neither the eradication of poverty nor a corporate fortune at the [bottom of the pyramid]."

Chapter 3

Problem Formulation: A Solution to Bridge the Gap

Chapter 2 mentioned the plethora of rural electrification schemes that have been developed for, and implemented in, the developing world. So why are there still such a variety of options being implemented? Why do we not see one or two schemes becoming the dominant, viable solutions to this global problem? To reiterate the conclusions from Chapter 2, both categories of electrification (individual systems and microgrids) have unique advantages and disadvantages, and, in the opinion of this author, no solution exists that is able to sufficiently bridge the gap between these groups. The developing world does *not* need more of the same; rural electrification needs a “paradigm shift”.

Section 3.1 introduces a few, very recent schemes that provide some mechanisms to the overcome these hurdles.[1] But, as will be shown, even these concepts do not go far enough to truly enable the paradigm shift which will enable a scalable solution for electrical energy in the developing world. Section 3.2 recognizes the steps made by these cutting edge technologies and proposes a modified SHS which brings the technology one step closer to being a real solution for rural electrification. This is demonstrated in an economic simulation in section 3.3.

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[1] The device simulated in this research is very similar to the ones discussed in 3.1 but these concepts were developed autonomously, without knowledge of the other.

3.1 Cutting Edge Solutions

3.1.1 SimbaLink

The first project of note in rural electrification is the SimbaLink project [7]. The researchers have teamed up with Solar Energy Foundation (SEF) to develop a device which monitors panel and battery voltages of SHSs in what is otherwise a very classic and straightforward development project in rural electrification. The project was spending large amounts on operations and maintenance costs and needed a way to stay informed about the health of each SHS without sending a technician. The resulting device is installed in every SHS and has GSM (cellular) capability. It sends out regular text messages summarizing the voltage profiles for the SHS between reporting periods. In analysing this information technicians can know without visiting the location when there might be a fault in the system (such as dirty panels or a consistently under-charged battery) that is causing the system to run sub-optimally or which may lead to a component failure. The researchers have developed this Arduino-based device mainly for the purposes of monitoring the health of an SHS and offsetting the cost of regular visits by technicians to maintain the systems.

Although the paper does not explicitly discuss using mobile banking infrastructure to charge for electricity, it does mention the possibility of such a device enabling solar co-ops or allowing local entrepreneurs to sell power in their community by having the ability to turn power on and off. Unfortunately, the specifics of the device are vague in the report and the preliminary testing that is reported on is very rudimentary. Most significantly, the researchers do not mention any methodologies of distributing or sharing power between systems. This means that the maximum load must be within the capability of each individual system.

3.1.2 Private Endeavours

Currently, this author is aware of two private start-ups, Stima Systems (`www.stimasystems.com`), based out of Nairobi, Kenya and Simpa Networks (`www.simpanetworks.com`), based out of Bangalore, India, that also embed cellular phone technology into SHSs. By using hardware very similar to that presented in [7], these companies are able to provide a means for their customers to pay for electricity in micro-payments. Once approved, a customer receives an SHS installed at their residence. Then, instead of walking to town to purchase the kerosene needed for that evening's activities, the user is able to send "credit" for a certain amount of energy to the SHS by means of a text message from their cell phone.[2] The system is then enabled (turned on) until the user has used up their energy quota. The credit goes to back to the company and is used as payment against the initial capital expense of the SHS and as profit. Once the user has paid off the entire SHS, the unit is unlocked; they now own the system and all the energy is available for use.

This ingenious scheme is still in its infancy, but is poised to disrupt the developing world electrification paradigm. The business model seems solid and the potential customer base is vast.

In this author's opinion, there are a few limitations that hinder sales of these units. For one, the distribution channel all goes through the company (either Simpa Networks or Stima Systems) and this presents a bottle neck. There is no means for middle level entrepreneurs to purchase this technology outright and start profiting from it directly. As well, each system only allows for a single recipient of power. There are numerous benefits to embedding more than one output into a single system so that multiple users can be purchasing power from a single system. Although this might create ownership issues later on, when combined with enabling entrepreneurs to utilize the technology for their own benefit, having multiple outputs has some very interesting implications. This is explored more in Section 3.3.

3.1.3 Shared Solar

The final related example is presented in [25]. This research recognizes the value of providing a mechanism to enable micro-payments for electricity but starts from the microgrid perspective. These researchers from Columbia University have developed hardware that allows customers to purchase electricity in a prepaid manner via their cell phone.

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[2] It is important to keep in mind that while over one and a half billion people do not have electricity, the majority of these have their own cell phones, and the vast majority have cell phone coverage and access to a cell phone. The prevalence of cell phone technology in these emerging markets cannot be overstated. In the space of a decade, cell phones have gone from a rarity to being ubiquitous. People living in the most basic of homes, without power, will often have one cell phone or more. Cell phones in these contexts have become essential, not only for communication, but for business as well. More recent is the development of mobile banking, cellular providers offer banking services to their clients who, for a myriad of reasons, would very likely not have access to a normal bank. The providers allow users to exchange funds stored on their standard cell phone account for real currency. Most significantly, transferring these funds is as easy as a simple text message. Thus, people in the city are able to easily and securely support their family living in rural areas. The most well-known example of this is the mPesa system provided by Safaricom in Kenya. It has already begun to disrupt all sorts of businesses and is still maturing rapidly.

The researchers have assembled or developed the hardware necessary to provide electricity on a prepaid basis to 10-20 customers in a microgrid. From a central, PV-based, generation and distribution station, power is delivered via a star topology to each customer. The station is able to track power usage per customer, and thus, when a customer has used up the energy that they have paid for, their power is switched off. Customers are able to get more power by purchasing scratch cards and sending the revealed code to a central server that tracks the power usage for all the micro-grid users. Thirteen test installations are currently in place in Mali and Uganda. The electricity price has been set to be equivalent to the price of kerosene that would be required for the equivalent amount of lighting.

These installations are not only a step forward for electrification projects in terms of overcoming the economic, maintenance, and operational challenges facing SHSs, but also provide invaluable insights into how this customer base purchases and uses electricity. Unfortunately, up until now, the projects have been heavily subsidized by aid and research agencies. Although the total cost per installation is not provided, it was acknowledged that both the initial capital costs as well as the operation and maintenance costs are not currently economically viable. The paper mentions this and discusses factors that will lower these costs significantly in the future. The paper also discusses how the relatively high operational costs will be lowered by integrating the payment schemes with existing mobile money networks.

However, there is another issue with this model. Like the traditional, grid it is based on centralized generation and control. One of the challenges the paper mentions is that since all the micro-grids are controlled and monitored by a central server, cellphone network reliability has been a challenge. For example, if the network access to the central server is down, then customers are unable to purchase electricity, even if they have network access in their region. Meanwhile, the local central generation and distribution for each micro-grid creates the very high initial costs mentioned earlier.

From a reliability perspective, it also means that any problems at the central server or the micro-grid power station affect all the micro-grids or the local micro-grid. The paper does not discuss any reliability challenges, but these will probably surface with time as the equipment starts to age under fairly harsh environmental conditions. In this case, the ownership of the generation station is clearly the aid agency (similar to [16]) while each household owns its connecting line from station to house; each party knows the equipment for which they are responsible. However, in other projects, such as [20], ownership is not so clear which presents a problem in terms of paying for operation and maintenance costs. Note that none of these projects have done significant follow up to see how the operation is continuing after some time.

Another more subtle, but significant, critique of the scheme presented in [25] is that any for-profit micro-grid installations using this admittedly expensive approach almost certainly means that the revenue is leaving the community. Obviously, many successful businesses operate this way but the viability of these micro-grid schemes would be greatly increased if the initial costs could feasibly be borne by relatively wealthy individuals or co-ops within a community.

3.2 Nexus of Considerations

Table 3.1 attempts to summarize the vast body of criticisms held against each technology while highlighting the benefits each solution holds and why it might work best in a particular situation.

Table 3.1: Summary of technology survey.

	Kerosene/Status Quo	Solar Home Systems	Microgrids
Advantages	Clear ownership. Very affordable capital and daily expenses.	Clear ownership. Some access to various loads such as lights, radios, cell-phone chargers, possibly small TVs and laptops. Some economic benefits for owner.	Very broad range of economically beneficial loads such as fridges, power tools, welding, etc. Lowest long term costs.
Disadvantages	Very expensive long term costs. Limited applications (lighting and cooking). Polluting.	Somewhat inaccessible capital costs. Not applicable for high power applications.	Ownership is not clearly defined and leads to disrepair of entire system. Very high capital costs.

Thus, the ideal solution combines the very low daily costs of using kerosene with the wide range of loads (and economic benefits that go with them) of the microgrid. Starting with the technology being promoted by Simpa Networks and Stima Systems, what if these same systems were given the capability to sell power to other users? In other words, once the initial user had paid for the capital, suppose they were then able to provide electricity to their neighbour(s) and benefit economically.

3.3 Economic Demonstration

Following is a summary of an economic analysis written in Matlab to help better understand the implications of the device just described. As referred to earlier, the lack of integration between technology and economics is the reason many RE efforts have not succeeded so far. However, as demonstrated here and in Section 3.1, the emergence of mobile banking technology links these two areas.

This economic model uses a hypothetical cellular-enabled SHS, or ceSHS, with four controllable outputs to explore the possibility of how a micro-grid might grow organically based on supply and demand. The basic idea is that the owner (an agent) of a ceSHS is able to sell the electricity in their system to up to four of their neighbours (other agents) who want to purchase the energy since it is cheaper than the equivalent cost of kerosene.

The overall simulation is laid out in Figure 3.1 while the full Matlab code can be found in Appendix D. Note that the economy in the simulation *only* includes the money being spent on kerosene for lighting and assumes that households have a source of income that generally covers their needs. As the simulation progresses, each agent is driven to satisfy their daily lighting needs in the cheapest way possible.

When the simulation runs without any ceSHS (the control run), the only available lighting option is kerosene and the community continues on in the status quo. On a daily basis, most agents are able to purchase enough kerosene to cover the evenings lighting needs. Sometimes agents fall short of their needs and have less hours of lighting than they need, others end the day with a bit of surplus, but on average, agents cover their lighting needs. In this mode, the cash in the simulated community reaches a steady state and the amount of funds available neither increases nor decreases, as shown in Figure 3.2.

The focus of this preliminary economic research is on what happens when a ceSHS is inserted, or seeded, into the community. When an agent sees that their neighbour has a ceSHS, they are driven to start saving (by slightly reducing their normal kerosene consumption) for the purchase of a 11W, 12VDC, fluorescent light. After buying a light, agents are able to use the electricity from their neighbour, paying less than the equivalent amount of kerosene. At the same time, the owner of the ceSHS is earning money and is encouraged to expand on their system so that they can sell more electricity. As time goes

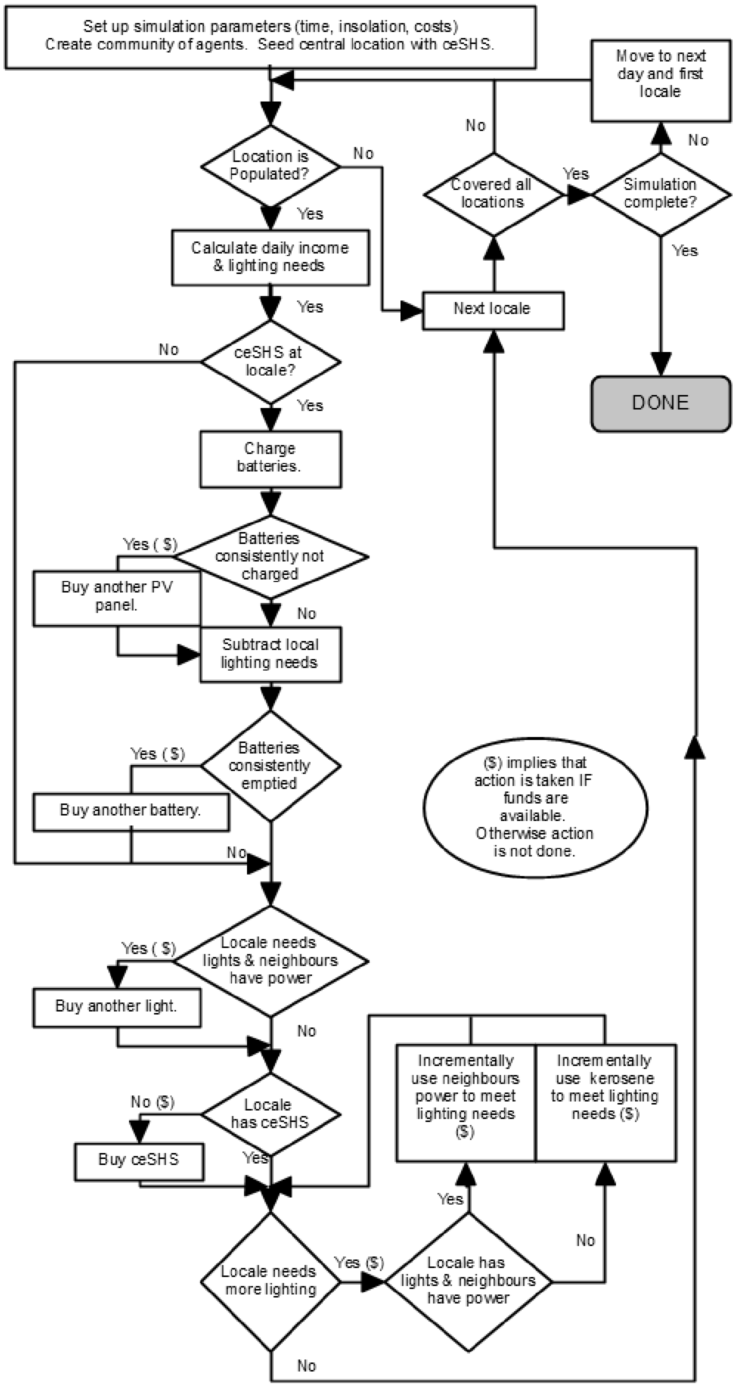
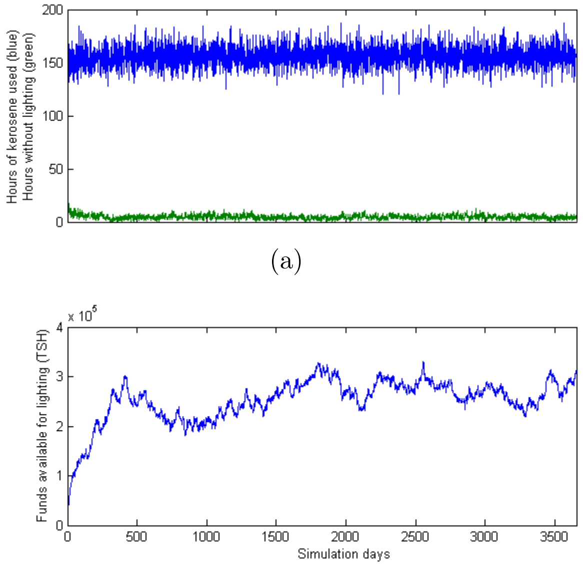


Figure 3.1: Flowchart outlining the Matlab-based economic simulation of the growth of a ceSHS-driven solar neighbourhood.



(a)

(b)

Figure 3.2: Results of running the economic simulation without any ceSHS. 3.2(a) shows the hours of kerosene being used (blue) and the total hours in the community that people are having to go without lights due to lack of funds (green). 3.2(b) shows the total cash available in the community at the end of the day.

on, the agents eventually save enough money to purchase their own ceSHS and the process repeats with *their* immediate neighbours.

After some examination of the flow chart, it is evident that each system grows into the demand around it; its size is not predetermined. The number of lights purchased is dependent on the lighting needs of the agent; they purchase lights as needed and are able. As the the number of lights increases, the battery bank ends up being continuously drained and so, assuming funds are available, more batteries are purchased. A larger battery bank implies that they may not get fully charged every day and so more panels are purchased. [3]

Running this high-level economic simulation reveals a number of interesting observations. Primarily, over time, the systems spread throughout the community as each agent takes advantage of the cheaper lighting option as it becomes available. For example, the

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[3] It is well understood that mixing batteries, and to some extent panels, of different types and ages is not ideal as the system only operates at the level of the lowest quality components. This consideration is beyond the scope of this work. However, it should be noted that in the "real world" people often implement solutions that work for them, despite the technical non-idealities.

results of running a 10-year simulation are shown in Figure 3.4.

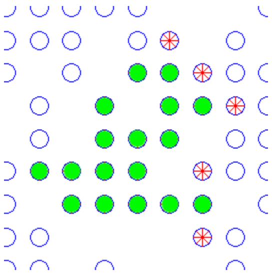
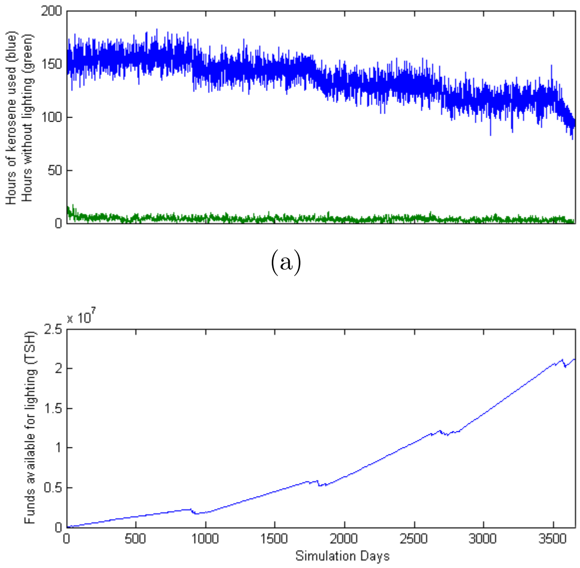


Figure 3.3: Community of ceSHSs emerging from economic simulation. Populated location = ❍, location with lights = ✳, location with full ceSHS = ●



(a)

(b)

Figure 3.4: Geographic and economic demonstration of the growth of a ceSHS-based solar neighbourhood. 3.4(a) shows the total kerosene usage in the community (blue) decreasing over time while the total time spent without light (green) holds steady. 3.4(b) shows the available total cash in the community increasing over time.

The results demonstrate a number of things. Most significantly, the agents in this simulation (representing people in the developing world) *are* able to pay for the full cost of a ceSHS given the proper mechanism to overcome the initial capital costs. Another result, not shown in these figures, is that each system is left oversized compared to its

Table 3.2: Costs of components used for economic simulation. Other parameters include insolation level 5kWHr/m^2 per day, 1,000TZS/L kerosene. *charge controller with cellular capability, see Appendix B for further details.

Item	Cost
11W fluorescent light	13,000TZS ($9)
14W PV panel	85,000TZS ($57)
26AHr battery	45,000TZS ($30)
5A ceSHS*	120,000TZS ($80)

load. The algorithms of the program drive each system to try to meet demand; if batteries run empty (high demand) and funds are available, an agent purchases more batteries and panels to meet that demand. Eventually, those agents driving demand are able to purchase their own ceSHS, needing only negligible power from their neighbours, leaving the original ceSHS with excess generation and storage.

3.4 Chapter Summary

In conclusion, this chapter has presented some emerging technologies and endeavours that can be utilized in rural electrifications efforts. By slightly modifying the hardware concepts presented in 3.1, this research demonstrates the spread of SHSs based *only* on funds already being spent within the community and without any outside support. The result of this simulation is a community of SHSs, each having overcome the initial hurdle of capital expense (except the seed system) and enjoying the benefits of cheaper lighting, power for small electronics, and reduced CO_2 emissions.

However, referring back to Table 3.1, the full technical and economic advantages of a microgrid are yet to be realized. The final step is to connect all these systems together to turn this collection of ceSHSs into an interconnected solar neighbourhood, in other words, a microgrid.

Chapter 4

Development of Power Sharing Technology

The results of the economic simulation in Chapter 3 show a populated area with numerous SHSs, each of which is economically feasible because it is able to sell electricity to adjacent neighbours. But in order to achieve the full benefits of the microgrid, the systems should be able to actively exchange power. In this way, the excess funds available in the community could be put towards income-generating devices such as power tools, welding equipment or refrigerators.

This question is interesting from an economic perspective, but, at its heart, is technical in nature. This chapter reviews the design process for creating an electrical model of a micro-grid made up of multiple, interconnected SHSs, and provides the resulting simulation tools.

4.1 Introduction to Simulation

There are a number of purposes to developing a technical model for the device and corresponding microgrid conceived in the economic simulation. The driving purpose of the simulation is to analyse the make-up and behaviour (from a power perspective) of a microgrid which has emerged out of a situation described in the economic simulation and quantify the benefits, if any, over the equivalent group of systems that would normally be required to power those same loads. A more specific purpose of the simulation is to develop a device that can enable such a micro-grid. The development and modelling of the device will help to understand the energy flows, voltage levels and currents involved in a ceSHS-based micro-grid. As such, the model should be fairly accurate from an electrical perspective.[1]

Being made up of numerous SHSs, the microgrid simulation should include models of PV panels, MPPTs and charge controllers, batteries, loads, and, of course, the power sharing device. The inputs for the model should include insolation and temperature profile data, community topography (i.e., a geographical map of the community), load profiles of the community members as well as the sizes of the battery banks and PV arrays for each site. Ideally, the model should provide the SoC profiles of each battery bank as well as information about how much (if any) of the load has not been serviced due to lack of charge in the battery bank.[2] Following is a discussion of the technical model used for each component of the SHS.

4.1.1 Photovoltaic Panel

PSCAD does not have any photovoltaic (PV) panel in its standard library of components. The authors of [31] and [32] have developed such models, but they are not available for download. Directly implementing the equations made available in [31] and [33], a PV model can be developed in PSCAD.

$$I_{panel} = I'_{SC}(1 - K_1(e^{V/K_2V'_{OC}} - 1)) \tag{4.1}$$

$$K_2 = \frac{(V'_{MAX}/V'_{OC} - 1)}{\ln(1 - I'_{MAX}/I'_{SC})} \tag{4.2}$$

$$K_1 = (1 - I'_{MAX}/I'_{SC})(e^{-V'_{MAX}/K_2V'_{OC}})) \tag{4.3}$$

where I_{panel} is the current produced by the PV panel (which is modelled as a current source), V is voltage at the panel terminals, I'_{SC}, V'_{OC}, I'_{MAX} and V'_{MAX} are modifications

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[1] There are numerous electrical simulation programs that could be used to develop a model for a bi-directional power converter, including PSCAD, PSim and Simulink (Matlab). Due to its reputation within the academic and power communities, PSCAD was chosen as the simulator of choice. However, PSCAD is most commonly used in 3-phase AC applications and so has a limited library of DC components.

[2] This last requirement provides better insight and method of comparing systems when dealing with insufficient power. For example, two systems might go without power for 3 hours because the batteries are drained. However, if one of the systems has a 200W load that does not have power, while the other only has a 5W load without power for that time, then the first system is 600WHr short of the power it needs, while the second system is only 15WHr short.

of parameters provided by the data sheet (see Equations (4.6) to (4.9)), and K_1 & K_2 are correction factors.

$$\Delta T = T - T_{ref} \tag{4.4}$$

$$\Delta S = \frac{S}{S_{ref}} - 1 \tag{4.5}$$

$$I'_{SC} = I_{SC}\frac{S}{S_{ref}}(1 + a\Delta T) \tag{4.6}$$

$$V'_{OC} = V_{OC}(1 + c\Delta T(\ln(1 + b\Delta S)) \tag{4.7}$$

$$I'_{MAX} = I_{MAX}\frac{S}{S_{ref}}(1 + a\Delta T) \tag{4.8}$$

$$V'_{MAX} = V_{MAX}(1 + c\Delta T(\ln(1 + b\Delta S)) \tag{4.9}$$

where ΔT is the difference between the actual temperature, T, and the reference temperature of the panel, T_{ref}, and ΔS is the ratio of the actual insolation, S, to the reference insolation of the panel, S_{ref}. These parameters are then used to modify the I_{SC}, V_{OC}, I_{MAX} and V_{MAX} specifications from the datasheet (which are valid only at the reference temperature and insolation) for actual temperature and insolation levels experienced by the panel. And finally, from [31], the coefficients *a, b* and *c* are 0.00055, 0.5, and 0.00288, respectively.

Eventually, a publicly available model created by A. Rajapakse from the University of Manitoba [34] replaced the in-house model created from these equations. This model is based on the double diode equivalent circuit of a PV cell and so the equations, and therefore inputs, are different. The new model needs cell specific information including the band-gap energy of the solar cell material and the diode ideality factor. The model also needs the number of cells in series and parallel per array, the approximate surface area, the series and shunt resistance for each cell, the saturation and short circuit currents, and the temperature coefficient for the photo current. Although all these values can be determined from manufacturer datasheets, they are not usually provided directly. Therefore, in order to use this model, a PV panel has to be characterized as follows.

1. Adjust the number of cells in series and parallel along with the short circuit current to achieve the panel's short circuit current.
2. Adjust the diode ideality factor to match the open circuit voltage of the panel.

3. Adjust the series and shunt resistances to fit the normal operating conditions of the panel. (Note that normal operating conditions are usually different from the reference temperature and insolation.)

The remaining values, such as surface area and band-gap energy of the cell junction, were inferred from the size of panel and properties of the PV technology used respectively.

These simulations were based on a 135W panel from Kyocera. The final parameters used for this panel are given in Appendix A.1.

4.1.2 Maximum Power Point Tracker and Charge Controller

The authors of [34] have also provided a maximum power point tracking (MPPT) module. There are a number of algorithms to find the MPP of a panel; this module uses the incremental conductance algorithm which is based on the fact that at the point of maximum power, the derivative of current and voltage (on I vs P or V vs P curves respectively) will be 0. The flowchart of the algorithm is given in Figure 4.1.

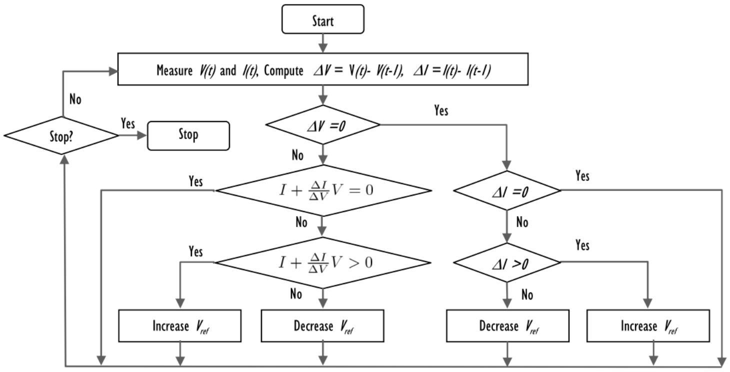
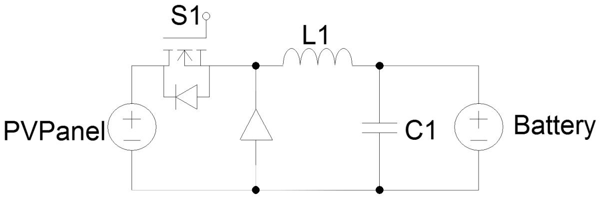


Figure 4.1: Flow chart of the incremental conductance algorithm. [35]

The MPPT module controls the duty cycle of a buck converter whose input is the voltage from the panel and whose output is the battery voltage. To keep the simulation times reasonable, the buck converter, Figure 4.2(a), operates at a frequency of 30kHz. In reality a 250W, 12V/24V, DC/DC converter would probably operate at much higher frequencies (e.g. 200-400kHz). A range of component values are shown in Table 4.2(b). At first glance these seem like very large allowances for voltage and current ripple. There are two reasons for this: (i) This keeps the size of components, and therefore the cost, down. (ii) The output of this converter connects to a battery which is not very sensitive to voltage and current ripple as compared with small electronics.



(a) Schematic of a buck converter where PVPanel > Battery.

Freq (kHz)	30	50	100	150	200	300	500
L1 (μH)	9	5.4	2.7	1.8	1.3	1	0.5
C1 (μF)	78	47	23	16	18	8	5

(b) Component sizes for a buck converter for various frequencies of operation using 20% current ripple, 10% voltage ripple, and 25% margin of safety.

Figure 4.2: Buck converter for use as an MPPT.

Recalling Section 2.1.3, the MPPT should also incorporate a charge controller. As this is to maintain the health of the battery, it is beyond the needs of this simulation. Therefore the MPPT simply incorporates on/off controls depending on the SoC of the battery, i.e. when the battery is full, the MPPT turns off.

4.1.3 Battery

PSCAD does not have any built-in model for batteries. Batteries, in general, have notoriously non-linear characteristics, but by using [36], [37], and [38], a fairly accurate battery model can be developed. The equivalent circuit of this battery is shown in Figure 4.3.

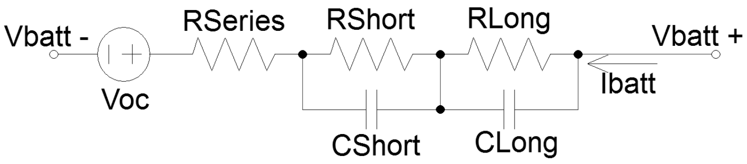


Figure 4.3: Equivalent circuit of a battery used for PSCAD simulation.

The most important piece of information to know about a battery is its state of charge (SoC). This is generally done by measuring the amount of power (or charge) going in and out of the battery to predict the SoC. The formula used to track battery model SoC is given in (4.10).

$$SoC(t) = \frac{1}{SoC_{Max}} \int \left(\frac{Eff}{3600} * V_{OC} * I_{Batt} - \frac{SelfDis}{3600} * SoC(t-1) * SoC_{Max} \right) dt + SoC_{Init} \tag{4.10}$$

where $SoC(t)$ is the state of charge of the battery at time t, SoC_{Max} is the capacity of the battery in Watt hours, Eff is the percent efficiency of the battery to store charge, V_{OC} is the open circuit voltage of the battery at its terminals, I_{Batt} is the current flowing *into* the battery, $SelfDis$ is the self discharge rate of the battery in $\%/Hr$, and SoC_{Init} is the initial charge of the battery at the start of the simulation in percent, i.e., $SoC_{Init} = 1$ represents a full battery.

Two other crucial characteristics of a battery are its open circuit voltage, V_{OC}, and series resistance, R_{Series}. These are a function of SoC and this model uses Equations (4.11) and (4.12) from [38].

$$V_{oc}[SoC(t)] = 5.429e^{-117.5SoC(t)} + 11.32 + 2.706SoC(t) - 2.04SoC^2(t) + 1.026SoC^3(t) \tag{4.11}$$

$$R_{Series}[SoC(t)] = 1.578e^{-8.527SoC(t)} + 0.7808 - 1.887SoC(t) + 2.404SoC^2(t) - 0.649SoC^3(t) \tag{4.12}$$

And finally, in order for the battery model to properly exhibit the transient behaviour of real batteries four other equations, (4.13) to (4.16), are needed for the transient RC circuits.

$$R_{Transient_{Short}}[SoC(t)] = 2.771e^{-9.079SoC(t)} + 0.22 \tag{4.13}$$

$$C_{Transient_{Short}}[SoC(t)] = -2423e^{-75.14SoC(t)} + 55 \tag{4.14}$$

$$R_{Transient_{Long}}[SoC(t)] = 2.771e^{-9.079SoC(t)} + 0.218 \tag{4.15}$$

$$C_{Transient_{Long}}[SoC(t)] = -1240e^{-9.571SoC(t)} + 3100 \tag{4.16}$$

The overall equivalent circuit is given in Figure 4.3. Parameters given by Equations (4.11) to (4.16) are for a single 12V, 1.2Ah battery (LEOCH LP12-1.2AH) as used in [38]. (These characteristics were scaled up to represent a 50AHr battery. Multiples of this were then used to make up the battery bank for each SHS.)

4.1.4 Loads

The economic simulation discussed in 3.3 utilized a semi-random population. However, this technical simulation is implemented in a network of loads and geography based on a physical location.

As a starting point, a group of buildings from Mugumu, Tanzania was selected as a typical scenario for a micro-grid. Mugumu is a relatively rural town in the Serengeti District of Tanzania. The grid only reached Mugumu in about 2004 and so it is not heavily industrialized. The group of buildings (Figure 4.4) currently has electricity and the loads in this groups of buildings represents a broad range of typical loads that are found throughout Mugumu. (Initially, the micro-grid included more buildings (to the right of the current group) but due to limitations of the PSCAD software, the total number of SHSs in the simulation had to be reduced to eight.)

Identification of building occupants drove the number and type of load for each location. Then the load profile for each location can be calculated using load profile data for each specific type of load collected during field visits to similar rural regions. (Further load information can be found in in Appendix A.2.)

4.2 Bi-directional power converter

4.2.1 Design Criteria

The very first decision when designing a converter to exchange power in this situation regards the voltage. A 120V, AC (or 240V, AC) connection medium has a number of advantages. For one, the line losses at these voltages are much less than those at lower voltages. Therefore, much smaller gauge wire (which is cheaper) can be used to cover longer distances. As well, an AC connection allows units to connect to one another, to typical loads, or even to the national grid using the same interface.

Figure 4.4: Aerial view of the town of Mugumu, Tanzania for context. The main intersection is in the lower right while the large quadrilateral group of buildings in the upper right is the town market. The buildings used for the simulation are highlighted and numbered on the left side of the image. ©2012 GeoEye, Cnes/Spot, Digital Globe, & Google

However, there are a number of problems with this convention. From a safety perspective, these AC voltage levels are dangerous and can be lethal. Since this microgrid is envisioned to be built and maintained by lay people, safety is of paramount importance.

Technically, AC voltages present some challenges as well. Without neither a central controller nor a mechanical generator (often call a prime-mover) to generate a 60Hz reference for the system, each unit needs to help control the magnitude and frequency of the voltage at the corresponding bus. As well, units need to be capable of exchanging power on a common bus. Although not insurmountable, these requirements add significant complexity to the system which in turn means higher costs. Since the target population have very low incomes, keeping total costs low is of critical importance to the success of the technology.

For these reasons, 24V, DC is a better choice of medium for exchanging power between units. The higher voltage (as compared to 12V, DC) reduces system losses and increases viable distances between units but is still low enough so as not to impose any special safety requirements. A 24V, DC standard promoted by the Emerge Alliance also provides stability and foundation to a 24V, DC protocol.[3]

Therefore, the target device for transforming a collection of SHSs into a solar neighbourhood is a bi-directional 12V/24V, DC/DC converter, assuming a battery bank voltage of 12V. The unit needs to maintain proper voltage levels on the common bus while sending and receiving power autonomously without a centralized controller.

4.2.2 Applicable Research into Bi-directional DC/DC converters

Similar converters have been described in [39], [40], and [41], but these converters are generally much more powerful and too complex, and therefore costly, for this application.

The research in [39] seems applicable to this application, specifically Section 4.2.4. Unfortunately, the converter used is a dual active bridge and much more complex and expensive than is needed in this application. As well, in analysing the system response characteristics, the authors do not consider how the converters might respond when controlling a common bus. However, the techniques developed could likely be adapted for this application based on the considerations put forth in Section 4.2.4.

[40] develops a converter for use in a similar application with SHS, but its main focus is on regulating the power supplied by the non-dispatchable PV panel. The converter is quite powerful and, again, the control scheme makes no mention of using these converters in parallel on a common bus.

The bi-directional converter described in [41] is a good fit for this application. Although this converter is designed for a very different application, its size and capabilities make it a very close match to the requirements laid out previously. Unfortunately, its application requires a large voltage conversion (400V/12.8V, DC) and as such uses a high frequency double half bridge technology which is slightly more than is required for this application. More specifically, the paper does not refer directly to the voltage stabilizing algorithm on the 400V side, implying that another source has fixed this voltage. Finally, in this application, the converters do not need to exchange power between them and so the control algorithms would need to be modified for this application.

Thus, it remains for a much more basic converter to be adapted for use in this specific application.

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[3] This 24V protocol is availabled from the Emerge Alliance at `www.emergealliance.org`. Among others, the Emerge Alliance members include OSRAM, Philips, Johnson Controls, GE and Intel.

4.2.3 Converter

A generic bi-directional buck-boost converter is shown in Figure 4.5. Close inspection will reveal that it is really an overlapping buck converter and a boost converter and so the relevant equations for each converter can be utilized in the design.

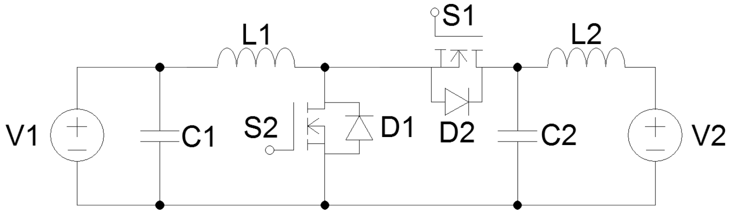

Figure 4.5: Schematic of a generic bi-directional buck-boost converter where $V1 < V2$. C1, L1, D1 and S1 form a standard buck converter. Similarly, L1, S2, D2 and C2 are the standard components of a boost converter. L2 works with C2 to form a second order filter for the boost converter.

These overlapping converters (the buck and the boost) need to be controlled together for proper operation of the entire circuit. Inspection of the schematic reveals that S1 and S2 should never be on at the same time or else the effect of the corresponding diodes will be nullified. Operating S1 at a duty cycle of $V1/V2$ and S2 with a complementary switching signal will result in no power being exchanged between V1 and V2. By *increasing* this duty ratio slightly (and simultaneously *decreasing* the duty ratio of S2), the converter operates in buck mode and transmits power from V2 to V1. Conversely, by operating S1 at a slightly *higher* duty ratio than $V1/V2$ (and adjusting the S2 duty ratio accordingly), the converter operates in boost mode, transmitting power from V1 to V2. (For each mode of operation it is possible to turn the opposing switch off entirely, but, for control purposes, this may not be desirable as will be shown later.)

The sizing of the circuit components varies based on the operating frequency and power rating of the device. Although small, for practical purposes, a power rating of 250W is sufficient for exchanging power between systems for numerous reasons. Bear in mind that 250W is the amount of power being exchanged and not a limit to the size of a load that can be used in the micro-grid. The actual loads will be powered directly off the battery bank or through an AC inverter connected to the battery bank of the SHS. The converter for sharing power is solely for equalizing SoC levels between systems and ensuring that systems that have a high charge are distributing their energy to other systems with a lower charge. A 250W 12V/24V converter needs relatively small components depending on the operating frequency as shown in Table 4.1.[4]

Table 4.1: Component sizes for a 250W bi-directional 12V/24V DC/DC buck-boost converter based on Figure 4.5 for various frequencies. Values calculated for 20% current ripple, 10% voltage ripple and 25% margin of safety.

Frequency (kHz)	30	50	100	150	200	300	500
L1 (μH)	60	36	18	12	9	6	3.6
C1 (nF)	18.1	10.9	5.4	3.6	2.7	1.8	1.1
C2 (μF)	90.4	54.3	27.1	18.1	13.6	9.0	5.4
L2 (μH)	48.6	29.2	14.6	9.7	7.3	4.9	2.9

As well, at 24V, 250W works out to produce just over 10A of current. Presumably, the micro-grid will be made up of low-cost wire and will have limitations to the amount of current it can conduct. Table 4.2 shows the voltage drops involved when using various gauge wires over various distances. Section 4.2.4 discusses how the exchange of power in the micro-grid is predicated on voltage differences between converters and so having additional voltage drops due to wire will greatly affect the efficiency of the micro-grid.

Table 4.2: Percentage voltage drop for various gauge wires and distances when conducting 10A at 25°C. Voltage drops of 2-5% are acceptable; with excessive voltage drops comes high losses and therefore significant heat.

		Distances (m)					
		5	10	15	20	25	30
AWG Size	2	0.11%	0.22%	0.33%	0.43%	0.54%	0.65%
	4	0.17%	0.35%	0.52%	0.69%	0.86%	1.04%
	6	0.28%	0.55%	0.83%	1.10%	1.38%	1.65%
	8	0.44%	0.88%	1.31%	1.75%	2.19%	2.63%
	10	0.70%	1.39%	2.09%	2.79%	3.49%	4.18%
	12	1.11%	2.21%	3.32%	4.43%	5.54%	6.64%
	14	1.76%	3.53%	5.29%	7.05%	8.82%	10.58%
	16	2.80%	5.59%	8.39%	11.18%	13.98%	16.77%

This results in the hardware required for a bi-directional, 12V/24V, DC/DC converter that is able to either sink or source approximately 250W. Following is the development of

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[4] Similar to the buck converter used in the MPPT, these seem like very large allowances for voltage and current ripple. There are two reasons for this. (i) This keeps the size of components, and therefore the cost, down. (ii) The purpose of this is to exchange energy with other converters; no loads are serviced by this converter, therefore larger ripple values are acceptable.

the algorithms needed to effectively control the power flow between converters in multiple-SHS situations.

4.2.4 Controller

Simply having the correct hardware is not enough to ensure proper operation of the converter. The converter and its control algorithms need to behave differently depending on whether it is sending or receiving power. Analytically, it may seem that a controller simply needs to be aware of payment information in order to know whether to operate the converter in boost or buck mode. For example, if a controller sees that it has just received *credit* for 2kWh of energy, then it should operate in boost mode and send power to V2. Similarly, if a converter has sent credit to another converter then it should prepare to receive power and operate in buck mode. However, due to the costs of sending credit and even SMS texts (however slight) and for efficient operation of the entire micro-grid, each converter should, ideally, operate with an "open account" with the other converters it is connected to. In this way, power can smoothly flow between converters.

Power Sharing Algorithms

For operation in this way, the converters need to be able to somehow communicate and decide which will send power and which will receive power. Equation (4.17) is a simple algorithm that gives preference to systems with higher SoC, but also takes into account the size of each system. In essence, the algorithm calculates the number of watt hours in a system *that are available for sending* and biases the boost voltage of the converter accordingly.

$$V_{Target}(i) = V_{Bias} + \frac{(SoC(i) - SoC_{Lim}) * Batt_{Ah}(i) * V_{Sys}}{K} \tag{4.17}$$

where $V_{Target}(i)$ is the target value of each boost converter, V_{Bias} is the offset voltage, $SoC(i)$ is the state of charge of the battery bank of each SHS, $SoC_{Lim}(i)$ is the sharing limit (set by the owner or operator) which sets how much power in the system is available for sale, V_{Sys} is the voltage of the SHS battery bank, and K is a scaling factor.

The numerator of the second term can be viewed as the total watt hours available for sending. By changing the value of SoC_{Lim} the owner/operator can affect how readily their system sends or receives (i.e., sells and buys) in transaction with other converters. V_{Bias}

provides the biasing voltage and K simply scales the value of the watt hours available for selling. For the purposes of this work V_{Bias} is set to 24, V_{Sys} to 12, K to 500, and SoC_{Lim} to 0.5 (50%). It is assumed that each system's SoC will be above 20% and a maximum battery bank size of 300Ah produces a V_{Target} range of about 21.8V to 27.6V or -9% to $+15\%$ from a 24V bias. Recall that this voltage swing is somewhat mitigated by the voltage drops in the transmission lines between controllers.

Looking at the bigger picture, two or more converters will be connected to a common line at the high side of the converter. If each controller attempts to control its point of common coupling to be V_{Target}, then the voltage on the bus, V_{Bus}, will be the roughly equal to the averages of all the V_{Target}s on the bus. Recalling Figure (4.5) and the surrounding discussion, for converters with V_{Target} *higher* than V_{Bus}, this means they will be operating at a duty ratio *smaller* than the borderline duty ratio as seen in Equation (4.18). This means they are operating in boost mode and sending power onto the bus.

$$\frac{V_{Batt}}{V_{Target}} < \frac{V_{Batt}}{V_{Bus}} \quad (where \quad V_{Bus} < V_{Target}) \tag{4.18}$$

Conversely, those systems with V_{Target} *less* than V_{Bus} will operate at a duty ratio higher than the borderline duty ratio, i.e. in buck mode, and therefore absorb power from the bus.

Thus, Equation (4.17) provides a passive way for controllers to exchange power among one another. Unfortunately, this algorithm by itself is insufficient to ensure proper control of the voltage on the common bus. For example, if the controller is a PI controller (as it was in this simulation), then assigning similar gains and time constant values to every controller results in significant ringing on the transmission line.

System Response Algorithms

In order to maintain voltage stability on the shared bus for a broad range of situations, the controllers need to co-ordinate their responses to voltage transients. In other words, the response characteristics of the controller need to vary dynamically according to the state of the converter. Using a PI controller to control the buck-boost converter, the parameters of interest are the proportional gain and time constant values.

Intuitively, one can understand that the systems sending power have more effect on the stability of the bus than systems receiving power. As such, when a system is sending power, it should use a low value for the gain and a longer time constant which will generally result in voltage stability on the bus though. On the other hand, systems that are receiving power should affect the bus as little as possible and be able to respond quickly to voltage changes on the bus so they can absorb the energy from the bus regardless of the voltage. But, since a system could be receiving power one minute and then sending power the next minute, it also needs to transition between these varying parameters for gain and time constant as smoothly as possible.

Using arctan as the sigmoid function of choice to transition between these values results in the generic formulas given in Equations (4.19) and (4.20). The values are functions of the current, I_{Conv}, flowing out of the converter at any particular time; it is positive for systems sending power and negative for systems receiving power. When the desired response values are known for both the sending and receiving states, the parameters of these equations can be adjusted appropriately.

$$Gain(i) = K_{G1} \arctan(K_{G2} I_{Conv}(i) + K_{G3}) + K_{G4} \tag{4.19}$$

$$TimeConstant(i) = K_{TM1} \arctan(K_{TM2} I_{Conv}(i) + K_{TM3}) + K_{TM4} \tag{4.20}$$

where $Gain(i)$ and $TimeConstant(i)$ are the proportional gains and time constants of each system, K_x are scaling factors and I_{Conv} is the current flowing out of the system in Amps.

By experimenting with a broad range of scenarios, including the various combinations of large- and small-sized systems with high and low SoCs as well as similarly-sized systems with similar SoC's, some target values emerge. Overall, systems that are sending power operate best with a proportional gain of 1 and a time constant of 1 second. Values smaller than this for either parameter result in excessive settling time while values larger than this lead to increased noise during run time. Systems that are receiving power perform best with a fairly high gain of 500 and a faster time response of 0.1 seconds. Gain values higher than 500 put significant noise on the bus during steady state operation while gains less than this resulted in significant overshoot and ringing. Using time constant values higher than or similar to those used for systems sending power results in instability and ringing on the transmission line. Time constants lower (i.e., faster) than 0.1 results in slightly more noise during steady state operation but does not make a significant difference. These target values are achieved in Equations (4.19) and (4.20) with the associated scaling factors given in Table A.2.

The gain and time constant values for sending systems are expected values for a PI controller in this system. On the other hand, the high gain of 500, and short (fast) time

Table 4.3: (a) Gain and Time Constant values for systems that are either sending or receiving. (b) Scaling parameters to be used with equations (4.19) and (4.20).

(a)

	Sending	Receiving
Gain	1	500
Time Constant	1	.1

(b)

Parameter	Value
K_{G1}	-158.8
K_{G2}	50
K_{G3}	0.1
K_{G4}	250.4
K_{TM1}	0.286
K_{TM2}	50
K_{TM3}	0.1
K_{TM4}	0.55

constant of 0.1 second used for the systems receiving power are unusual. However, if these systems are considered to be passive loads, then the values begin to have meaning. Gain is $\frac{100\%}{ProportionalBand}$ where proportional band is the range of output available to the controller. A passive load has no control and so has a proportional band of zero, therefore it has a gain of infinity. Similarly, the time constant is the period over which the magnitude of the error is integrated; for a passive load, it has no "knowledge" of the error of the system and so this time is zero. However using these values in an actual system, especially a gain of infinity is unrealistic and so the values of 500 and 0.1 second are compromises. [42]

At their core, these equations and values give the systems that are sending power dominance over those that are receiving power, as well as a linear transition between states. Although very different in many aspects, this is similar to well known droop curve techniques for controlling voltage magnitude and frequency in large AC grids.

Limiting Values

Some consideration also needs to be given to the various limits implemented throughout the simulation. For example, since the MPPT model does not include a proper trickle charging charge controller, some hysteresis should be set for keeping the battery topped up without running into high frequency switching. Similarly, limits are needed for when the battery bank is being charged via the converter (i.e., from other ceSHSs in the microgrid). Discharging should also have some limitations. In order to maintain the health of the battery, its SoC should not fall below 20% (assuming deep discharge lead acid batteries).

Therefore, the local load is disconnected at this level and only reconnected once the battery has been charged for a while. Finally, the level at which the system starts to send power to other systems (SoC_{Lim} in Equation (4.17)) should have some buffering to ensure systems operate smoothly and do not enter any dynamical situations.

Table 4.4 lists the upper and lower hysteresis limits on SoC used in various aspects of the high-level (see Section 4.3 . These values were used for the high-level simulations; for low-level simulations the limits on SoC need to be very close so that the simulation can pass through the hysteresis band in a reasonable amount of processing time.

Table 4.4: Example hysteresis values needed for ceSHS operation. (Component references from Figure 4.5. In the actual converter, D1 is replaced by a switch to enable this functionality. See Appenedix C.)

		Lower Limit	Upper Limit	Enabled by turning off:
Charging from:	Panels	0.95	0.98	MPPT
	Microgrid	0.9799	0.98	Converter buck (S2)
Discharging to:	Local load	0.2	0.25	Local load
	Microgrid	0.5	0.52	Converter boost (D1)

4.3 High-Level Model Development

Sections 4.1 and 4.2 provide all the tools necessary to accurately simulate a micro-grid made up of individual solar home systems. These devices, i.e., the PV panel, MPPT / charge controller, battery, and loads, enable the simulation of an SHS within PSCAD while the last device, the DC/DC converter, enables the systems to be interconnected to form a micro-grid. These models are fairly accurate at low-level and are useful for observing short term behaviour of the system such as overshoot, settling time, and ripple. Unfortunately, simulating a number of SHSs comprised of these modules is computationally intensive and actually takes significantly longer than real time, even with relatively slow switching frequencies of 30kHz. However, when designing and simulating SHSs, one is mainly interested in their performance over the periods of days, weeks, months or even years. Therefore the tools developed in previous sections are not appropriate and need to be revised to accommodate longer periods of simulations.

The components driving the very short time steps needed for the low-level simulations are those with a high frequency component, namely the MPPT and buck-boost converter. Additionally, the RC circuits corresponding to short and long transients of the battery model are only relevant for transient behaviour of the battery and are not needed for longer term simulations.

4.3.1 High-Level PV Panel and MPPT Model

Since the MPPT works so closely with the PV panel, it is easiest if the two devices are combined for high-level analysis. This is easily done by assuming that, because of the MPPT, the panel(s) are always putting out the maximum power for a given level of insolation and temperature. These maximums can be found by using the multiple run feature of PSCAD. Running multiple simulations of the panel at various temperature and insolation values ahead of time results in a table of MPPs for the panel to be constructed. Then, the high-level simulation can simply reference this look-up table and use the resulting power output as the power coming from a single panel. (This number is scaled if there are multiple panels in the array.) Thus, the simulation does not need to perform the calculations used in the physical model of the PV panel, the processing of the incremental conductance algorithm in the MPPT, and the calculations involved in the high frequency electrical model of the buck converter. Figure 4.6 shows the resulting approximation of the PV Panel and MPPT device.

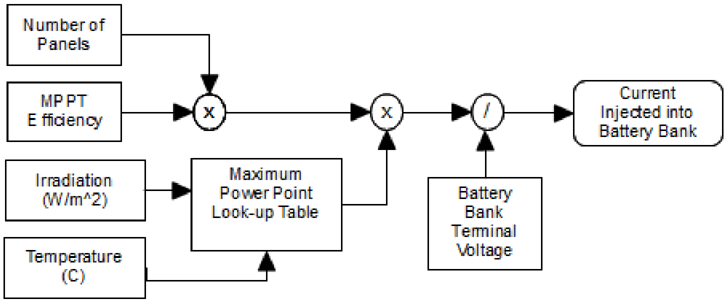
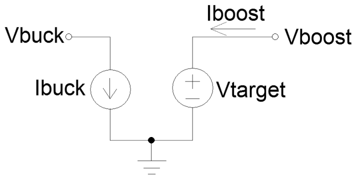


Figure 4.6: Summary of high-level approximation for PV array and MPPT device.

4.3.2 High-Level Bidirectional Buck-Boost Converter Model

The most significant assumption made in modelling the bi-directional converter of Section 4.2 is that the converter is always presenting V_{Target} (from Equation (4.17)) on the common bus. This can be done by setting a voltage source to V_{Target}. Then, by measuring the corresponding power flowing into or out of the converter on the boost side, it is possible to reflect the power flowing into or out of the battery on the buck side by using a current source. This is made clear in Figure 4.7.



(a)

$$I_{Buck} = \frac{V_{Boost} I_{Boost}}{V_{Buck} Eff}$$

(b)

Figure 4.7: High-level approximation of the bi-directional buck-boost converter developed in Section 4.2 where Eff = the efficiency of the low-level converter.

4.3.3 High-level Battery Model

The short and long transient RC circuits of the battery model are irrelevant to high-level simulation; so, it is simply a matter of removing these sub-circuits from the model (see Figure 4.3 and Equations (4.13) to (4.16)) while leaving the general formulas for SoC, V_{OC} and R_{Series} as in Equations (4.10), (4.11), and (4.12), respectively.

4.4 Chapter Summary

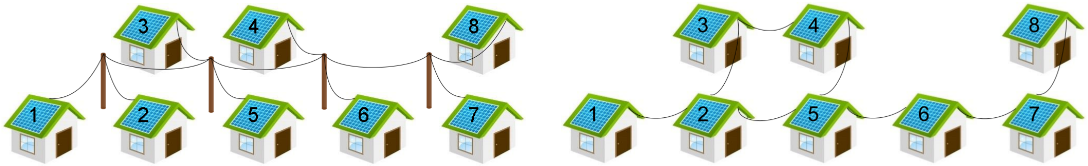
This chapter reviewed some of the technical details of simulating an SHS in PSCAD including the development of a PV array, MPPT and charge controller, lead-acid battery and load. It also provided a novel application for a buck-boost bi-directional converter and developed three original algorithms needed to implement this converter in this application. Finally, the chapter presented the development of high-level models of the previously mentioned components for use in long-term behaviour simulations.

Chapter 5

Simulation Results and Analysis

Chapter 4 presented the process behind the design of each individual component of an SHS. The results are all the tools necessary for simulating and analysing the behaviour of a range of systems, from a single, standalone SHS or community of them, to various topologies of microgrids built up from individual ceSHSs.

From an analysis perspective, there are three topologies that are of interest with each of these categories having high- and low-level versions of the simulation. The first topology (the status quo) is a community of standalone SHSs each sized for and servicing the local loads at that location. The next topology is akin to the national grid, where there is a single, common bus to which all systems connect and through which they exchange power. The final topology is related to the economic simulation of Section 3.3 where every ceSHS is connected to its immediate neighbours by a dedicated connection. The second and third topologies are illustrated in Figure 5.1.



(a) Solar neighbourhood using a common bus topology.

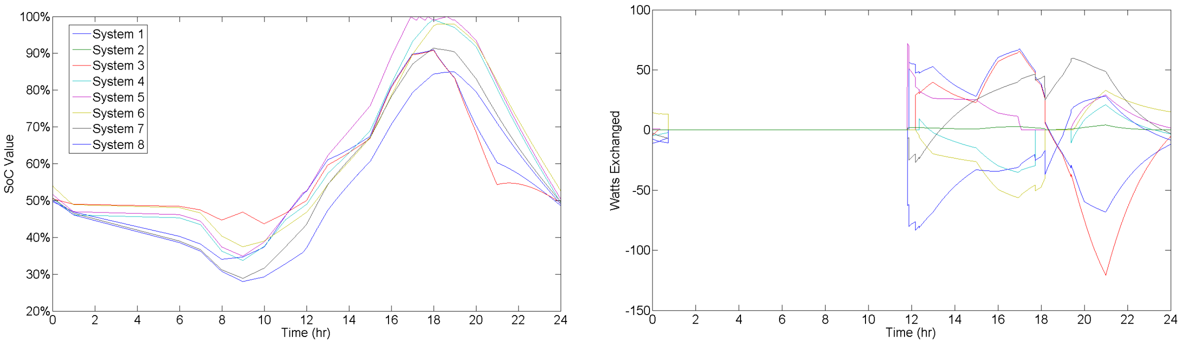
(b) Solar neighbourhood using point-to-point bus topology.

Figure 5.1: Example topologies for a solar neighbourhood. The status quo does not have any connections between houses.

As explained in Section 4.3, two levels of simulation are needed and each of these topologies needs to be simulated at a high- and a low-level. Once these six simulations are assembled and configured, the only thing remaining is to start running them and analysing the results.

5.1 High-Level Simulation Results

After constructing a full microgrid, the first order of business is simply to verify that it operates as expected. Do the systems transfer power between one another, i.e., does Equation (4.17) really work? What does the exchange of power actually look like? Figure 5.2 is a single day snapshot of a common bus grid. (Each SHS has been sized to meet all load requirements for the given insolation profile.)

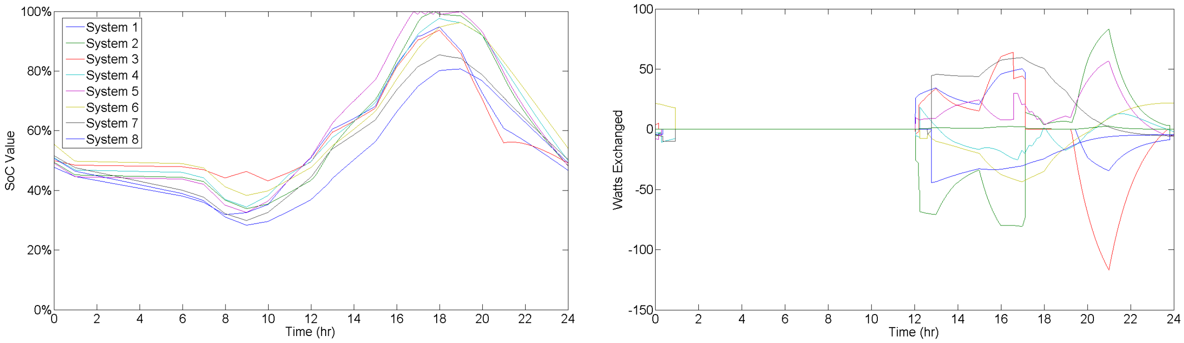


(a) (b)

Figure 5.2: Single day plot of the SoCs (a) and power exchange (b) of 8 systems in a common bus microgrid.

The plots show the SoC of each system (Figure 5.2(a)) and the power being exchanged between systems (Figure 5.2(b)). Between 8AM and 10AM, all the systems begin to charge. The loads are also increasing at this time, but the systems have been sized to still provide adequate charge. At around noon, the SoC of one of the systems crosses the sharing threshold and starts sending power to the other systems. At this point the lower plot shows the systems begin to exchange power. (From the left hand side of the plot, it is evident that some of the systems were still sharing power from the previous day at midnight.) Close inspection of the plot reveals a line that is approximately flat; this is the sum of powers being exchanged. Ideally, it should be zero but it is always positive, especially when significant power is being exchanged, due to losses in the system; so, there is always more energy being sent than received.

The plots for a microgrid using a point-to-point topology is shown in Figure 5.3. These plots are very similar to the plots from the common bus topology of Figure 5.2.



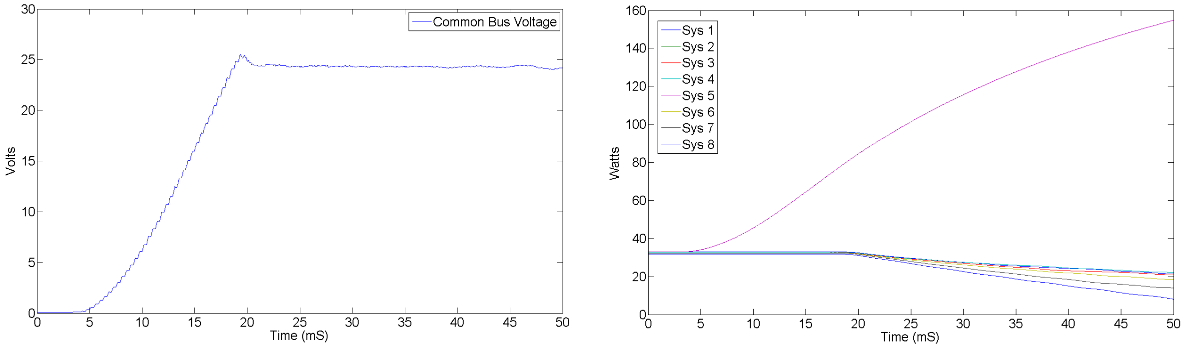
(a) (b)

Figure 5.3: Single day plot of the SoCs (a) and power exchange (b) of 8 systems in a point-to-point bus microgrid.

5.2 Low-Level Simulation Results

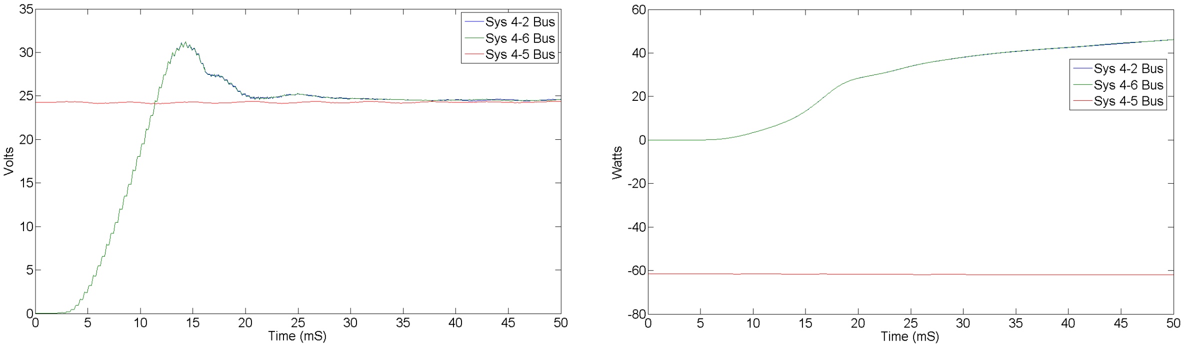
Having verified that systems send and receive power as expected, the next points of interest are the actual waveforms at times of interest. Figure 5.4 shows the common bus voltage and the power being exchanged when the first system in a common bus microgrid crosses the sharing threshold. Inspection of these plots reveals that the rise and settling time for the common bus is approximately 20ms, the overshoot is about 5%, and there is about a 2% voltage ripple on the line. The fact that the initial power being shared (shown in Figure 5.4(b)) is not zero is due to losses in the system.

The plots for one system, System 4, as it crosses the sharing threshold are shown in Figure 5.5. The SoC of System 4 has just reached the sharing threshold; therefore, it begins to send power to systems 2 and 6. The horizontal line in Figure 5.5(a) is the voltage on the 4-5 bus, showing that these systems are already sharing power. The horizontal line in Figure 5.5(b) is negative showing that System 4 is *receiving* power from System 5. For both the 4-2 and 4-6 buses, the rise plus settling time of the voltage is now about 28ms, the overshoot is 25% and the ripple is fairly negligible.



(a) (b)

Figure 5.4: Voltage (a) and power (b) plots when systems first begin to share power on the common bus of a common bus topology.



(a) (b)

Figure 5.5: Voltage (a) and power (b) plots when systems first begin to share power in a point-to-point bus topology.

Recalling that this 24V, DC line is only used to exchange power between systems and that loads are connected through other connections to the battery, these characteristics are quite acceptable. Therefore, from a technical perspective the converter operates as desired; exchanging power with systems that have less power in a controlled and stable manner.

5.3 Cost Analysis

5.3.1 Total Number of PV Panels and Batteries

From Section 3.3, by far the main advantage of a cellular-enable SHS is that it enables micro-payments for electricity. But beyond this, are there other economic advantages? Are the final economic costs of a microgrid formed in this way so significant that they outweigh the noteworthy benefit of enabling micro-payments? Can the initial costs be recovered within a reasonable amount of time? (i.e. How long is the payback period?)

The first step in answering this question is to establish a foundational situation for comparing system performance and cost. In this case, the criteria are defined as the minimum number of panels and batteries required to service all loads at a minimal level of insolation. [1]

Manually running the high-level simulation for each topography over the course of one day and adjusting the number of panels and batteries present in each SHS so that all loads are serviced is a straightforward, even though somewhat time-consuming, method to compare topologies. Performing this analysis results in the quantities listed in Table 5.1. (Note that it is possible for there to be more than one solution.)

Table 5.1: Minimum number of 135W PV panels and 50Ah batteries required to ensure that all loads are serviced for various topologies under minimum insolation.

		System								
		1	2	3	4	5	6	7	8	Totals
Standalone	Panels	9	3	9	4	3	3	4	4	39
	Batteries	3	2	3	2	2	2	2	2	18
Common	Panels	8	2	8	3	3	2	4	3	33
	Batteries	3	2	3	2	2	2	3	3	20
Point-2-Point	Panels	8	2	8	3	3	2	4	3	33
	Batteries	3	2	3	2	2	2	3	3	20

These results are interesting for a number of reasons. Most significantly, they demonstrate that *fewer* panels are needed for the microgrid topologies than the standalone topol-

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[1] An initial analysis of this situation leaves the impression that this is an optimization problem. The criteria include minimizing the number of panels and batteries while ensuring that all load requirements are satisfied. However, because the amount of power transferred between systems at a particular time varies dynamically based on the power in each system, this is a highly non-linear optimization problem. Solving the problem with an optimization program, such as GAMS, would be a small project by itself.

ogy. This is due to the fact that the total generation is able to be sized more accurately to match the total load. Six extra panels are required in the standalone topology due to the fact that, during the sizing procedure, one always needs to round up the number of panels or batteries required; if a load profile needs the equivalent of 1.5 panels and 3.2 batteries, then the system receives 2 panels and 4 batteries. The microgrid topologies combine all the systems and so, for example, if the total load requires the equivalent energy from 32.2 panels and 19.5 batteries, it is only required to round once resulting in 33 panels and 20 batteries. In other words, the rounding up does not take place at every individual system.

The fact that the point-to-point bus topology requires exactly the same number of PV panels and batteries, in the same locations is unexpected and unrealistic. Most likely, the efficiency of the components in the system such as the buck-boost converter and battery are very high and therefore, in the simulation, systems are able to transfer power to where it is needed in the microgrid without significant losses. In reality, there would be significant power loss each time the energy passes through a system. (Note that the power does not necessarily need to pass through the battery in each system since all the converters in an SHS in the point-to-point bus topology are connected in parallel at the battery terminals.)

Another intriguing result is that the microgrid topologies actually require *more* batteries than the standalone topology. This is due to a combination of factors. First of all, for the systems that require fewer batteries in a standalone topology (Systems 7 and 8), the minimum number of 135W panels required to service the load is significantly higher than that corresponding to the watt-hours required by the systems; i.e., these systems need slightly more energy than one panel could provide but much less than the energy provided by two panels. Secondly, the load profile coincides loosely with the insolation profile; therefore, with all the excess generation in the standalone topology, the energy is, to some degree, dispatchable for certain parts of the day and able to service the loads directly for significant lengths of time. The load remaining to be serviced during periods of low insolation is relatively small, thus requiring fewer batteries. When these systems are connected with other systems in the microgrid topologies, they no longer need the second panel. However, they do not have as much access to dispatchable energy and need to be able to store more energy to service the entire load profile.

By running the simulation with smaller sized components (such as 25W PV panels and 10Ah batteries) these differences could be reduced so that there is not so much discrepancy between the number of panels or batteries needed in the standalone and microgrid topologies.

Note that this is a very academic exercise. The way that the solar neighbourhood emerges in Section 3.3 implies that there is no final, optimal solution. The microgrid will grow (or shrink) based largely on socio-economic factors and the configuration at any one time will not be optimal. But, this will drive the microgrid to evolve. If there is excess generation, then people may lower the price they are willing to sell the energy for and loads may increase. Vice versa, if there is too much demand, the price of electricity may go up as well and people may invest in more generation and storage.

5.3.2 Cost of Buck-boost Converter

The fact that the microgrid topologies require fewer panels (by far the most expensive components of an SHS) than the standalone topology is very encouraging. But obviously this benefit is offset by the additional cost of the converter. As mentioned in Section 4.2, a 250W 12V/24V DC/DC converter is very small and therefore can be operated at fairly high frequencies using small (and low cost) components. Assuming a mark-up of 50% the final unit cost for an inverter would probably sell in the range of about $150 with the bulk of that cost coming from cellular (GSM) module. (Appendix B provides a preliminary estimate of the hardware cost of such a converter.)

One way of looking at this cost is to compare it to a PV panel of equivalent cost. As of 2012, the price per watt for small panels in Tanzania is approximately $3.00/Watt [11] so, the cost of a 135W panel (the only option available in the simulation) is about $400. Therefore, in the common bus microgrid it is quite beneficial to purchase a converter instead of another 135W panel. The six extra panels would cost $2,430 but the eight converters only $1,200.

In the case of the point-to-point microgrid, the economic benefits are less clear. Some of the SHSs were connected to 3 other systems, thus requiring three converters for a cost of $450. (This is approximately equivalent to buying a 150W panel.) Since, from Table 5.1, the difference between the number of panels required in the point-to-point bus topology vs. the standalone topology is never greater than one (1) for any SHS, it is *not* of benefit for the SHSs connected to three other systems to choose a microgrid option over buying more panels. (Although there are some savings for the systems with only one connection, without the systems with multiple connections there would be no microgrid to connect to in the first place.) Taken as a whole, the additional cost of the six, 135W panels ($2,430) required for the for the standalone topology is more or less equal to the cost of the 16 converters required for the point-to-point bus microgrid.

5.3.3 Summary of Costing Analysis

As a means to offset the final cost of an SHS, such a converter by itself is of limited benefit, especially considering some of the implications discussed in Section 5.4. However, this consideration is very much from a planning perspective. Recall that the foundation of this microgrid comes from the gradual penetration of ceSHSs due to the benefit of being able to buy electricity in micropayments. As demonstrated in Section 3.3, the functionality to buy and sell electricity *is* economically beneficial. If the *additional* functionality of being able to exchange power between systems using a converter is *added* to the hardware already required to sell power in incremental payments, then the converter is highly advantageous, economically. (From Appendix B it can be seen that the converter functionality is only 15% of the total cost.)

5.4 Behavioural Analysis

After the cost implications are considered, the analysis then falls on comparing the behaviour of the various simulations in different circumstances. Due to the very distributed nature of the microgrids in these simulations, another intriguing aspect is their robustness, or security, to react to losses in the infrastructure. Since every SHS is an independent producer, storer, and consumer of energy, how does the system perform when one of the systems is compromised?

Tracking the load watts that are not serviced reveals some interesting behaviour. If the loads are too high, the total load watts not serviced is higher (worse) for either of the microgrid topologies than for the standalone topology. This is because each system will draw power from the other systems as it needs it and drain all systems. For the standalone SHS simulation, one system might have excessive load, drain its batteries and have to go without power but it would not affect the other systems; so, the overall number of loads being serviced was higher (better).

This behaviour is of particular note because each of the users will put as much load on the system as they can without augmenting their generation or storage; so, the price of electricity within the grid needs to be high enough to encourage investors within the neighbourhood to purchase more generation and storage to sell to others. Another solution would be simply to make sure that each user can set their individual price points for both buying and selling electricity. The concept of storing energy and selling it to neighbours may be analogous to rain harvesting tanks. These tanks simply collect rain water off the roof of a house and store it for use at a later time. Unfortunately, for many reasons people in developing regions often choose *not* to install these tanks, in part because of social dynamics that it may create within the community. The concept of storing “freely”-gained electrical energy and then selling it to ones neighbours may fall prey to the same dynamics.

5.5 Chapter Summary

This chapter has demonstrated and analysed a solar neighbourhood using the components developed in Chapter 4. Presenting various topologies for the solar neighbourhood, this chapter reveals the advantages and disadvantages to each topology from a performance as well as cost perspective.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

This work has developed and demonstrated a technical simulation of a microgrid that can emerge when cellular technology is paired with SHS technology.

In reviewing current electrification efforts in the developing world, this research showed how far short these endeavours fall of their lofty goals. Most of these efforts are unmaintainable, unrepeatable, or un-scalable.

However, recent methods of incrementalizing the payments for solar home systems are emerging in East Africa and in India. By embedding cellular technology in an SHS, end-users are able to utilize micro-payments to pay off the capital expense of the system. This research takes this concept one step further and suggests that these system be configured so as to allow multiple people to purchase power from a system. This creates entrepreneurial opportunities for those in the community with the means to purchase an SHS. This is validated with an economic simulation which reveals the growth of solar home systems within a community when the systems are able to sell power.

This research also introduces the idea of a solar neighbourhood. The addition of a bi-directional 12V/24V DC/DC converter to the systems enables them to exchange power with one another. This enables end users to use loads larger than their SHS would normally allow, spurring on economic development and driving the growth of the grid even further.

Using customized algorithms and techniques analogous to AC grid droop control methodologies, the resulting bi-directional power converter is able to autonomously exchange power and control voltages on a common bus shared with other converters.

The additional cost of this DC/DC converter over and above the hardware already required for the ceSHS is relatively low. The basic cellular and microprocessor hardware makes up the bulk of the costs and is already economically justified through the economic simulation. [1]

The research presented in this thesis addresses the items on the United Nations Secretary General's list of barriers that need to be overcome as follows:

1. *Path dependence.* By putting the growth of the microgrid squarely in the hands of the users and private business, this technology should disrupt the energy economics sufficiently to force a review of policies and politics. This will encourage the discovery of better solutions.

2. *Financial obstacles caused by high initial costs of clean energy technologies.* This research clearly demonstrates a method to overcome the high initial cost of clean energy technologies.

3. *Pricing policies that diminish returns on capital and impede private investment.* Similar to the first barrier, this new technology should force politicians to revisit pricing and regulatory policies.

4. *Business models that worked well for establishing national grids but are not applicable in rural areas.* The ceSHS is clearly a paradigm shift in electrification. It does away with the traditional style of central generation, transmission, and distribution which is progressing far too slowly in the developing world, and approaching serious limitations in the developed world. [2]Recalling that one of the main challenges of rural electrification is low population density, even with the 12V/24V converter, this technical solution does not allow for large distances between ceSHSs. Hence, there are some very sparsely populated areas where this technology will not work. However, the benefits of a ceSHS begin with even a small group of homes in close vicinity; a situation where standard grid expansion would be completely uneconomical.)

In conclusion, the marriage of cellular technology to all forms of distributed generation is quite beneficial and imminent. This research has demonstrated that cellular enabled

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[1] Finally, from a subjective perspective based on field experience as well as data from this research, the concept of a ceSHS that enables people to sell electricity to their neighbours is highly viable and should be pursued further. The additional functionality of having the ceSHSs exchange power is not so clearly beneficial, despite its small incremental cost. It may be better to modularize this functionality so that it can be added when and if desired.

[2] (

solar home systems not only are a solution to rural electrification in the developing world but present a paradigm shift in the electrification process that will have many unforeseen applications and benefits.

6.2 Future Work

The implications of cellular-enabled SHSs is still in its infancy. Even during this research new ideas and directions emerged that could not be fully explored.

First of all, further work is needed to optimize the control algorithms involved. Studying other research related to using autonomous controllers with a common connection point and doing a proper analysis of each controller from a control systems perspective will likely result in changes to the preliminary algorithms presented in Equations 4.17, 4.19, and 4.20. There are likely better choices for the gain and time constant values of sending and receiving systems, and possibly a better way to transition between these states.

As touched upon, running the simulations with only 135W panels and 50AHr batteries may not have provided the most accurate results. Using smaller panels and batteries in the simulations might provide more realistic insights when comparing the standalone topology with microgrid topologies.

Additionally, it would be very interesting to replace the bi-directional buck-boost converter and the corresponding control algorithms with a similar current source converter. This may be better suited for controlling both the currents and the voltages on the bus while exchanging power.

The simulation should also be repeated with software, such as PSPICE, which is better suited for lower DC voltages and has better models for low and high side drivers. To be thorough, these simulations should include proper charging of the battery (following Figure 2.2), as well as current limiting, to ensure that wire ampacities, battery bank charging limits, and converter limits are not exceeded.

Behaviourally, the effects of each agent dynamically changing their sharing limit (SoC_{Lim}), and the price that they are willing to sell or to pay for electricity, might produce some interesting results. It could be that some sort of “tragedy of the commons” scenario emerges and the solar neighbourhood deteriorates.

Finally, one abstract concept emerged from the simulations. Given that each consumer also has some storage capability, there is now a possibility of energy “packets” being exchanged. A system could then purchase and actively “download” a certain amount of energy from another system when storage and transmission capacities allow. This opens up some interesting conceptual possibilities from an operations perspective. (This concept is somewhat analogous to how electric vehicles and their owners may interact with the national grid, buying and selling power at various rates at particular times.)

In reality, the technology and concepts presented here are simple enough that future work should, realistically, simply involve physically building a small solar neighbourhood using these bi-directional converters to fully analyse and understand all of the implications that will emerge from such a technology.

Only time will tell what work the future holds for those living without electricity and if the technology presented here really does have the capability to provide these people with access to this incredible resource.

APPENDICES

Appendix A

Details used in simulation

A.1 PV Panel Specifications

Table A.1: General specifications and inferred parameters for a 135W, KD135SX-UPU, PV panel from Kyocera.

Parameter	Value
Maximum power	135W (± 5%)
Short circuit current	8.37 A
Open circuit voltage	22.1 V
Maximum power current	7.63 A
Maximum power voltage	17.1 V
# of modules connected in series per array	1
# of modules connected in parallel per array	*dependent on SHS*
# of cells connected in series per module	36
# of cell strings connected in parallel per module	1
Reference insolation	1000 W/m^2
Reference cell temperature	25 °C
Effective area per cell	0.009 m^2
Series resistance per cell	0.009 Ω
Shunt resistance per cell	2000 Ω
Diode ideality factor	1.045
Saturation current at reference conditions (per cell)	1 x 10^{-9} A
Short circuit current at reference conditions (per cell)	8.37 A
Temperature coefficient of photo current	0.001

A.2 Loads

Table A.2: Background load information for each household used in the high- and low-level simulations.

(a)

Building	Description
1	Pharmacy
2	Multi-family home
3	Stationary shop
4	Restaurant
5	Multi-family home
6	Multi-family home
7	Store and home
8	Store and home

(b)

Building Number	1	2	3	4	5	6	7	8
11W CFL Bulb	5	8	7	8	10	8	7	7
20W CFL Bulb	2	0	1	2	0	0	1	1
Radio	2	4	1	4	4	4	4	4
TV	1	0	0	0	0	0	0	0
Desktop PC	1	0	2	0	0	0	0	0
Phone Charger	5	6	5	6	6	6	6	6
Fridge	0	0	0	0	0	0	1	0
Chest Freezer	0	0	0	0	0	0	0	1
Ceiling Fan	1	0	0	1	0	0	0	0
Photocopier	0	0	1	0	0	0	0	0

Appendix B

Preliminary Bill of Materials for ceSHS Converter

Table B.1 provides a preliminary costing for a cellular enabled, bi-directional 250W 12V/24V DC/DC converter operating at 300kHz.

Table B.1: Preliminary bill of materials for technology. (a) Hardware required for selling power to other households. (b) The additional hardware required to allow ceSHS to exchange power. Prices from `www.digikey.ca` and `www.sparkfun.com` in March, 2012.

(a)

Item	Cost($)	Comments
Switches	4.20	4x 28A, N-channel MOSFET for controlling power
MOSFET Drivers	4.10	2x drivers for the MOSFET switches
μprocessor	2.05	8bit, 10MHz Atmega with 6 ADC, 6 PWM, 4KB flash
Power Supply	3.05	3.6V, 2.5A power supply based on LM21305
Hardware	10.00	Enclosure, connectors, PCB, etc
GPRS/GSM	60.00	Based on SM5100B module
Antenna	10.00	
Total:	93.40	

(b)

Item	Cost($)	Comments
Buck L	3.00	5.6μH, 20A
Buck C	1.03	1.8μF, 50V, 10%
Boost C	1.13	10μF, 100V, 20%
Boost L	2.54	4.8μH, 10A
Switches	3.15	3x 28A, N-channel MOSFETs
MOSFET Drivers	4.10	2x drivers for the 3 MOSFET switches
Total:	14.95	

Appendix C

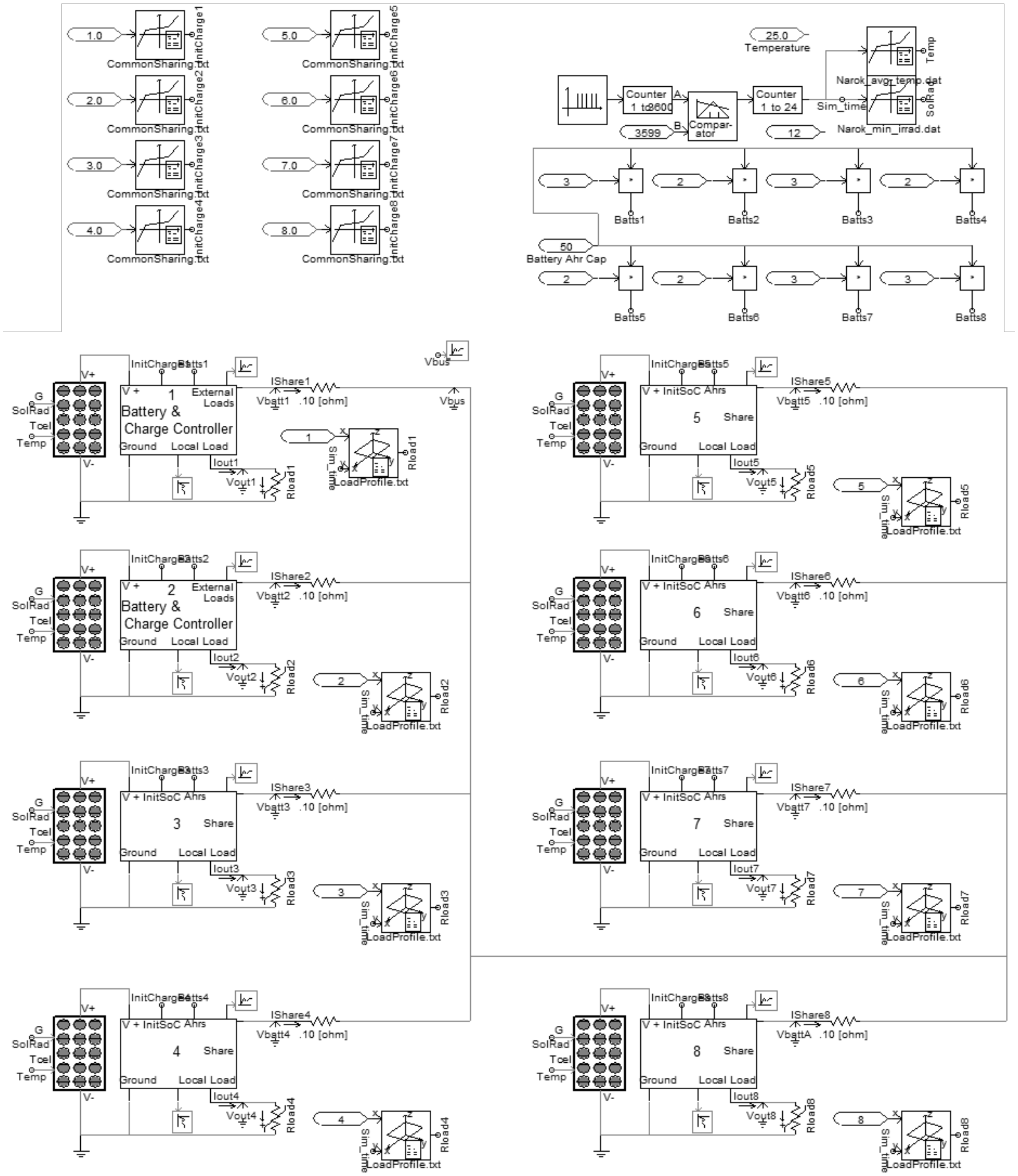

Figure C.1: PSCAD realization of a microgrid of solar home systems connected in a common-bus topology.

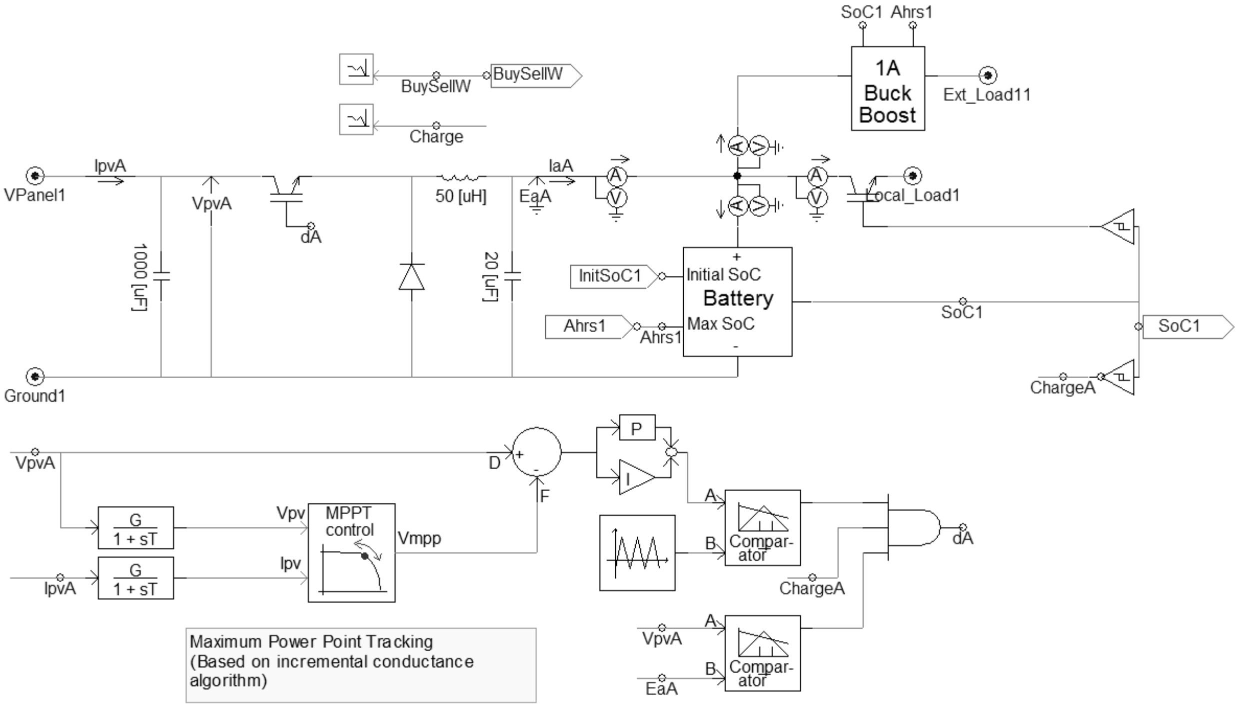

Figure C.2: PSCAD realization of a solar home system

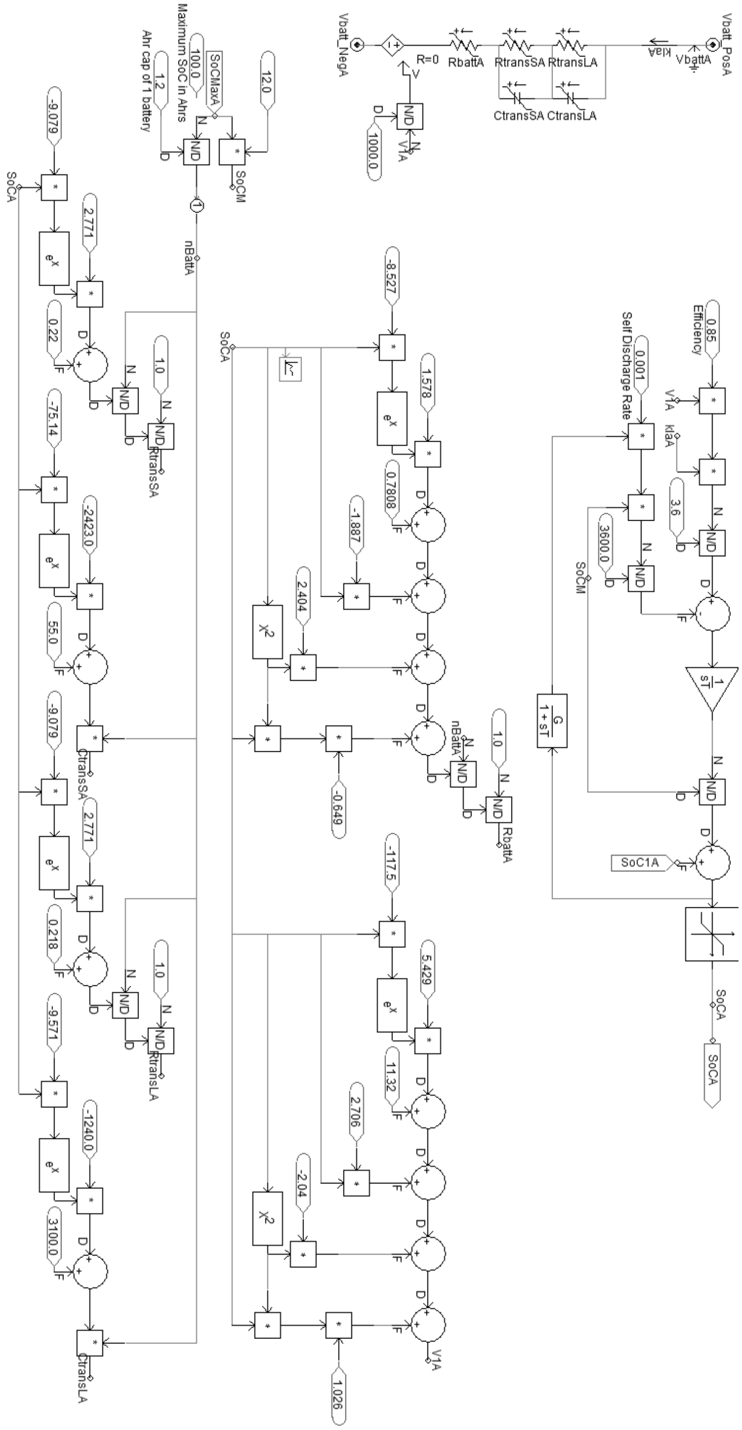

Figure C.3: PSCAD model of a lead acid battery bank.

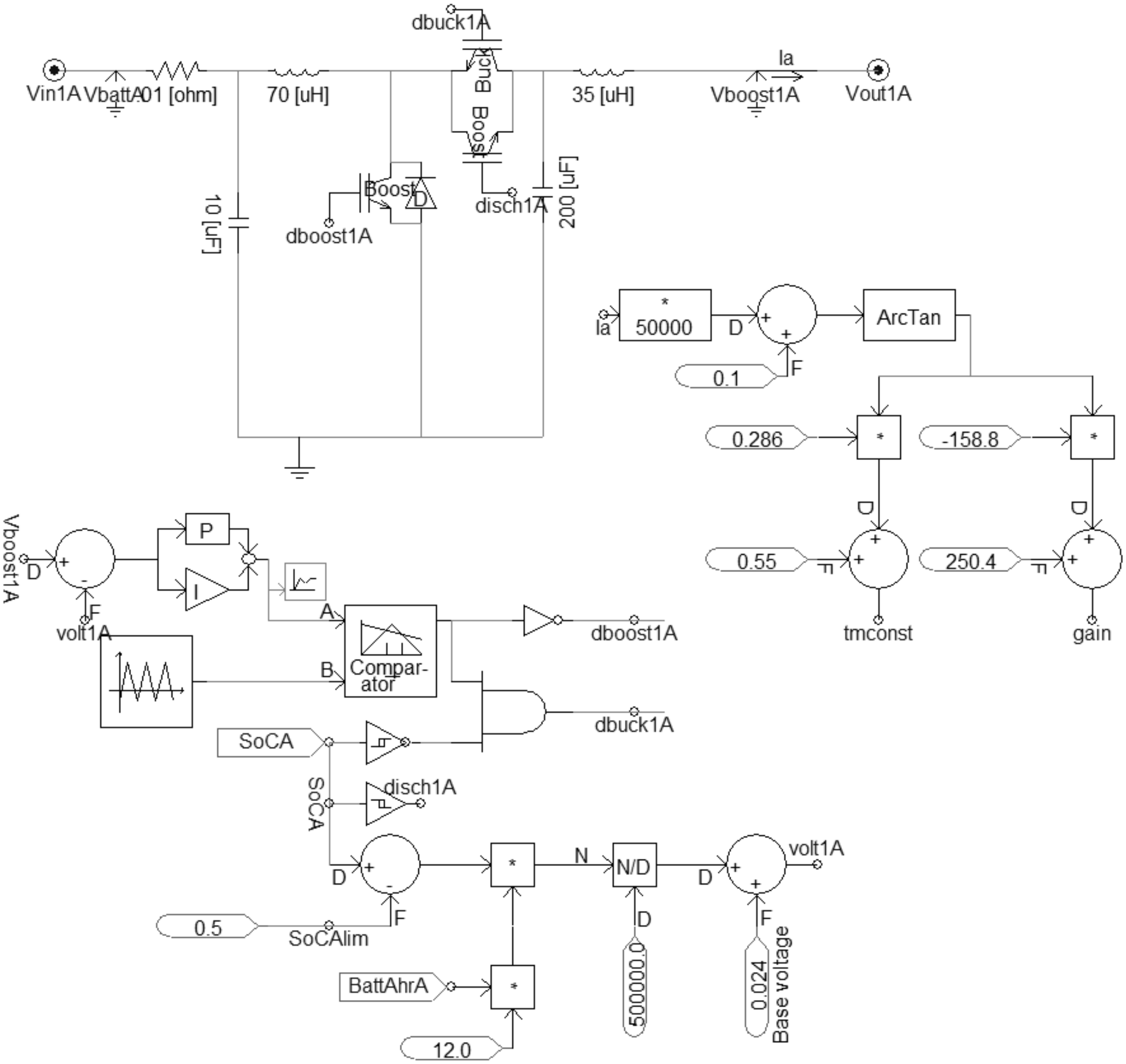

Figure C.4: PSCAD model of a 12V/24V DC/DC converter.

Appendix D

Matlab Code for Economic Simulation

Matlab Code for Simulation of Organic Growth of Solar Neighbourhood

==

```
% Economic model for the organic growth of a rural micro grid based on
% the concept of a cellular-enabled microgrid.
%
% This script provides a theoretical basis to the theory that, given the
% appropriate technology, rural electrification could happen organically
% rather than being injected by various developmental bodies.
%
% Kurtis Unger, March, 2012

clear all;
close all;
tic
ms = 20;            % size of community for simulation
sim_days = 10*365;   % length of simulation
insolation = 5.02;  % insolation in region of interest, 5.02 for East Africa
kero_cost = 250;    % TSH/hr average
avg_lt_needs = 2.37;
```

```
avg_mth_income = avg_lt_needs*kero_cost*365/12; %18000; %

wh_ratio = .5;                    % ratio of electricity to kerosene

    tot_PV = zeros(ms,ms);          % track PV locations & watts
    tot_Ahrs = zeros(ms,ms);        % track Ahrs
    tot_acc = zeros(ms,ms);
    tot_lt_watts = zeros(ms,ms);
    is_pop = zeros(ms,ms);
    all_pop = 0;
    all_PV = 0;
    all_Ahrs = 0;
    all_lt_watts = 0;
    has_PV = 0;
    avg_PV_watts = 0;
    avg_batt_Ahrs = 0;

    sim_acc(sim_days) = 0;          % track economy at the start
    tot_cash = zeros(ms,ms);
    tot_pow = 0;
    sim_num_PV(sim_days) = 0;    % how often the batteries get full
    sim_hrs_kero(sim_days) = 0;   % track amount of kerosene used
    sim_nolight(sim_days) = 0;    % how much people go without light
    std_dev = .5; % control the standard deviation of the random variables
    sys = kuemrg;
    wh_cost = kero_cost*wh_ratio;

    % defining a pseudo random village
    v(1:ms,1:ms) = agent;
    uni_r = rand(ms);

    for i=1:ms
        for j=1:ms
            if uni_r(i,j) > .33 %vary this according to population density
%could make this into a pseudo bell curve
                v(i,j).is_pop = 1;
%load profile calc so that without solar people should break even
  v(i,j).hrs_lt_avg = avg_lt_needs;
```

```
            v(i,j).day_income = (avg_mth_income*12/365);
            v(i,j).num_PV = 0;          % to start no one has pv system
        end
    end
end

% seed one site with PV system
% could create "investor account"
v(ms/2,ms/2).PV_watts = sys.PV_watts;
v(ms/2,ms/2).batt_Ahrs = sys.batt_Ahrs;
v(ms/2,ms/2).num_PV = v(ms/2,ms/2).num_PV + 1;
v(ms/2,ms/2).is_pop = 1;
v(ms/2,ms/2).hrs_lt_avg = (avg_mth_income*12/365)/
 kero_cost*abs((1+ randn));
v(ms/2,ms/2).acc = avg_mth_income*abs((1+randn));
v(ms/2,ms/2).day_income = (avg_mth_income*12/365);
v(ms/2,ms/2).num_PV = 1;
v(ms/2,ms/2).watt_hrs=0;
v(ms/2,ms/2).num_lights =
 floor(v(ms/2,ms/2).hrs_lt_avg/(sys.light_watts*2.5));
%}

% run simulation
for d=1:sim_days
    for i=2:ms-1
        for j=2:ms-1

            if (v(i,j).is_pop == 1)
                % calculating income
                v(i,j).acc = v(i,j).acc + v(i,j).day_income*(1 +
                 std_dev*randn);
                % calculating hours of lighting needed for location
                light_hrs_needed = v(i,j).hrs_lt_avg*abs((1 +
                 std_dev*randn));

                % if location has PV, how much stored and how much used
                if (v(i,j).PV_watts > 0)
                    % how much into the system
```

```
               v(i,j).watt_hrs = v(i,j).watt_hrs +
                insolation*v(i,j).PV_watts*sys.eff*abs((1 +
                 std_dev*randn));

% if batteries full then max out system and just count it for now
               if v(i,j).watt_hrs > v(i,j).batt_Ahrs*sys.V;
                   v(i,j).watt_hrs = v(i,j).batt_Ahrs*sys.V;
                   v(i,j).batt_full = v(i,j).batt_full + 1;
               elseif v(i,j).watt_hrs <= .75*v(i,j).batt_Ahrs*sys.V
                   v(i,j).batt_not_full = v(i,j).batt_not_full + 1;
               end

               % Get more panels if batteries are not getting full
               if v(i,j).batt_not_full >= 4 && v(i,j).acc >
                sys.PV_cost;
                   v(i,j).PV_watts = v(i,j).PV_watts + sys.PV_watts;
                   v(i,j).acc = v(i,j).acc-sys.PV_cost;
                   v(i,j).batt_not_full = 0;
                   v(i,j).num_PV = v(i,j).num_PV + 1;
               end

               % how much out of the system
               if (v(i,j).watt_hrs > 0) && (light_hrs_needed > 0)
                   if (v(i,j).watt_hrs > light_hrs_needed)
                       v(i,j).watt_hrs = v(i,j).watt_hrs -
                        light_hrs_needed;
                       light_hrs_needed = 0;
                   else
                       light_hrs_needed = light_hrs_needed -
                        v(i,j).watt_hrs;
                       v(i,j).watt_hrs = 0;
                       v(i,j).batt_empty = v(i,j).batt_empty + 1;
                   end
               end

               % Get more batteries if insufficient for total demand
               if v(i,j).batt_empty >= 4 && v(i,j).acc >
                sys.batt_cost
```

```
                            v(i,j).batt_Ahrs = v(i,j).batt_Ahrs +
                             sys.batt_Ahrs;
                            v(i,j).acc = v(i,j).acc - sys.batt_cost;
                            v(i,j).batt_empty = 0;
                        end
                    end

                    % if more lighting needed and neighbours or I have
                    % power get cheaper lighting
                    % (assume each light used for 1.5 - 2.5 hours)
                    if (v(i,j).hrs_lt_avg/2.5 > v(i,j).num_lights) &&
                     (v(i-1,j).PV_watts > 0 || v(i+1,j).PV_watts > 0 ||
                      v(i,j-1).PV_watts > 0 || v(i,j+1).PV_watts > 0 ||
                       v(i,j).PV_watts > 0)
                            % randomly reduce consumption to save up
                            light_hrs_needed = rand*light_hrs_needed;

                            % get another light if I can afford it
                            if (v(i,j).acc > sys.light_cost)
                                v(i,j).light_watts = v(i,j).light_watts +
                                 sys.light_watts;
                                v(i,j).num_lights = v(i,j).num_lights + 1;
                                v(i,j).acc = v(i,j).acc-sys.light_cost;
                            end
                    end

                    % Get CEMI for the first time if able
                    if (v(i,j).acc > (sys.PV_cost + sys.batt_cost +
                     sys.CEMI_cost)) && (v(i,j).num_PV == 0)
                        v(i,j).acc = v(i,j).acc - (sys.PV_cost +
                         sys.batt_cost + sys.CEMI_cost);
                        v(i,j).PV_watts = v(i,j).PV_watts + sys.PV_watts;
                        v(i,j).batt_Ahrs = v(i,j).batt_Ahrs + sys.batt_Ahrs;
                        v(i,j).num_PV = v(i,j).num_PV + 1;
                    end

                    %watt_hrs_needed =
sys.light_watts*v(i,j).load_prof*abs((1 + std_dev*randn));
```

```
% if I have lighting already, cash and availability
 allow, use neighbours solar
% (Could reduce to series of while statements alone)
% (Could include diagonal neighbours)
if (v(i,j).acc > 0) && light_hrs_needed > 0 &&
 v(i,j).num_lights > 0
    while (v(i,j).acc > 0) && (v(i-1,j).watt_hrs > 0) &&
     (light_hrs_needed > 0)
        v(i-1,j).watt_hrs = v(i-1,j).watt_hrs - .1;
        v(i-1,j).acc = v(i-1,j).acc + wh_cost*.1;
        v(i,j).acc = v(i,j).acc - wh_cost*.1;
        light_hrs_needed = light_hrs_needed - .1;
        % record demand
        if (v(i-1,j).watt_hrs <= 0)
           v(i-1,j).batt_empty = v(i-1,j).batt_empty + 1;
        end
    end

    while (v(i,j).acc > 0) && (v(i+1,j).watt_hrs > 0) &&
     (light_hrs_needed > 0)
        v(i+1,j).watt_hrs = v(i+1,j).watt_hrs - .1;
        v(i+1,j).acc = v(i+1,j).acc + wh_cost*.1;
        v(i,j).acc = v(i,j).acc - wh_cost*.1;
        light_hrs_needed = light_hrs_needed - .1;
        % record demand
        if (v(i+1,j).watt_hrs <= 0)
           v(i+1,j).batt_empty = v(i+1,j).batt_empty + 1;
        end
    end
    while (v(i,j).acc > 0) && (v(i,j-1).watt_hrs > 0) &&
     (light_hrs_needed > 0)
        v(i,j-1).watt_hrs = v(i,j-1).watt_hrs - .1;
        v(i,j-1).acc = v(i,j-1).acc + wh_cost*.1;
        v(i,j).acc = v(i,j).acc - wh_cost*.1;
        light_hrs_needed = light_hrs_needed - .1;
        % record demand
        if (v(i,j-1).watt_hrs <= 0)
```

```
                           v(i,j-1).batt_empty = v(i,j-1).batt_empty + 1;
                        end
                    end
                    while (v(i,j).acc > 0) && (v(i,j+1).watt_hrs > 0) &&
                    (light_hrs_needed > 0)
                        v(i,j+1).watt_hrs = v(i,j+1).watt_hrs - .1;
                        v(i,j+1).acc = v(i,j+1).acc + wh_cost*.1;
                        v(i,j).acc = v(i,j).acc - wh_cost*.1;
                        light_hrs_needed = light_hrs_needed - .1;
                        if (v(i,j+1).watt_hrs <= 0)
                           v(i,j+1).batt_empty = v(i,j+1).batt_empty + 1;
                        end
                    end
                end

                % use kerosene for lighting if solar is not available
                if (v(i,j).acc > 0) && (light_hrs_needed > 0)
                    while (v(i,j).acc > 0) && (light_hrs_needed > 0)
                        v(i,j).acc = v(i,j).acc - kero_cost*.1;
                        sim_hrs_kero(d) = sim_hrs_kero(d) + .1;
                        light_hrs_needed = light_hrs_needed - .1;
                    end
                end

                if (v(i,j).acc <= 0) && (light_hrs_needed > 0)
                    sim_nolight(d) = sim_nolight(d) + 1;
                end

            %get total economy
            sim_acc(d) = sim_acc(d) + v(i,j).acc;
            sim_num_PV(d) = sim_num_PV(d) + v(i,j).num_PV;
            end
        end
    end
end

for i=1:ms
    for j=1:ms
```

```
            tot_PV(i,j) = v(i,j).PV_watts;
            tot_Ahrs(i,j) = v(i,j).batt_Ahrs;
            tot_acc(i,j) = v(i,j).acc;
            tot_lt_watts(i,j) = v(i,j).light_watts;
            all_lt_watts = all_lt_watts + tot_lt_watts(i,j);
            all_PV = all_PV + tot_PV(i,j);
            all_Ahrs = all_Ahrs + tot_Ahrs(i,j);
            if (v(i,j).num_PV) > 0;
                has_PV = has_PV + 1;
            end
            is_pop(i,j) = v(i,j).is_pop;
            all_pop = all_pop+v(i,j).is_pop;
        end
    end

is_pop
tot_PV
tot_Ahrs
tot_acc
tot_lt_watts
coverage = all_PV/all_pop

spy(is_pop);
hold on
spy(tot_lt_watts,'-y.');
spy(tot_PV,'-r.');
all_PV
all_Ahrs
all_lt_watts
avg_PV = all_PV/has_PV
avg_Ahrs = all_Ahrs/has_PV

toc
```

Parameter file

==============

```
classdef kuemrg  % Kurtis Ungers Electronic Module for a Rural microGrid
```

```
    %{
    % fixed system properties
    properties
        V = 12;
        eff = .9;                   % efficiency of the system after various
         losses are included
        light_cost = 13000;         % TZS for 11W light
        light_watts = 11;
        PV_cost = 85000;            % est cost per W PV panel
        PV_watts = 14;
        batt_cost = 45000;          % est cost per AHr battery
        batt_Ahrs = 26;
        CEMI_cost = 50000+70000;    % est cost for CEMI device (5A charge
         controller, 150W inverter) end
    %}

    % incremental system properties
    properties
        V = 12;
        eff = .9;                   % efficiency of the system after various
         losses are included
        light_cost = 13000;         % TZS for 11W light
        light_watts = 11;
        PV_cost = 85000/14;         % est cost per W PV panel
        PV_watts = 14/14;
        batt_cost = 45000/26;       % est cost per AHr battery
        batt_Ahrs = 26/26;
        CEMI_cost = 50000+70000;    % est cost for CEMI device (5A charge
         controller, 150W inverter)
    end
    %}
end
```

Agent

=====

```
classdef agent          % definition of a household in the community
```

```
    properties
        is_pop = 0;     % boolean for if the plot is occupied
        hrs_lt_avg = 0; % average lighting needs
        acc = 0;        % total cash available
        day_income = 0; % income for this house
        num_PV = 0;     % number of systems
        PV_watts = 0;   % total PV watts of panels
        batt_Ahrs = 0;  % total Amp hours of batteries
        watt_hrs = 0;   % balance of watts stored
        num_lights = 0; % number of lights needed at location, used for
         economic purposes only
        light_watts = 0;% quantities of various components in the house
        batt_empty = 0; % counters for how much the battery's are used
        batt_full = 0;
        batt_not_full = 0;
    end
end
```

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