Interconnection of Solar Home Systems as a Path to Bottom-Up Electrification

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Abstract

Solar Home Systems (SHSs) have revolutionised electricity access for offgrid communities, but have a number of significant limitations. They have limited demand diversity, produce excess energy and lack a clear pathway to scale alongside growing energy demand.

Electrical interconnection of existing installed SHSs to create minigrids could offer a way to both scale up energy demand and make use of wasted energy. This bottom-up approach has the potential to be flexible to the changing needs of communities, by using SHSs as a starting point for wider electrification, rather than the end goal. Despite this potential, little analytical work has been undertaken to model SHS interconnection, particularly accounting for demand diversity and long term system performance.

This thesis presents a time sequential stochastic model of interconnected SHSs, to investigate these systems under multi year operational timescales at high temporal resolution. It is shown for case study systems based on real SHS topologies that there exists significant demand diversity, with small clusters of 20 houses with identical appliances exhibiting an average peak demand of less than 70% of the combined worst case peak for individual SHSs. Excess generated energy is shown to be an average of 100 Wh a day for the smaller system types and 1000Wh a day for larger systems.

Interconnection of these systems demonstrates a significant reductions in LCOE for all system types compared to islanded operation, through more optimal dispatch of battery storage assets and use of excess energy. This resulted in a final LCOE of \$0.63/kWh for a network of 12 large SHSs - a reduction of 48.12% compared to islanded operation and an LCOE \$0.703/kWh for a network of 12 small SHSs - a reduction of 55.23% compared to islanded operation. This informed an investigation of possible operational business models for a network of SHSs, with three approaches proposed - an Energy System Operator with direct control over all users systems, an Aggregator model, where the system operator facilitates an energy market and a Peer to Peer model with direct consumer to consumer energy trading.

This thesis provides a robust evidence base for SHS interconnection - demonstrating that the approach can lower cost of energy and facilitate demand growth for offgrid energy consumers and proposes appropriate business models to deliver this affordable and clean energy.

Acknowledgements

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List of Acronyms

- SHS - Solar Home System
- SOC - State of Charge
- LCOE - Levelised Cost of Energy
- HDI - Human Development Index
- UNSDG - United Nations Sustainable Development Goal
- CAPEX - Capital Expenditure
- OPEX - Operational Expenditure
- NGO - Non-Governmental Organisation
- LED - Light Emitting Diode
- USB - Universal Serial Bus
- DNO - Distribution Network Operator
- DSO - Distribution System Operator
- GSM - Global System for Mobile Communications
- DC - Direct Current
- AC - Alternating Current
- PAYG - Pay As You Go

- MTF - Multi-tier Framework
- PV - Photo-voltaic
- ADMD - After Diversity Maximum Demand
- LLP - Loss of Load Probability
- SD - Small Domestic
- SC - Small Commercial
- LD - Large Domestic
- LC - Large Commercial
- USD - United States Dollars

Chapter 1

Introduction

This thesis reports on the investigation into the limitations of one solution to providing rural electricity access - the Solar Home System (SHS). They have limited demand diversity, produce excess energy and lack a clear pathway to scale alongside growing energy demand. The thesis proposes electrical interconnection of these systems to form minigrids of distributed SHSs as one possible solution to these limitations and presents an analytical framework to explore the benefits to cost of energy and wider societal benefits of SHS interconnection.

Electricity access is undeniably vital to human development. The 8th United Nations secretary general Ban Ki-moon famously referred to energy as [18]:

> "The golden thread that connects economic growth, social equity, and environmental sustainability."

Figure 1.1: The 17 United Nations Sustainable Development Goals [1]

This importance is reflected in the United Nations Sustainable Development Goals, shown in figure 1.1. Goal 7 is “Affordable and Clean Energy” and one of the four targets against which goal 7 is measured states:

> “7.1 By 2030, ensure universal access to affordable, reliable and modern energy services”

Since both the inception of the UNSDGs and the start of this PhD in 2015, significant progress has been made to achieve target 7.1. More than two hundred million people previously lacking electricity were connected between 2015 and 2017 [19], with distributed solar minigrids and Solar Home Systems making connection of even the most remote communities possible, where previously the extension of a national grid could have taken decades [20].

However, this figure does not capture the full story. Access to electricity does not always represent the same service. The cost, quality and scalability can vary greatly. The ends of this golden thread are frayed.

Progress towards goal 7.1 is contingent on the definition of “affordable, reliable and modern energy services” used. Connection to a 50 Wp Solar Home System is certainly more affordable in most cases than the alternative of burning kerosene or buying dry cell batteries to power a torch. The energy provided is reliable, within the limitations of using no more than 4 LED lights and a few hours of TV and phone charging a day. The services are based on "modern" technology. Yet this service is clearly not equivalent to the national grid connection enjoyed by those in more economically developed countries. Comparing these solutions only to the existing "traditional" fuels is disingenuous.

The bills paid by consumers using one of these off grid energy solutions can be 20 times greater per kWh than those connected to a national grid [20]. The magnitude of the energy they can draw is much lower, prohibiting most productive, industrial and income generating end uses of energy.

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	No electricity	1-50W	50-500W	500-2000W	>2000W	
Duration	<4hrs	4-8hrs		8-16hrs	16-22hrs	>22hrs
Reliability	Unscheduled outages				No unscheduled outages	
Quality	Low quality			Good quality		
Affordability	Not affordable		Affordable			
Legality	Not legal			Legal		
Health & Safety	Not convenient				Convenient	

Figure 1.2: ESMAP Multi-Tier Framework for Measuring Energy Access from [2]

The human development benefits of electricity access are not only dependent on having access to any amount of electricity. The benefits scale with magnitude and cost. The World Bank established an energy tier framework, shown in figure 2.7, as an attempt to define differing levels of electricity access. These tiers offer a more comprehensive framework, moving beyond a simple, binary measure of have and have not, but are not currently considered as a key part of the process of electricity access planning. This process predominantly focuses on this short term target of providing universal access for the lowest cost, without consideration of the tier of energy being provided or the long term impact of selected solutions.

The appeal of the UNSDGs is that they offer a comprehensive, high level and simple targets. But if the goal of universal electricity access under its current definition is pursued without considering the long term ramifications, the end result could be a more stratified and unequal global society, where everyone technically has "access" to electricity. It is easy to envisage a world where target 7.1 has been met, but the benefits are disproportionately allocated to those in urban locations and more economically developed countries.

So what can be done to address this fundamental challenge? How can planning approaches be adapted to consider a more nuanced view of electricity access? Given that the prevailing drivers seem unlikely to change quickly, how can off grid distributed resources be upgraded over time to provide higher tier energy access? What role can technological innovation play in this process?

These are the key questions this thesis aims to address.

1.1 Research Scope

The core research question of this work is: "Can connecting together existing small offgrid energy systems to create minigrids offer improved performance and value over standalone systems?"

This thesis will consider how the following factors impact the Levelized Cost of Energy of a system, with a focus on the operational impacts on:

- Demand and generation diversity between different clusters of real world system types.
- Dispatch approaches for generation and storage assets.
- Battery lifetime and replacement
- Business models for operating this novel system type
- Increased use of energy both domestically and in flexible productive uses

A range of factors are considered outside the scope of this work, but their impact are investigated in discussions and highlighted in further work:

- Capital costs of installing and connecting communities low voltage DC networks
- The impacts of distance between properties on losses,
- Voltage and power flow simulations
- Detailed technical examination of controller design and control schemes

1.2 Existing Solutions for Electricity Access

In order to understand the current and future trends in electricity access, we must first investigate the different methods for providing electricity access. These can roughly be divided into three: grid extension, community scale offgrid electrification using minigrids and household scale offgrid electrification via Solar Home Systems.

1.2.1 Grid extension

In traditional, modern power systems, infrastructure deployment occurs from a top-down perspective, with centralized generation, large scale transmission assets and distribution networks providing electricity to domestic consumers and businesses.

This approach benefits from the economies of scale offered by large generation assets and both temporal and geographical diversity in generation and demand but requires a significant capital investment and is time intensive, with many locations in under served countries unlikely to be connected to a national grid in the next 10 years. In addition, many national energy systems are highly unreliable, with regular planned and unplanned blackout [21]. Connection costs can be in the \$100s or \$1000s [22] for domestic customers, prohibiting connection of even some communities close to existing grid infrastructure, but unable to meet these costs of connection. The result for rural offgrid communities is uncertainty regarding whether the national grid will ever expand to meet them and whether they will be able to afford to connect if it ever does arrive.

The proliferation of distributed generation assets such as solar PV at the distribution level and increasingly storage technology, is beginning to disrupt this approach in many countries [23]. However, in developing countries this presents unique challenges and opportunities in the deployment of solar PV, both on and off grid, which will require innovative new approaches to electrification planning strategies to ensure appropriate coordination of bottom-up and top-down approaches.

1.2.2 Off grid Electrification

Off grid energy systems are islanded energy systems not connected to a national scale grid [24]. This enables quick deployment to those in remote and rural locations that the national grid has not reached or where the service provided is highly unreliable.

The system types investigated in the work are divided into two main categories, Solar Home Systems and minigrids. Both systems comprise generation and storage, which is designed to meet a predicted user load in the most cost effective and reliable manner for both the system developer and the end user.

On the smallest end of the scale is the Solar Home System. These systems comprise a solar panel, typically between 10-100 Wp, a battery between 10-100 Wh, a charge controller and a range of DC loads [25]. These loads include high efficiency LED lighting, phone charging, and often TVs, radios and productive appliances such as hair clippers.

As the batteries, panels and most loads operate at DC, the system is designed to operate natively at DC. This offers significant efficiency benefits, due to the removal of the requirement for inverters to convert from AC to DC for many of the loads on the system. These systems can be deployed quickly, with relatively low upfront investment in even very remote locations, but provide only 'basic' tier 1-2 electricity access [26], often limited to only basic lighting and phone charging.

Minigrids represent a middle ground between SHSs and national grid infrastructure. They can range from 1 kW to multi MW systems and can serve a range of demands, from domestic lighting and phone charging to healthcare centres, schools and larger productive and industrial applications [27]. Minigrids are most suitable in locations with a high population density where the economies of scale associated with centralised generation and the benefits of demand diversity can best be realised.

The limitations of a microgrid is the increased cost of energy when compared to the economies of scale possible by connection to a national grid and significant planning uncertainty, particularly in relation to planning reinforcements to accommodate demand growth [28]. In addition, there are many unaddressed challenges surrounding appropriate and sustainable business models, as well as system operation and maintenance in areas often with limited skills capacity [29].

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1.3 Summary of Motivation

The sections above form the key motivation for the work described in this thesis. To summarise:

- Access to electricity can be shown to have a strong correlation with and impact on multidimensional poverty indicators.
- Improving electricity access can form part of an enabling environment to improve the lives of many people, particularly those in remote and rural areas of developing countries, and help to address the stated aims of the UNSDGs to achieve a sustainable, equal and affordable energy for all.
- Significant progress has been made in the past 20 years to address the lack of access, both through large scale infrastructure projects such as expanding national grids and increasingly through decentralised solutions such as minigrids and Solar Home Systems. Offgrid energy systems can quickly and cost effectively meet the initial lifeline needs of communities, but are usually designed as one size fits all solutions, lacking plausible paths to upgrade.
- The access to electricity provided by these interventions can range in cost, quality and reliability. This can mitigate much of the benefit.
- There is little consideration surrounding how to upgrade these systems as the needs of communities change over time, other than upgrading systems on an ad-hoc basis.

Therefore this work presents evidence of SHS interconnection as an appropriate solution to this problem, which takes a long term view of planning and results in systems that:

- Are cost-effective for developer and consumer
- Can flexibly accommodate growth in household demand
- Connect more customers to a reliable energy supply

1.4 Bottom-Up Electrification

This thesis presents the results of investigation into an alternative methodology for planning, upgrading and improving the provision of electricity access for off grid systems in areas with more than one SHS or minigrid in close proximity. This is achieved by electrically interconnecting islanded systems using low voltage DC networks, to build larger interconnected systems. This approach is referred to as swarm electrification, bottom up electrification or system interconnection respectively in the existing literature [26], which is investigated in more depth in chapter three.

This interconnection can take place at a number of scales, from interconnection of SHSs in villages to form community minigrid, to larger scale interconnection of multiple minigrids over larger distances. Figure 1.3 shows the potential progression of a set of systems, beginning with isolated SHSs which are then interconnected to from a distributed microgrid, utilising the excess generation of each system and the created demand diversity to offer an improved service to each customer. Additional centralised generation and storage can then be added, in line with the changing demands of the community. After this, a number of proximate microgrids can be interconnected, further increasing the demand and in some cases generation diversity and allowing coordinated dispatch of assets.

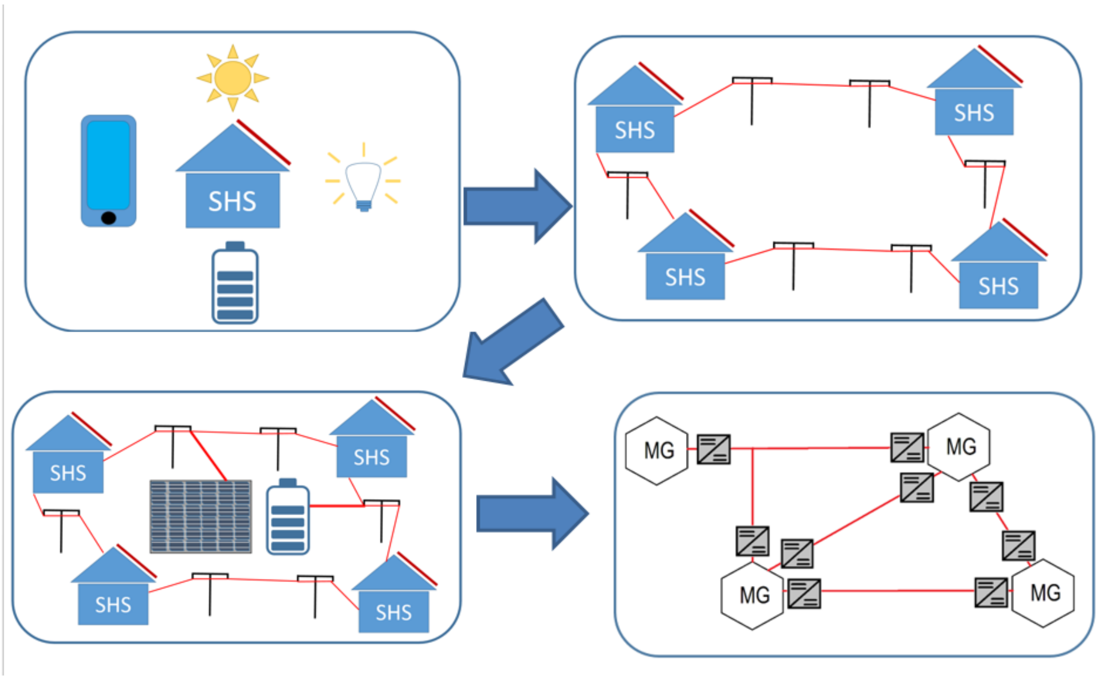

Figure 1.3: The process of bottom-up electrification

This approach offers a number of potential benefits, each of which will be explored further in this thesis:

- Connecting a larger number of energy users can increase diversity of demand, smooth peak demand and flatten demand profiles. This is particularly impactful in cases where systems with diverse demands are connected but benefit can also be demonstrated for systems with identical loads and behaviour patterns due to the stochastic behaviour of users.
- Unlock unutilised energy in oversized systems such as large SHSs commonly deployed in East Africa, which can waste more than 50% of generated energy [30].
- Smart utilisation of assets can optimise dispatch of shared generation and storage to mitigate the variability of renewable sources and increase system reliability.
- Reduced cost of energy due to more optimal dispatch of both battery storage and diesel generators to minimise utilisation.

- Allow more cost effective future investment in centralised or shared generation and storage assets that can be utilised by all interconnected systems, rather than needing to upgrade each system separately, as is the case currently for SHSs
- Facilitate a more incremental approach to investment in rural electrification, aligned with and driven by evolving community needs. SHSs or other small systems can be deployed quickly to meet the urgent human development needs of communities with the intention of interconnection as an optional upgrade at a time matching the changing needs and ability to pay of communities.
- Less speculative investment is required upfront, reducing investor risk, as additional capital can be invested into communities with proven ability and willingness to pay and demonstrated growth in energy demand. This can be key to engaging the private sector in such projects and to meeting the targets of SDG 7.
- Allow new and innovative business models such as peer to peer energy markets offer the possibility of increased energy literacy and engagement with production, as well as possibilities for increased community cohesion.

The literature detailing existing work on interconnection of offgrid energy systems is explored in greater detail in chapter 4. Work on bottom-up or swarm electrification covers technical discussion and simulation of systems on an operational timescale of minutes to days and covers detailed technical analysis of how to connect systems.

There is a significant gap in offering a methodology to allow the long term performance of system interconnection to be assessed quantitatively against a range of metrics informed by the Multi Tier Framework. This methodology can facilitate comparison with traditional reinforcement in a range of situations and inform planning.

1.5 Thesis Overview

This thesis considers how to asses the viability of upgrading offgrid energy systems via the novel approach of electrical interconnection of islanded systems.

- Chapter two outlines the importance of electricity access to human development and establishes and compares current approaches to providing electricity access.
- Chapter three explores how electricity access is planned, elaborating on the difference between bottom-up and top-down approaches to planning before investigating the most prevalent planning methodologies and tools and their limitations.
- Chapter four introduces the concept of bottom-up electrification and lays out the theoretical framework motivating its investigation, with reference to the shortfalls in exiting approaches presented in chapter three. Existing work in this area is reviewed and examined, with the aim of clearly identifying academically valuable, novelty and relevant gaps in literature and locating the contributions of this work within that context.
- Chapter five outlines a proposed stochastic methodology utilizing Time Sequential Monte Carlo Simulation for quantifying the impact and uncertainty associated with interconnection of islanded offgrid energy systems. The requirements of the methodology are first explored and a number of potential approaches suggested. The selected methodology and attendant model is then further detailed, with each modular component of the system described and validated with relevant results. These modules are then combined into a full model, which can be applied to evaluate interconnection of offgrid energy systems of all sizes on a number of metrics.
- Chapter six applies the developed methodology to SHSs in order to investigate the limitations of these systems and the potential merits of interconnection. It is established that under the expected demand growth of 8% per year set out in widely used planning methodologies, SHSs become unsuitable in less than 10 years without significant retrofitting. It is also shown that SHS generate excess energy which could be utilised by interconnection. It is then established that battery replacement is a dominant cost for SHSs and that more optimal battery management and dispatch in an interconnected network could lead to lower LCOE. Finally it is shown that significant diversity of demand is present

in aggregated clusters of SHSs. All of these factors form the motivation for the investigation of interconnection in chapter seven.

- Chapter seven then applies the model and methodology to the interconnection of microgrids. First the more complex question of dispatch in systems with multiple forms of generation is addressed then a number of indicative case studies explore the impact of different numbers of interconnected systems and battery dispatch approaches on LCOE

- Chapter eight discusses the wider context of the findings in chapters six and seven, delving into the possible business, ownership and operational models for interconnected system, market operation, policy and planning implications and recommendations.

- Chapter nine concludes the work, summarising the key results and findings and presents potential further topics for investigation.

1.6 Key Contributions

The key contributions of this work are:

- Literature based exploration of the limitations of SHSs in delivering modern energy services and SHS interconnection as a route to address these issues.

- Development of a novel, time sequential Monte Carlo simulation methodology to investigate questions of demand and generation diversity of SHSs and the impacts of SHS interconnection in a stochastic manner.

- Application of this methodology to a range of different case-study SHSs - demonstrating the presence of demand diversity, excess energy generation and the lifetime limitations of the systems due to battery degradation.

- Modelling of interconnected SHSs under a range of system dispatch regimes, demonstrating significant potential to extend battery lifetime and reduce LCOE

- Investigation of operational business models for interconnected SHSs, informed by both simulation results and literature.

1.7 Publications

1.7.1 Papers and Reports

- Soltowski, B., Bowes, J., Strachan, S., & Anaya-Lara, O. (2018, June). A simulation-based evaluation of the benefits and barriers to interconnected solar home systems in East Africa. In 2018 IEEE PES/IAS PowerAfrica (pp. 491-496). IEEE.

- Bowes, J., Booth, C., & Strachan, S. (2017, August). System interconnection as a path to bottom up electrification. In 2017 52nd International Universities Power Engineering Conference (UPEC) (pp. 1-5). IEEE.

- Bowes, J. Pay-As-You-Go and Mobile Money Services for Off Grid Solar PV in Malawi Status, Barriers and Opportunities A Working Paper produced by the University of Strathclyde through the Scottish Government funded SOGERV project October 2018, https://strathclydee4d.files.wordpress.com/2018/11/malawi-payg-report-final.pdf

- Davies, Kathleen, Alfred Alsop, and Jonathan Bowes. ”Poverty Mapping in Sub Saharan Africa Using Night Time Light Pollution Data.”, in IEEE Global Humanitarian Technologies Conference 2020

1.7.2 Conference Posters and Presentations

- CIGRE General Meeting 2018, Paris, working group Study Committee C6 special contribution

- IEEE International Conference on DC microgrids 2019, Matsue, Japan, Poster Presentation

- United Kingdom Energy Research Council Conference 2018, Bath, UK, Poster Presentation
- United Kingdom Energy Research Council Conference 2019, Oxford, UK, Oral Presentation
- Energy Technology Partnership Conference, Dundee November 2019
- SmartFuturES 2019 and 2020 Oral Presentation and Poster
- UK Low Carbon Energy for Development Network Conference, Loughborough, 2018, Poster Presentation
- UK Low Carbon Energy for Development Network Conference, Glasgow, 2019, Oral Presentation

1.7.3 Awards and Prizes

- Winner of Strathclyde Three Minute Thesis competition 2016 and UK Semifinalist
- Winner of CIGRE Next Generation Network Presentation Competition
- Best Poster Award Energy Technology Partnership Conference - Dundee November 2019
- Winner Scottish Power Iberdrola Innovation Competition 2017
- Winner Strathclyde PropTech Competition 2017
- European Winner and Global Finalist IEEE Empower a Billion Lives Competition

Chapter 2

A Review of Existing Approaches to Providing Electricity Access

2.1 Introduction

This chapter establishes the landscape of electricity access, presenting its contribution to human development and the prevailing solutions used to provide electricity.

Section 2.2 presents the empirical evidence linking electricity access and positive human development outcomes, the scale of the challenge of achieving universal electricity access and current trends and progress in the area.

Section 2.3 addresses the issue of overlapping definitions used to describe different ways of providing electricity access. The terms minigrid, microgrid and nanogrid are often used interchangeably but for the purposes of this work, unambiguous definitions are established.

Section 2.4 presents the most common forms of electricity access provision: macrogrids, microgrids and Solar Home Systems (SHSs). The relative strengths and weaknesses of each are explored.

Finally section 2.5 contrasts the approaches presented in section 2.4, leading onto a deeper discussion of how the decision making process of electricity access planning in chapter 3.

2.2 Energy Access

840 million people (11% of global population) lack access to electricity as of the most recent available statistics in 2017 [19]. A further 2.4 billion live with connections deemed unreliable or unfit for purpose [5].

Figure 2.1: The 17 United Nations Sustainable Development Goals

Low cost and reliable energy is considered vital to human development. The United Nations Sustainable Development Goals [1] (UNSDGs) highlight electricity access as one of their 17 high level global goals (number 7), with a sub target of achieving universal electricity access by 2030.

Electricity access transcends goal 7 to form a vital enabling environment for progress on a number of other goals. Clean, affordable and reliable energy can facilitate a wide range of life changing technologies: medical devices and vaccine cold chains; education through internet access and lighting to study; improved agricultural yields through water pumping and agrotech. Enumerable other synergies link electricity to each of the other UNSDGs [31].

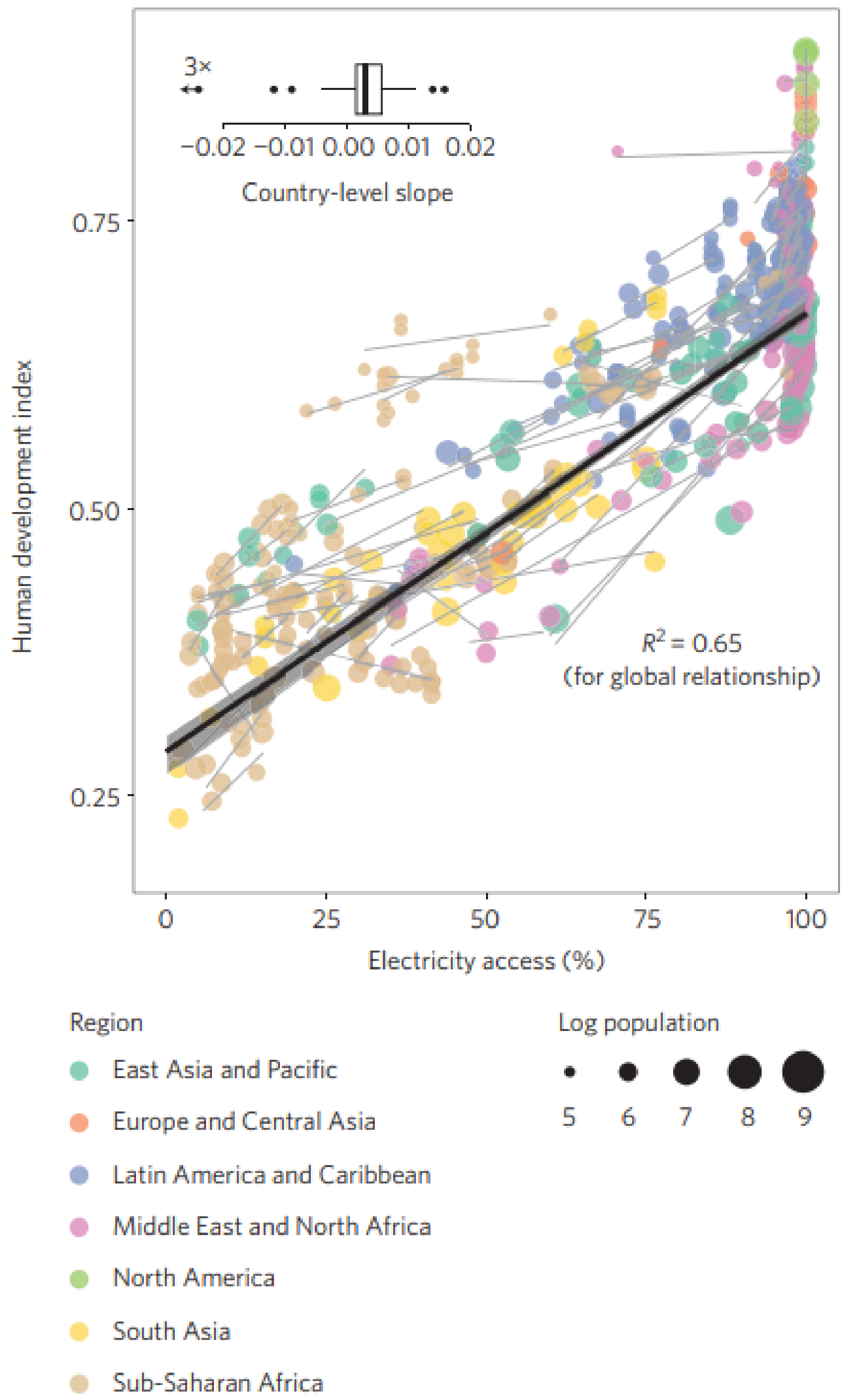

Figure 2.2: Electricity access vs HDI [3]

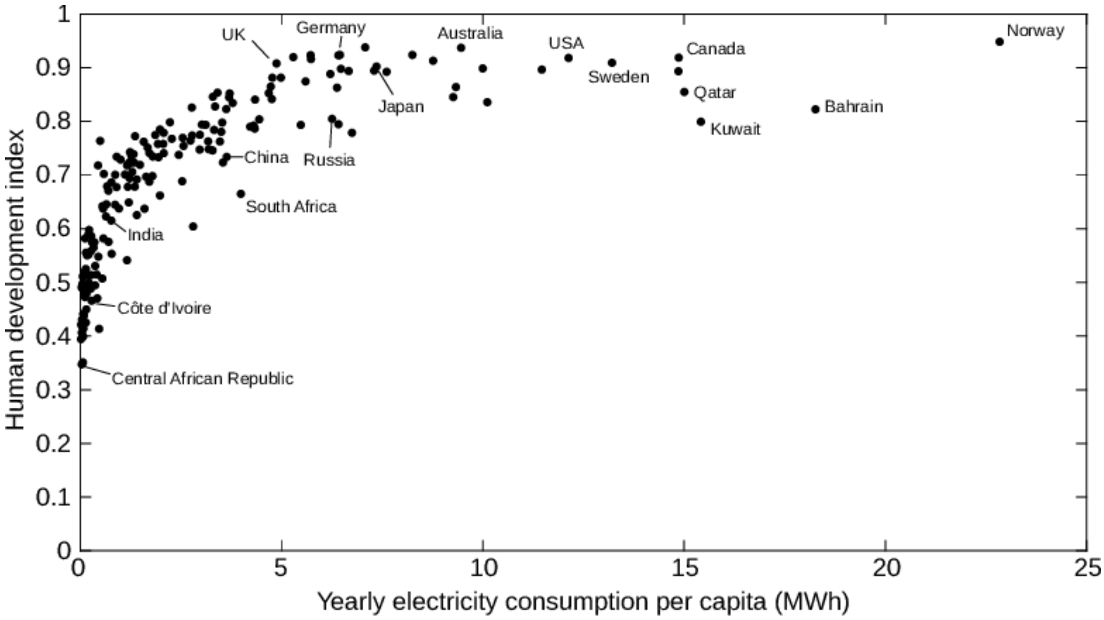

Figure 2.3: Primary final energy usage vs HDI [4]

2.2.1 Energy and Human Development

A strong correlation can be demonstrated between Human Development Index (HDI) [32], a compound measure of poverty comprising health outcomes, GDP per capita and educational attainment and access to electricity, shown in Figure 2.2 [3].

It is generally accepted that a two way causal link exists between these two factors, with electricity facilitating improvements in HDI and a greater likelihood of more developed nations (with higher HDI) having a higher incidence of grid connection [33]. To put it simply, the more energy people have access to and use, the higher their quality of life becomes and as their quality of life improves, the more energy they require.

Correlation can also be demonstrated between HDI and primary energy consumption, shown in Figure 2.3. This implies a coupling of energy use and development outcomes, although this trend encompasses all primary energy use, not just electricity.

As with electricity access, the correlation between primary energy use and HDI does not directly imply a causal link. This aligns directly with the coupling of energy use and economic output traditionally seen in manufacturing led economies [34], although this direct link between GDP and energy intensity is observed less in "transition economies" moving to more service led models of economic value [35].

Both the proportion of electricity connection and primary energy use per capita have a demonstrable correlation with HDI and accepted mechanisms exist to explain this correlation [36]. Therefore, to improve human development and achieve the aims of a prosperous, sustainable and equal planet, the provision of electricity access must be considered in more detail, both in terms of connection rate and magnitude of energy provided.

To understand the mechanisms of impact for electricity access in more detail, it is useful to investigate the impact at national and sub-national levels. [37] investigates the relationship between HDI and electricity access in 50 countries between 1990 and 2009 and shows a bidirectional causality between the two metrics over the long run and recommends that electricity provision should be a focus of public service provision in order to improve human development. [38] show that the potential for economic development within a community is directly enabled by not only the provision of electricity access, but its reliability and cost.

2.2.2 Progress Towards Universal Electricity Access

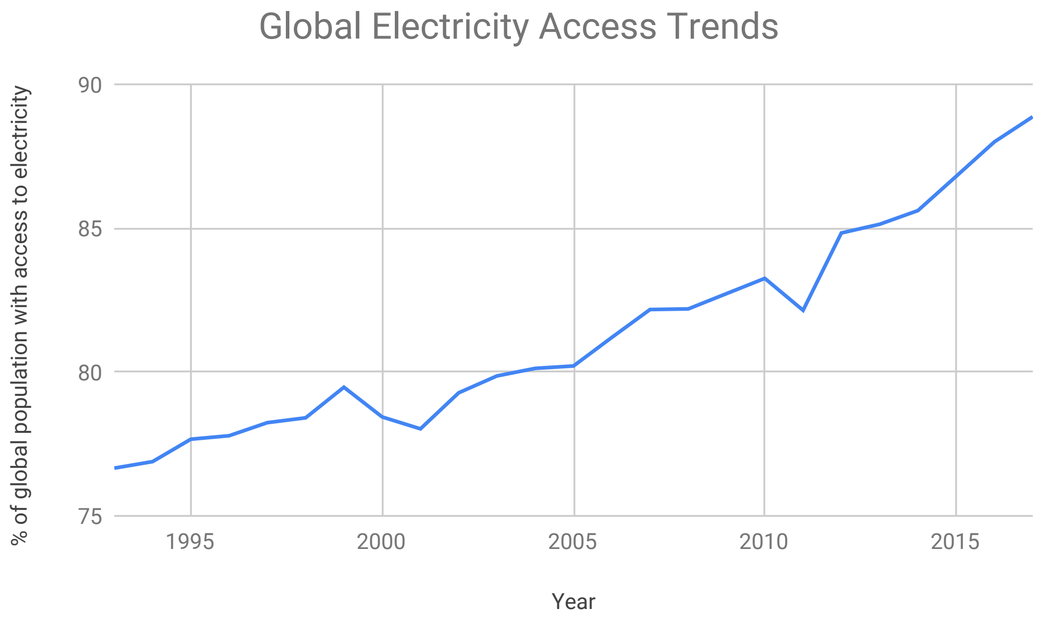

Figure 2.4: Global electricity access trends. Data from [5]

Figure 2.4 shows the trend of access as a percentage of population since 1993. Globally, access to electricity has been increasing systematically since recording began in the early 1990's [5], shown in Figure 2.4. Even since the beginning of the work presented within this PhD, the proportion of people lacking access has shifted from 14% to 10% representing a reduction in absolute terms of more than two hundred million people.

A large proportion of these gains to date can be attributed to top down initiatives expanding national grid infrastructure undertaken by the World Banks, National Governments and other international bodies [39]. These initiatives tend to disproportionately target those in urban areas, in densely populated areas close to existing grid infrastructure. As a result, 97% of urban population globally have electricity access, in contrast to only 78.6% for rural populations.

In addition, the bulk of those lacking access are located in developing countries in the global south shown in Figure 2.6, creating a significant global inequality in access to electricity and the human development gains enabled by reliable and cost effective energy access. Increasingly, off grid solutions are providing access for more remote and rural communities and this thesis will focus on this technology vector.

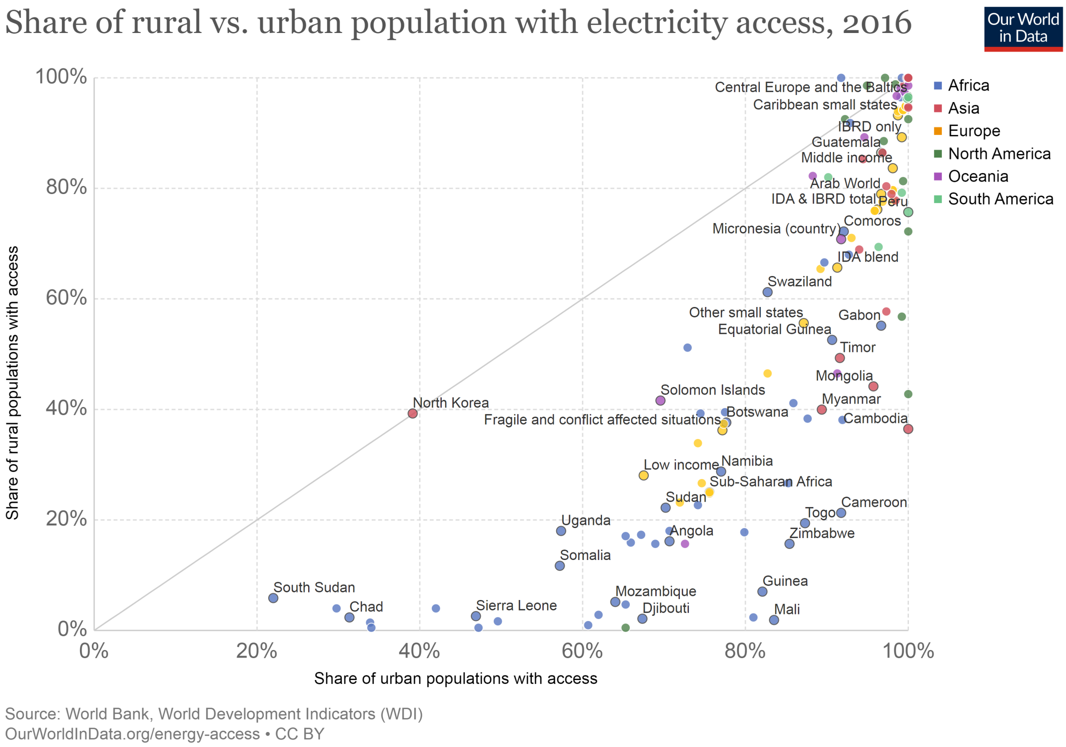

Figure 2.5: The rural/urban split in electricity access [6]

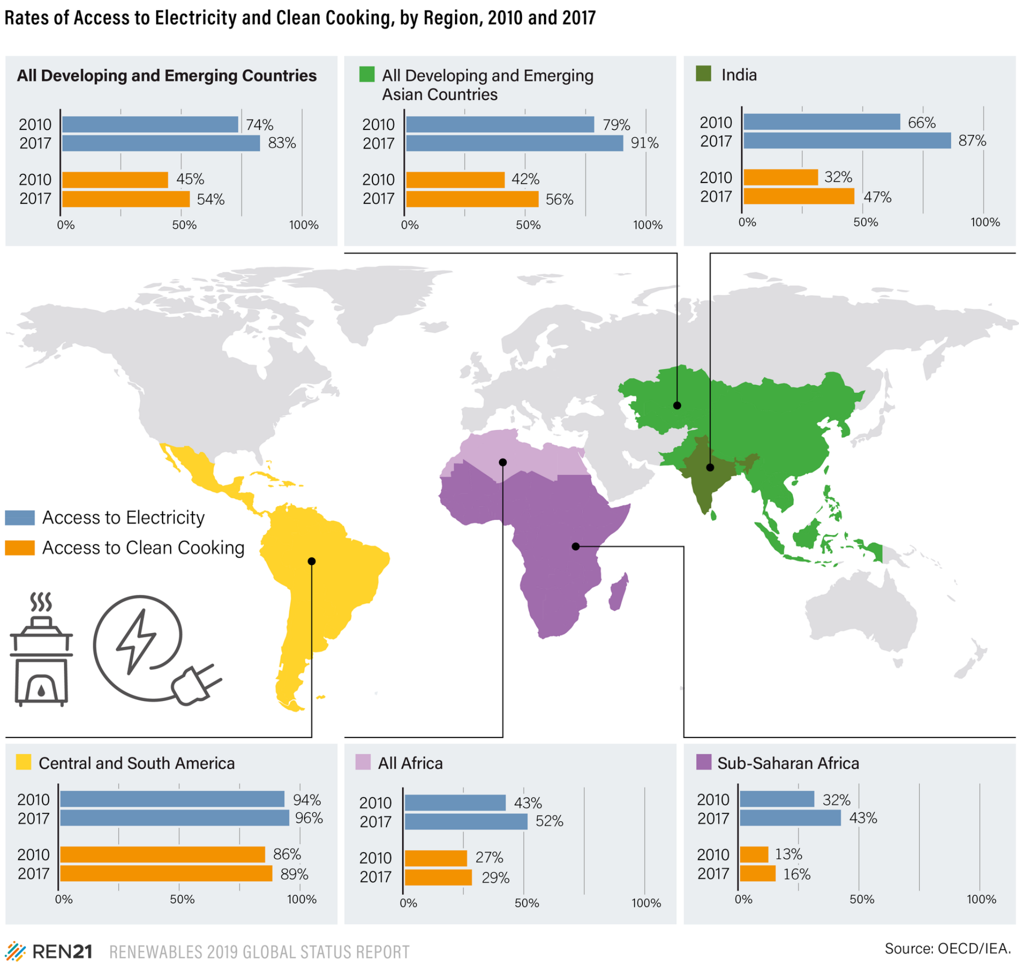

Figure 2.6: Map of world trends in access to electricity [7]

Despite this inequality, the trend represents significant progress towards achieving universal electrification. However, current projections show that the UN's "leave no-one behind" objective will fall short, with 650 million people remaining without access to electricity by 2030 [19]. 90% of these people will be located in Sub-Saharan Africa.

2.2.3 The Binary Electricity Access Measures

Most measures of electricity access rates are based on a binary measure of "electricity access" [5], considering populations with a connection as the basis for calculating electrification rates. It is this measure that results in the often quoted figure of 840 million people without electricity access, but it does not tell the whole story. This approach in gathering figures made sense under the assumption that all connections at equal, made to a reliable national grid, but fails for two reasons:

- Many national grids are unreliable, expensive to use or connect to and unfit for larger industrial applications [40].
- A significant portion of new connections are not being made to national grids, but instead to minigrid and SHSs offering a range of costs, reliability, power and energy limitations depending on system design and context [26].

There remains significant doubt that electricity access as a binary measure, without consideration of quality, reliability, cost and a range of other factors have a meaningful impact on multi-criteria poverty indicators [41].

Some attempt to formalise a more nuanced approach to measuring the quality of energy access has been made in the "ESMAP Multi-Tier Framework for Measuring Energy Access", which acknowledges the importance of considering "the reliability and quality of the energy being accessed" [2].

Figure 2.7 shows the "ESMAP Energy Tier Framework" for household energy established in Beyond Connections: Energy Access Redefined [2] which attempts to define 6 tiers covering a range of quality of service assessed against a range of key metrics. The report also outlines similar frameworks for clean cooking technology and productive uses of energy, allowing differing solutions to be compared not just on their ability to provide a binary measure of "electricity access" but also the magnitude, quality, affordability and other metrics vital for human development.

Instead of viewing energy access as this binary measure, it should be acknowledged that there are actually 'degrees' of access available, depending on the type of system end users have access to.

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	No electricity	1-50W	50-500W	500-2000W	>2000W	
Duration	<4hrs	4-8hrs		8-16hrs	16-22hrs	>22hrs
Reliability	Unscheduled outages				No unscheduled outages	
Quality	Low quality			Good quality		
Affordability	Not affordable		Affordable			
Legality	Not legal			Legal		
Health & Safety	Not convenient				Convenient	

Figure 2.7: ESMAP Multi-Tier Framework for Measuring Energy Access [2]

2.3 Nomenclature and Definitions

Definitions of off grid energy systems vary greatly and terms such as minigrid, microgrid and nanogrid are often used interchangeably in different contexts across literature and practice.

The usage of the prefixes nano, mini and micro imply the size of the system defines it, but no clear and constant delineation exists. Systems many orders of magnitude different in energy consumption can be referred to by the same name.

The technical, social and economic challenges faced by different systems depend more on the presence or absence of a distribution network or connection to a national scale grid and these factors will be used to delineate the different system types investigated in this work.

This section contains a short discussion of each term, based on the available literature and use in practice and establishes consistent, distinct and clear definitions. Each approach to providing electricity access will then be discussed and compared in more detail in section 2.4 below.

2.3.1 National Grid or Macrogrid

A national grid or macrogrid is a country scale system for the provision of electricity consisting of a transmission network, distribution network and large-scale centralised generation, although smaller scale distributed generation has become integrated with national grids with the growth of renewable technology. The key factor differentiating a macrogrid from a minigrid is scale, optionally defined by the voltage level of network infrastructure or peak power demand.

2.3.2 Minigrids and Microgrids

Sources of differentiation between the two system types could include voltage level, geographic size, number of customers, capacity to connect to a national grid, installed generation and storage capacity, but there is no established standard definition of a minigrid or microgrid nor the difference between them.

For the purpose of this work, the following definitions will be used, taken from established sources. A microgrid is defined by the US Department of Energy (DOE) as [42]:

> A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.

And a minigrid is defined by the European Union Energy Initiative [29] as:

> A small-scale electricity generation (10 kW to 10MW) which serves a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks.

These definitions classify both microgrids and minigrids as consisting of generations, distribution and loads, with the option for storage. The key difference is the presence in a microgrid of a connection to a larger macrogrid, allowing a net flow of power between the two systems. An always islanded system with no connection to a macrogrid is termed a minigrid.

2.3.3 Nanogrid

A nanogrid can be considered as analogous to the minigrid but serving only a single location or household without a distribution network. A nanogrid is therefore comprised of generation, loads and optionally electrical storage [43].

2.3.4 Solar Home Systems

A Solar Home System (SHS) is a nanogrid comprising solar photo voltaic panels as its only form of generation, battery storage and loads serving a single household or demand such as a shop or small business [44].

2.3.5 Pico Solar Product

Pico solar devices are currently the most prevalent and smallest off grid energy solution. They consist of a small lamp, solar panel and battery all integrated into a single enclosure [45].

2.4 Types of Electricity Access Provision

In order to investigate innovative approaches to electricity access planning, it is first necessary to understand the existing approaches, how, why and where they are used and their relative strengths and weaknesses. Existing provision of electricity access is driven by this binary measure, but a more multidimensional view of electricity access, acknowledging quality of connection will be taken in this comparison

The five most commonly utilised approaches to meet energy needs are: Traditional energy sources such as combustible fuels; connection to a macrogrid; connection to a minigrid; Solar Home Systems and pico-solar products. We will take nuanced view of their relative place within existing electricity access planning while establishing their limitations.

2.4.1 Energy Use in Non-Electrified Communities

Regardless of the provision of electricity access, every human has energy needs that contribute to their wellbeing. These include cooking to make the nutrients in food more easily available to the human body, consuming the food, warmth, lighting and increasingly the ability to charge phones and other electronic devices deemed integral to a happy and productive existence.

Globally, it is estimated that 643 million people without access to electricity are covered by mobile networks [8]. This represents more than half of those without electricity access. A higher proportion of the global population now having access to Global System for Mobile Communications (GSM) signal than electricity, as shown in 2.8.

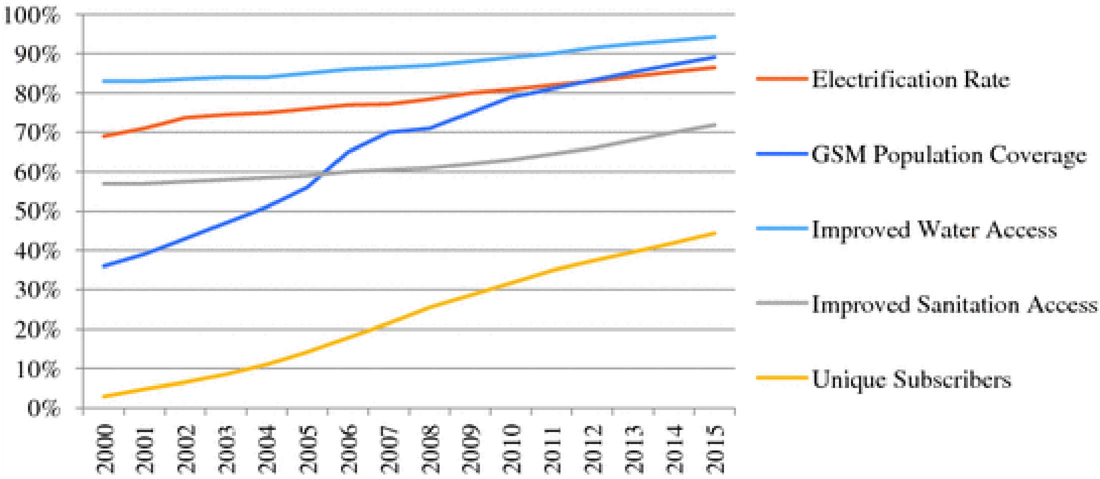

Figure 2.8: Percentage of global population with access to a range of technologies (from [8])

This means that these consumers are charging phones by other means, either paying those in shops or houses with electricity access of some form or using dry cell batteries [46]. Both of these options present significant economic cost and dry cell batteries represent a significant environmental challenge for safe processing and disposal.

Lighting services can be provided by torches powered by the same dry cell batteries or by lamps burning fuels such as Kerosene [47]. Indoor air pollution results in 4 million preventable deaths a year [48]. Alongside cooking, pollution from kerosene lamps is a significant contributor [49] to this pollution and also present safety concerns due to fire risk [50].

[51] shows the use of different offgrid sources for lighting on non-grid connected communities in 2016, clearly showing the range of energy services utilised across East Africa. LED lamps powered with dry cell batteries are widely utilised in the sample, with between 27% and 100% of respondents in 6 sample countries reporting their use.

[9] also examines energy use in pre-electrified communities and shows the trend in falling use of kerosene and the increase in use of dry cell batteries, showing that even in non-electrified communities the vectors for lighting are rapidly shifting.

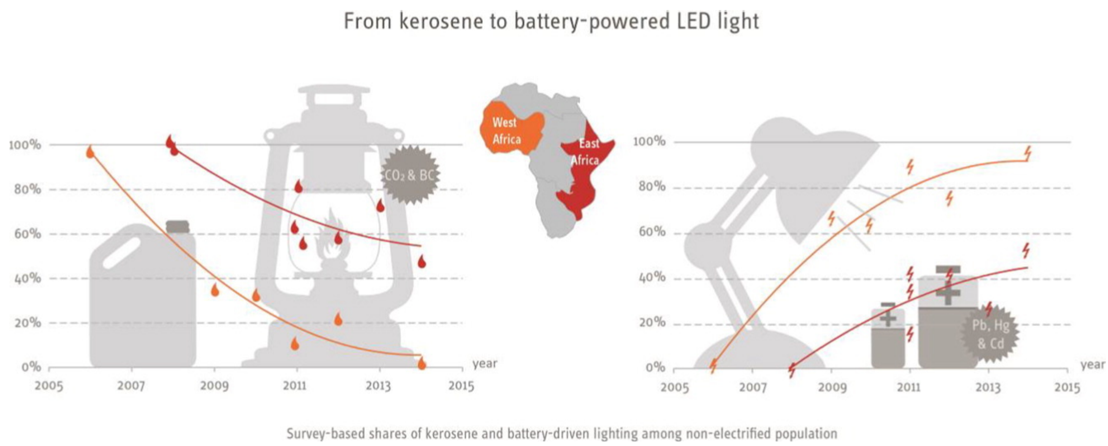

Figure 2.9: Trends in non-electrified communities energy services for lighting from [9]

We should also consider cooking, the largest energy demand for most off grid consumers. 3 billion people globally still cook with solid fuels. This requires either buying or collecting fuels such as charcoal or wood, requiring money, time or both [52].

eCook or battery assisted electric cooking is an area of increasing interest, seeking to utilise the historic fall in battery and solar PV module prices and high efficiency electric cooking devices like pressure cookers to shift this solid fuel demand to electricity [53].

As we can see, even communities classified as without electricity access have a range of energy services they use every day. A lack of consideration of the existing energy use and the connected culture, behaviours and economics is one of key ways the common idea of electricity access as a binary measure breaks down.

Many of those classified to be without access to electricity do have access, albeit in an inconvenient or expensive manner, and many of those classified as having access to electricity rely on traditional solid fuels as the source of energy for significant proportions of their primary energy use, such as cooking or portable lighting. This exemplifies the importance of moving beyond a binary when considering electricity access and aiming to understand the specific contexts and needs of communities and individuals and motivate the need to consider incremental bottom-up energy infrastructure to support changing needs of communities.

2.4.2 Grid Extension

A macrogrid, as defined above, has three key components: generation, transmission and distribution, shown in figure 2.10.

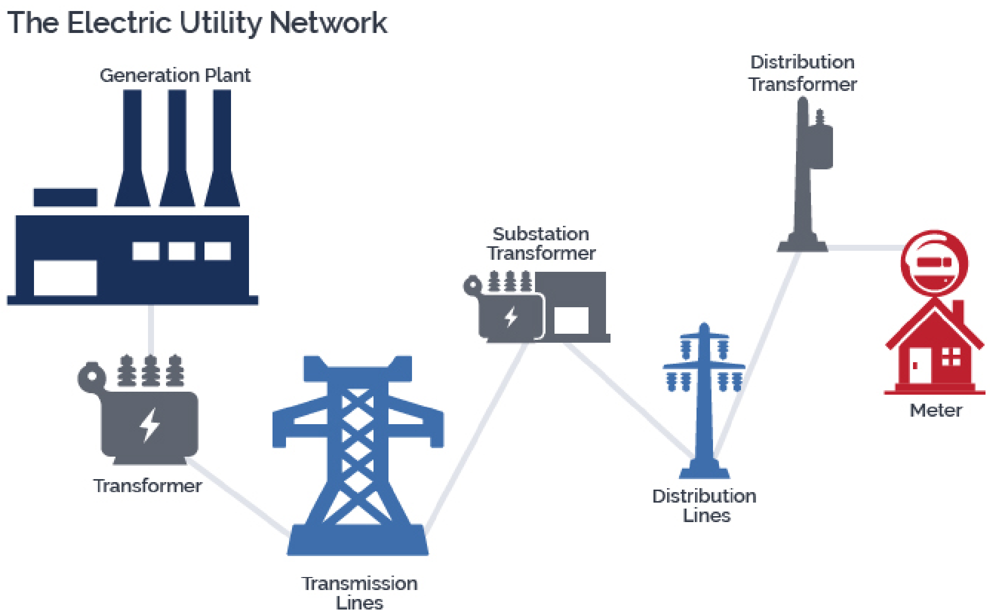

Figure 2.10: Traditional macrogrid topology [10]

Generation is based on utilisation of large, centralised generation usually in the form of large power plant, such as hydro or fossil fuel combustion [54], although distributed renewable generation is becoming increasingly prevalent, presenting new barriers and opportunities explored in section 2.4.2 on smart grids.

High voltage lines, referred to as transmission move bulk power over large distances, from the locations of generation to consumers. The voltage levels of these networks vary around the world, but range from 100 kV to more than 400 kV.

Due to a high level of reliance on these networks, they are generally secured to N-1 [55] security levels in developed countries, meaning that any single line can fail and the system can still operate a maximum capacity. This option significantly improves system reliability, but in developing countries the additional cost of ensuring N-1 security is often prohibitive [56].

Lower voltage distribution networks connect houses, businesses and industry. In the UK the voltage levels of distribution networks vary from 132kV to 230V.

In most countries there is significantly more km of distribution network than transmission, as these networks must reach each consumer. For example in the UK there in 20,000km of transmission networks and 2,000,000 km of distribution These networks tend not to be secured to n-1 due to the the relatively lower impact (in terms of customer minutes lost and interruptions) caused by the loss of one line in the event of a system fault.

In most developing countries, existing grid infrastructure is concentrated around densely populated urban areas, with rural locations under served, leading to the urban/rural split in access outlined in 2.5.

For the purpose of this work we define grid extension as:

> "The construction of transmission networks and/or distribution networks and additional generation (and other ancillary assets) and its connection to an existing national scale grid in order to connect new users or generation capacity. This may require reinforcement of existing network sections to accommodate increased power flows and/or improve reliability.

The advantages of this approach are significant:

- Macrogrids are capable of providing tier 5 energy to consumers.
- Macrogrids generally provide the cheapest cost of installed generation and Levelized Cost of Energy in most situations where they are installed, due to economies of scale [7].

- Energy is often subsidised by government, particularly in the form of common "lifeline" tariffs, where an amount of energy can be consumed each month at a reduced rate [57] [58], providing a significant social benefit for the poorest consumers [57].

- The large geographical coverage of macrogrids can allow more optimal placement of renewable energy resources, dependent on locational wind speeds or solar insolation. This can also result in increased diversity of generation and demand, helping to mitigate the variability of renewable generation.

- More diverse and numerous customer base can result in greater demand diversity.

- Grid extension is the most established method of electricity access provision, with many decades of operation experience globally and established business models, market mechanisms and ownership models.

- Ability to support large demands such as heavy industrial applications of energy, both in terms of available power and cost of energy.

Despite this, grid extension can have a number of disadvantages:

- The process of extending a grid is capital intensive. It was estimated in 2015 that the total cost of providing electricity access for 100,000 people utilising grid extension would cost $150,000,000 [59].

- Planning and deploying grid infrastructure can take significant time, in some cases many decades. In the context of grid extension aiming to provide universal electricity access, the length of time taken by a solution is an important metric, as it will result in people being without the established human development benefits of electricity access. This particularly impacts on those in the most remote areas, who's needs will be met last by grid extension, potentially exacerbating inequality.

- Uncertainty about grid extension plans can result in investors and governments being unwilling to provide interim solutions, such as minigrids due to fear of lost investment and stranded assets in the case of eventual grid extension making a microgrid redundant [60].

- In less densely populated areas, more geographically dispersed populations result in greater cost for distribution network infrastructure per household, as the network must be longer. In locations far from existing grid infrastructure, grid extension cost is more expensive, as the network must cover more distance.

- The combination of these two points are one of the key reasons for the often observed rural/urban split in electricity access % in developing countries [61], [62]. The cost of deploying networks in urban centres with dense populations means that the most cost effective approach to providing electricity access and increasing the figures of population % access to electricity with grid extension is to focus on urban and peri-urban locations. This is also exacerbated by the 'inability to pay' of rural communities.

- Grid connection costs are often high. In many locations, consumers must pay a fee to get their house connected to the national electricity grid. These costs can often be significant [12] and un-affordable for many communities. This can lead to the phenomenon of so-called "under the grid" communities, people who live close to a national grid infrastructure but are unable to connect due to prohibitive connection costs.

- Macrogrids traditionally utilise thermal generation based on fossil fuels as a key component of their generation mix, emitting CO2 resulting in the electricity and heating sector being responsible for 25% of global emissions attributed to anthropogenic climate change [63]. Although there is a shift away from this in many developed nations as grid scale wind and solar become cost competitive [64], macrogrids are still reliant on thermal plant to provide dispatchable generation and inertia [65]. In order to meet the ambitions targets of the Paris Agreement [66], a significant shift in how macrogrids are designed and operated will be required.

- This reliance on fuel also makes macro-grids vulnerable to price variations in fuel and supply chain issues in most countries, which lack domestic fossil fuel production on the required scale.

- Macrogrids are vulnerable to cyber attacks. They represent a single point of failure for a countries energy infrastructure, in contrast to the distributed nature of the other solutions explored here. To date, there have been a number of high profile examples of cyber attacks on grids [67].

- In the case of blackouts, the process of "blackstart" for a macrogrid can be complex and time consuming, requiring the islanding and synchronisation of the grid, region by region. This process has historically taken a number of days, [68] leaving a large number of consumers without energy and impacting society, including significant consequences for public health [69]

- In many developing developing countries there are significant capacity shortfalls already existent in the national grid, either in terms of power, energy or both, resulting in both planned and unplanned blackouts [70]

Smart Grids

In recent years, there has been significant technological change in how macrogrids operate, away from utilising only a few large, centralised generators to a more distributed approach. These changes will have interesting consequences for how future power systems may be planned and deployed in developing countries.

Distributed renewable generation such as solar PV and wind, connected on the distribution network along with "smart" technologies including remote monitoring, demand side management and storage are resulting in a shift from centralized to decentralized operation [71] and from one way power flows from generation to consumer to complex and changing two way power flows.

Under this paradigm, many distribution network feeders often resemble self sufficient systems of generation, storage and demand, connected to a large network from which they can import and export energy as required.

This increased complexity is exemplified by the move from calling those responsible for the planning and operation of distribution network Distribution Network Operators (DNOs) to Distribution System Operators (DSOs) [72], reflecting the changing challenges of this new, more complex, technologically enabled system.

The impacts of these technologies is gradual on existing grids, as technologies are retrofitted to infrastructure not designed with "smartness" in mind. For developing nations with less existing infrastructure, this technological shift can be seen as a potential opportunity to design networks from the ground up to take advantage of technological developments and more effectively integrate distributed energy resources.

2.4.3 Minigrids

This shift towards local generation is also observed in the rising popularity of minigrids. Minigrids offer an alternative to grid extension. They do not require connection to a macrogrid, making minigrids suited for locations far from existing macrogrid infrastructure, where the majority of those classified as unelectrified are located [61].

The economics of deploying minigrids have shifted in recent years due to falling cost for distributed generation [11] and battery storage [73]. This economic shift has led to the rise of renewable minigrids, utilising solar, wind and other renewable forms of generation, hybridised with battery storage and diesel generators for backup.

The advantages of minigrids for providing electricity access are:

- Minigrids can be purposely designed to best utilise geographically varying local renewable generation resources, such as hydropower, solar photovoltaic or wind. If properly designed this can result in both lower cost of energy and more sustainable and reliable systems, reduce requirement the delivery of fuel and the risk exposure price volatility of fuels such as diesel and gas, which can affect those microgrids and fossil fuel burning microgrids.

- For remote locations far from an existing macrogrid, deploying a minigrid can be significantly quicker than waiting for grid extension, although slower than deployment of individual SHSs.

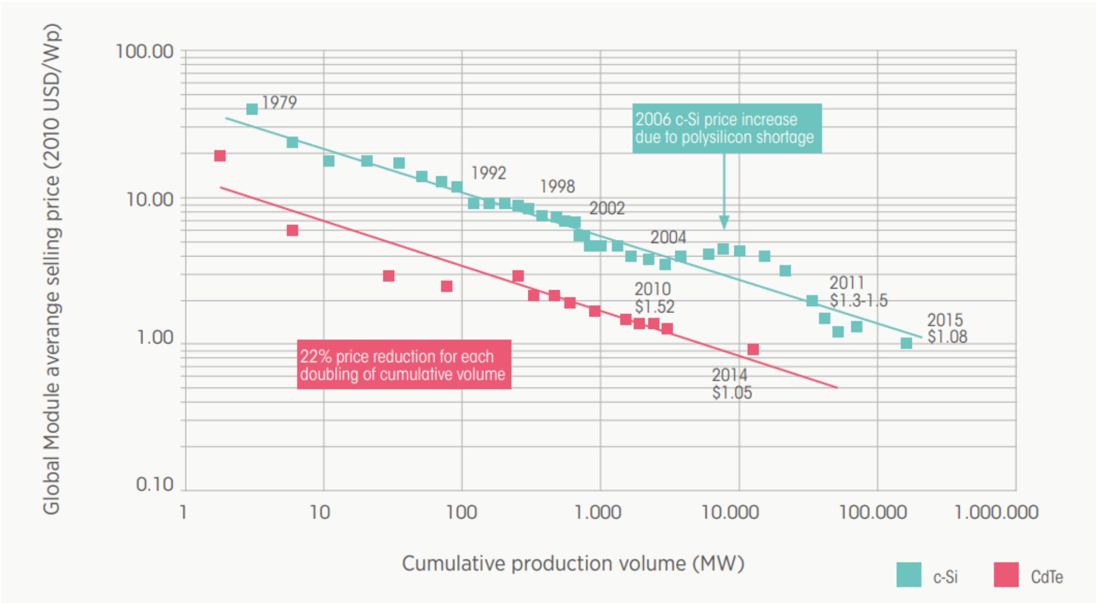

Figure 2.11: Cost of Solar PV modules between 1980 and 2014 [11]

- Minigrids provide more reliable, higher quality energy than SHSs.
- Can support larger loads, small industrial loads and other productive use activities.
- Generating and consuming energy in the same place removes the infrastructure cost, operational cost and losses associated with bulk energy transfer via a transmission network. minigrids therefore require less capital investment than grid extension in more remote locations, further from exiting macrogrid infrastructure.
- Less generation/storage capacity to serve a community than the combined generation/storage capacity required of SHSs to serve the same community, due to interconnection and demand diversity.

Minigrids present a range of unique challenges:

- Both macro grids and solar home systems have established and proven business models supporting their deployment but this is less true for minigrids. One of the key challenges for their successful deployment is establishing a viable business model that is both economically and technically sustainable as well as being acceptable for the community in question. In order to achieve sustainability a minigrid must be able to cover repayment of initial capital cost as well as maintaining funds for maintenance and repairs. Payback periods can be long and investment considered risky, which has resulted in more third sector engagement in their development than private sector engagement.

- There is a need for capacity building to ensure the necessary skills within communities to operate and maintain systems.
- Green minigrids require exploitable renewable energy resources. For communities in Sub-Saharan Africa, solar resource tends to be high, but can result in unreliable performance due to seasonality of weather.
- Uncertainty about demand within communities makes sizing minigrids a challenge. If the generation or storage are undersized, the system will be unreliable. Too large and the system will not able to sell enough energy to recoup its costs.

Minigrids can be designed to provide a range of tiers of energy access, dependent on the specific needs of the community in question, typical from tier 2 - tier 4. In some cases tier 5 energy access can be provided, such as on the Scottish island of Eigg [74], although the cost of providing tier 5 electricity on Eigg is almost £40,000 per connection which is prohibitively expensive for most communities in developing countries.

2.4.4 Solar Home Systems

Solar Home Systems (SHSs) are standalone, off grid solar photovoltaic (PV) systems, serving a single house or other load, such as a school or health center. Most consist of a set of solar panels, a charge controller, battery and loads, often operating natively at DC, requiring specialist appliances or the use of an inverter. SHS's are designed to provide basic energy access, such as lighting and phone charging at a relatively low cost. SHSs commonly range in size from 10Wp- 200Wp. Typically SHSs can provide tier 1-3 electricity access, with service beyond this requiring prohibitively large and expensive batteries and solar PV [75].

There has been huge growth in the market for solar home systems over the last few years. In 2016 over 4 million new SHS's found homes in Bangladesh, providing basic electricity access to over 16 million people [76].

The advantages of SHSs include:

- SHSs can be quickly deployed. Each system requires no attendant infrastructure to be installed and can be safely fitted with relatively little training due to the inherently safe SELV system voltages [77] (i.e. typically 48V, 24V or 12V) and their simple "plug and play" design, although this is still dependent on installation standards and training.

- Serving each house locally, without constructing a distribution network removes of the costs associated with the procurement, installation and maintenance of a network, making them particularly cost effective in locations with geographically dispersed populations.

- There can also be resilience and reliability benefits, as there is no single point of failure for a community as there could be for a system featuring centralised generation or storage.

- Systems can even be redeployed relatively easily to other communities in the case of grid expansion or the installation of a minigrid offering better quality of service, mitigating some of the risk of stranded assets.

- SHSs have a lower upfront capital cost than minigrids or grid extension, with 2015 Global Tracking Framework stating that providing 100,000 new consumers with electricity using SHSs would cost only $20,000,000, compared to the cost of $150,000,000 for grid extension. [59]. This is appealing if the aim of an intervention is to achieve the highest number of electricity connections, but does not compare like for like in terms of the tier of electricity access provided.

SHSs also have a range of disadvantages compared to other modalities of electricity access:

- The lack of any benefit from diversity means each individual system must be sized to meet peak demand for the connected loads, resulting in greater installed generation capacity for a given load than either of the other approaches discussed here [78].
- SHSs are even more reliant on storage than minigrids, and require more installed capacity for a given peak load in household, due to the lack of diversity of generation or demand and to account for days of autonomy.
- SHSs tend to be effective mainly due to the low energy demand from highly efficient DC appliances like LED lighting, phone charging, fans and radios, but this means they have limited ability to support higher power and AC loads.

The predominant business model for SHSs, particularly in East Africa is a "Pay As You Go" model, defined in this work as:

> Pay As You Go Energy: Any system or business model where consumers do not pay entire cost of an off grid energy system upfront. This can include models where consumers have no ownership of the system pay only for energy consumed, micro finance loans used to buy systems that are repaid over time or rent to own agreements.

This model has effectively enabled the rapid deployment of SHSs globally, overcoming many of the traditional challenges of providing electricity for remote and rural communities. The SHS market has quickly grown over the past 10 years, but there are inherent risks to its long term success built into one of the prevailing models of operation. For many PAYG customers, the provider stops receiving income from consumers at the end of their contract.

The prevailing method for upgrading systems is to sign the customer up to a new contract, replacing or supplementing the existing panels and batteries with larger components. This is outlined in the GOGLA report [79].

2.4.5 Pico-Solar Products

Pico solar products are the smallest classification of offgrid electricity access solution, consisting of a small solar panel, battery, lamp and sometimes USB charging port integrated into a single casing. They are designed to be left outside in sunlight during the day to charge and to provide lighting and phone charging at night, rather than being permanently installed as with SHSs. They are commonly marketed as replacements for traditional kerosene lamps as a cheaper source of nighttime lighting and can provide tier 1 energy on the ESMAP energy tier access framework.

The advantages of pico-solar products include:

- Low upfront capital costs mean many customers in developing countries can afford to buy these products with cash, removing the requirement for more complex Pay As You Go business models requiring more financial capability and expertness to operate.
- Their low cost means they can easily be purchased for cash in many communities. This facilitates rapid deployment and can also facilitate local businesses to sell these products where the large cost and more complex business models of SHSs and minigrids are prohibitive [12].
- Pico-Solar products require no installation and only basic training to use.
- Pico solar products are also common in humanitarian disaster relief applications, where their small size, low cost and portability are an asset, facilitating quick deployment and easy transport [79].

Despite these advantages, pico-solar products have significant limitations:

- The most fundamental issue with pico-solar lanterns is that they only provide very low power and do so intermittently. Each device can only be used in one room or location at a time, often only providing enough light for a single user.
- They require the user to actively remember to move the device outside to charge. This can result in opportunities for the device to be damaged while being moved,

risk the device may be placed in shaded or partially shaded locations, or the possibility of users forgetting to charge the device.

- Although a large number of high quality products do exist, many of them affiliated with GOGLA, there have been many cases of low quality products proliferating in SSA. This has had significant impact on the perception of the solar industry as a whole and pico solar products on particular.

2.4.6 Upgrading and Scaling Systems

Off-grid energy systems tend to be designed for a single predicted community need, informed by modelling, surveys and heuristics. This demand is both hard to predict and volatile [80]. Many systems fail because they do not correctly predict the electricity demand, resulting in a system that is too optimistic (oversized) and therefore too expensive or too conservative (undersized) and so inherently unreliable.

The conventional option open to the microgrid operators in accommodating demand growth is load-related grid reinforcement; removing and replacing existing cable and plant with higher rated equivalents. This can be costly and time-consuming, and can result in the stranding or decommissioning of existing assets as they are replaced with larger alternatives.

Some of this risk can be mitigated by planning systems with the intention of upgrading them over time as a clearer understanding of the community needs is developed. For example, many system designs now feature oversized cables and inverters compared to the predicted initial minimum requirement, as the marginal cost of these oversized assets is considered a justifiable cost to mitigate against full replacement of a system if the community demand grows [81].

For SHSs, the existing upgrade paths are less well established, due to the lack of maturity of the industry, but prevailing trends follow the paradigm of replacing battery and generation assets with higher rated alternatives in line with demand growth [12]. This approach, shown in figure 2.12, can be favourable for the companies providing the SHSs as it amounts to selling a slightly larger version of the same product to the same consumer a number of times, but can prove costly for the end user.

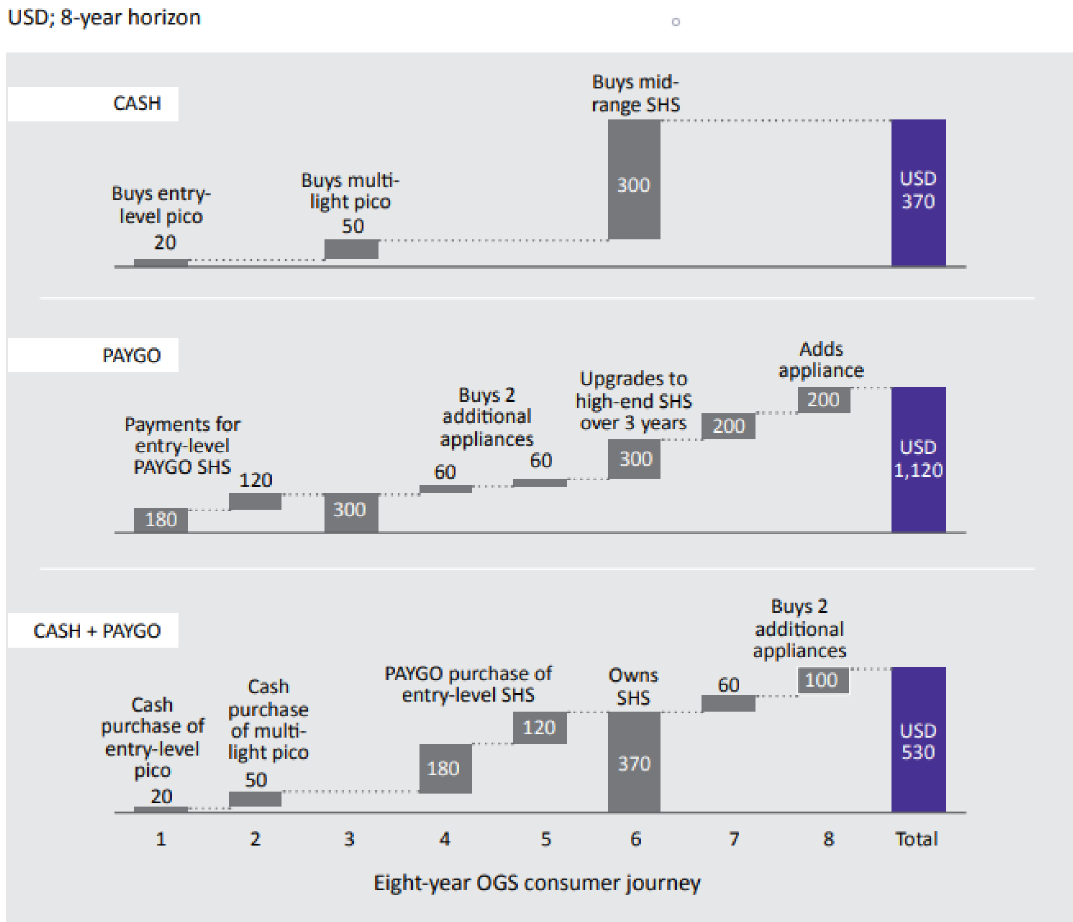

Figure 2.12: Proposed upgrade path for offgrid solar consumers from [12]

Due to the lack of diversity of demand and generation exhibited by SHSs, 100% of demand must be met at the level of each household. More than 50 % of generated energy [82] is dumped in some popular designs for SHS commonly deployed in East Africa, due to the design paradigm of over-sizing PV panels. Upgrading the size of systems as proposed in [12] does not address this wasted resource.

There is a clear motivation to utilise SHSs and minigrids to quickly and cost effectively meet the needs of remote and rural communities, but flexible upgrade paths to improve the quality of electricity access and mitigate the uncertainty associated with the offgrid energy market must move to the core of design thinking to realise the full potential of offgrid energy in a development application.

2.5 Comparison of Existing Electricity Access Solutions

Making a comparison between the different forms of electricity access outlined above is challenging due to the ability of each solution to provide a range of different qualities of service. Despite this, some generalisations can be made to allow comparison between 5 different solutions.

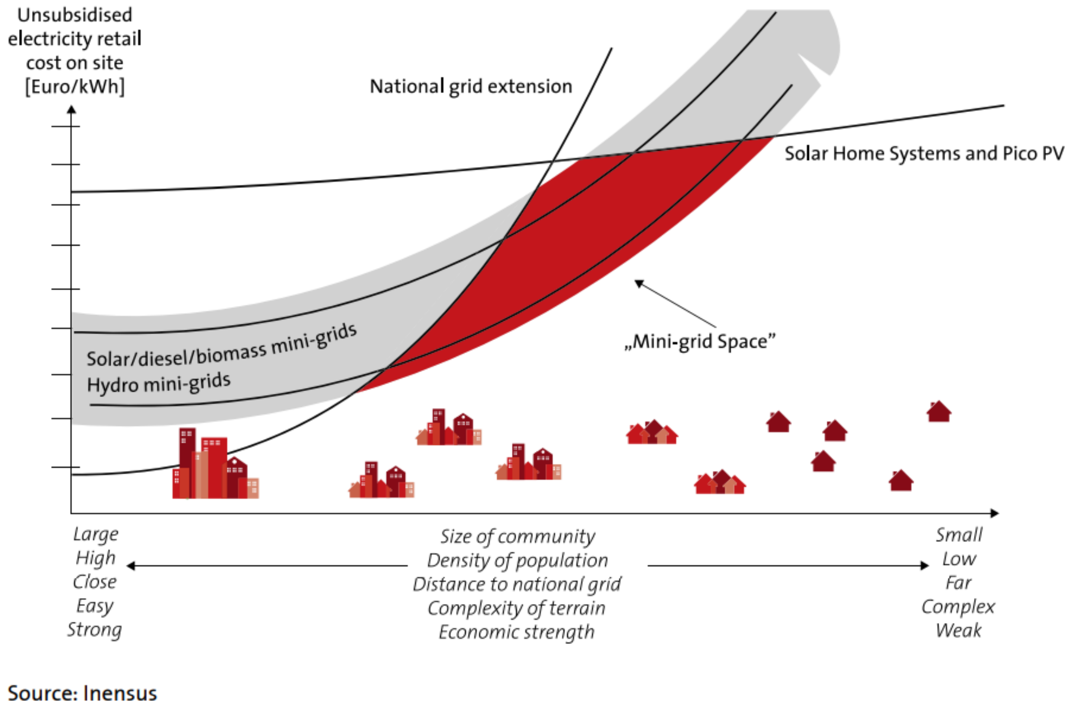

Figure 2.13: Minigrid space

Figure 2.13 from [83] visually represents the perceived trade-offs when considering differing methods of electrification, showing the perceived impacts of five different variables on the final cost of energy in a qualitative manner.

The graph shows that the levelised cost of energy for grid extension in densely populated location, close to an existing group is low, but the cost of extension increases exponentially as the distance and sparsity of the consumers served increases.

In contrast the cost per household providing energy through SHSs is considered higher in dense or urban populations but the increase in costs to sell more dispersed population is relatively small, creating an inflection point where it becomes cheaper provide individual SHSs than to build the extensive distribution infrastructure required to reach its population.

Minigrids in this example occupy a middle ground between these two solutions, serving populations far from existing grid infrastructure, but with a high enough density population to justify the additional costs of installing distribution network.

This image is oversimplified and does not capture the nuance of the situation. For example so-called under the grid consumers, located close to a national grid, but unable to afford connection are not considered. In addition, it does not consider the quality of service provided by each solution or the long term economic or development impacts of that energy.

2.6 Summary

Energy access is a cornerstone of human development, but the simply having a connection does not necessarily enable the full intersectional potential of electricity. The cost, reliability and magnitude of the energy access also play a key part the puzzle.

Many different approaches can be utilised to provide electricity access. The changing landscape of technology and the challenge of connection remote and rural communities has led to innovation in off grid energy systems dependant on renewable energy. These off grid solutions provide a range of different levels of service, but are often treated as synonymous by national and international data gathering and tracking frameworks such as the UNSDGs

The process of deciding which solution is appropriate in each context falls under the remit of energy access planning and is covered in detail in the next chapter.

Chapter 3

Planning

3.1 Introduction

This chapter investigates how the deployment of power systems and electricity access are planned and outlines the limitations in these approaches.

The limitations in existing planning form the motivation for investigating the role of interconnection in providing high quality and affordable electricity access for all. This chapter also explores who is doing the planning - NGOs, private companies or governments and the differing motivations and priorities these actors.

3.2 Top-Down vs Bottom-Up Planning

In order to fully investigate the advantages of an integrated approach to building electricity infrastructure, it is first important to understand the difference between top-down and bottom-up planning approaches as academic concepts and investigate how this aligns with existing practice in electrification planning. This section will briefly look at top-down and bottom-up approaches in policy implementation to establish their relative merits and uses within electrification planning.

3.2.1 Policy Cycle

Policy implementation is conceptualised in the form of a five stage policy cycle, shown in figure 3.1 [84]. A top-down approach to policy is driven by a centralised decision

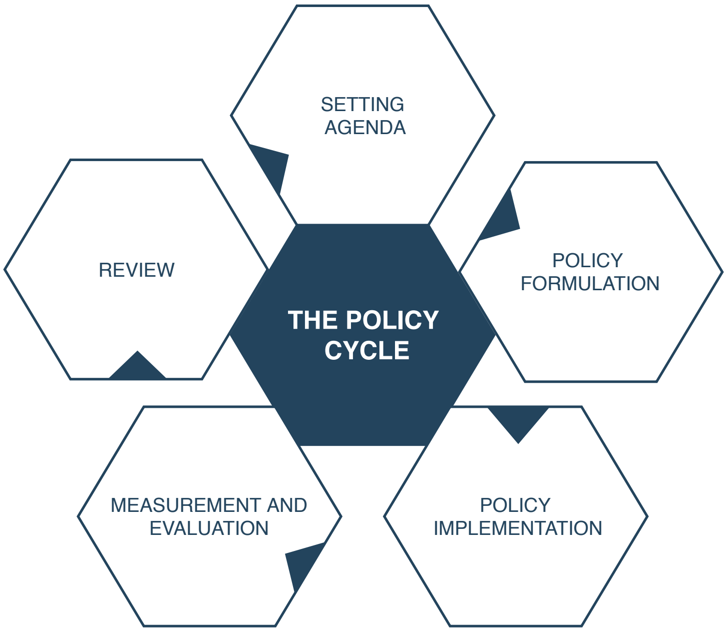

Figure 3.1: The classical policy cycle

maker, usually a government.

Stage one is the setting of an agenda through discourse. The motivating evidence for stage one in electricity access is strongly established both at the national and international level, outlined in chapter 1 and is represented as a high level global agenda in goal 7 of the Sustainable Development Goals.

Stage two is policy formulation. Through the passing of legislation by a centralised body, high level aims are set to achieve the goals established in stage 1. In the context of electricity access, stage two generally takes the form of national level targets for access percentage and a path to achieve this.

Stage three is the implementation stage. This involves developing and deploying a detailed plan to meet the goals set out in stage two. In the context of this work, we are most interested in this stage, where the detailed decision on how to achieve aims established in stage 1 and 2 are made and can utilise either a top-down or bottom-up approach.

Stage four is evaluation and measurement of existing policy. In the context of electricity access, we can look at progress towards universal electrification as the main measure being utilised to inform future policy. The tier of electricity access provided by interventions is not currently strongly integrated into this cycle and changing the focus in evaluation could be an effective way of implementing positive change.

Stage five is either the evaluation and re-contextualisation of the policy, depending on the results of the evaluation. This can mean stopping effort to implement a policy if the initial goals have been achieved or beginning another iteration of the cycle, informed by the findings of previous cycles if the goals have not been fully met.

3.2.2 Top-Down Policy Implementation

The seminal work in this field [85], defines a top-down approach to policy implementation as:

> " A top down approach starts with a policy decision by governmental (often central government) officials and then asks:
>
> - (1) To what extent were the actions of implementing officials and target groups consistent with (the objectives and procedures outlined in) that policy decision?
> - (2) To what extent were the objectives attained over time, i.e. to what extent were the impacts consistent with the objectives?
> - (3) What were the principal factors affecting policy outputs and impacts, both those relevant to the official policy as well as other politically significant ones?"

A top-down approach is considered suitable in the situation where one body has total oversight of the implementation. The examples given in the paper include the the UK's Open University program and the California Coastal Commission's ecological preservation activities. In the context of electricity access, provision provided by a centrally planned national grid tends to follow this top-down approach.

A number of weaknesses are identified in this methodology. There is a focus on the aims and needs of the centralised policy maker, resulting in an inability to adapt to the differing needs of communities [17]. This can result in ignoring the specific needs of individuals or communities. This can be particularly detrimental to marginalised groups within communities and those with less political capital who are unable to engage in the high level discourse that sets national agendas in a top-down implementation model.

Top-down approaches can be counterproductive in a case where there is no constant or dominant policy for a prolonged period of time, due to changing governments, where multiple interrelated, contradictory policy initiatives exist or where multiple agents are responsible for implantation of different elements of a policy program.

The current state of the off grid energy market can mostly be considered to fall into this category. Government, private sector and NGOs actors are all involved in often overlapping initiatives operating from a top-down perspective, with differing motivations and targets.

3.2.3 Bottom-up Policy Implementation

An alternative to top-down implementation is a bottom-up approach. [86] identifies bottom-up policy implementation as a new paradigm emerging in the late 1970s, aiming to address the perceived weakness of the top-down approach.

Bottom-up policy implementation is defined in [86] as:

> "The bottom-up approach of Hjern et al. [86] starts by identifying the network of actors involved in service delivery in one or more local areas and asks them about their goals, strategies, activities, and contacts. It then uses the contacts as a vehicle for developing a network technique to identify the local, regional, and national actors involved in the planning, financing, and execution of the relevant governmental and non-governmental programs. This provides a mechanism for moving from street level bureacrats (the 'bottom') up to the 'top' policy-makers in both the public and private sectors"

The bottom-up approach to policy implementation involves beginning with understanding the individual needs of a community and that context and needs of these communities differ across the area in question. The specific solution space for each context is explored, with direct participation and buy-in from each community, before deciding on an approach.

A bottom-up approach can capture the social, political and economic nuances of a particular context and form policy informed by the ground truth and experience of communities, rather than only the view of academics, politicians and bureaucrats. Bottom-up policy also includes the local stakeholders in all stages of the policy cycle, reviewing and reevaluating the effects of any intervention with direct buy-in from an informed community.

The focus of a bottom-up approach on the differing needs of communities result in this being an effective approach to combat the limitations of the top-down implementation outlined above. With reference to electricity access a participatory community approach can move beyond treating access to electricity as a binary measure and consider the specific needs and desires of communities. There is potential to consider a more detailed range of technical factors, such as reliability, quality and magnitude of supply in decision making, rather than simply aiming to minimise cost per connected customer.

A bottom-up approach is not without disadvantages. It requires significant resource to properly engage with the range of stakeholders required to make informed bottom-up decisions and this process can still be biased by the implementing bodies motivations. There is also a requirement for education and capacity building within communities to ensure that stakeholders have enough knowledge to effectively become involved in consultation, but this could also be considered a positive, increasing knowledge and engagement.

Considering only each communities local needs in isolation, without consideration of the bigger picture does not generally allow the same level of strategic oversight as a top-down approach. This can result in a situation where a series of locally optimal choices lead to a globally sub-optimal solution and in the case of multiple implementing bodies can result in duplication of work and wasted resources.

Table 3.1: Comparison of top-down and bottom-up approaches to policy implementation adapted from [17]

	Top Down	**Bottom Up**
Initial Focus	(Central) Government decision, e.g., new pollution control law	Local implementation structure (network) involved in a policy area ,e.g., pollution control
Identification of major actors in the process	From top down and from govt out to private sector	From bottom (govt and private) up
Evaluation criteria	Focus on extent of attainment of formal objectives	Less clear. Anything analyst chooses which is relevant to the policy issues or problem
Overall Focus	How does one steer system to achieve policy-maker's intended policy results?	Strategic interaction among multiple actors in a policy network.

3.2.4 Comparison of Bottom-up and Top-Down Approaches

In practice, few implementations are fully top-down or bottom-up, but rather a hybrid of the two approaches, with an emphasis towards a given approach.

The choice between top-down and bottom-up planning is often a question of scale and resource, with large scale problems being unsuitable for bottom-up planning, due to the additional resource required to perform the direct engagement with stakeholders required in a bottom-up implementation.

Top-down solutions are also preferable in cases where a policy intervention is homogeneous across a population, without varying local needs. For example, the implementation of vaccination

3.2.5 Electrification Policy

Traditionally, electricity access has been planned from a top-down perspective. This is due to the centralised structure of traditional electricity systems, discussed above and was practical when the only option for electricity access was connection to a macrogrid, which could provide electricity access suitable for a range of different stakeholders. Macrogrids are not generally constrained by energy supply. Any individual connection is unlikely to cause a significant issue, beyond potential need for local network reinforcement. Aggregated changes in demand may trigger the requirement for more generation assets, but these choices can be made from a top-down perspective. There is generally no requirement for direct community engagement from a bottom-up perspective of all stakeholders when connecting new customers to a macrogrid.

Off grid energy systems are far more sensitive to small shifts in supply and demand and the nature of access provided by connection can vary significantly particularly in the case of off grid electricity access. Macrogrids connections are generally expected to provide tier 5 electricity access, but minigrids and SHSs can provide a much wider range, of services, so understanding the requirements of the target community is vital to ensure the system is not oversized and therefore too expensive or undersized and unfit for purpose.

Bottom-up planning is generally not being appropriately utilised in the offgrid space, where the success of interventions are still assessed by a binary measure of connection numbers. One size fits all SHSs are commonly designed and deployed from a top-down perspective.

3.3 Overview of Planning Approaches for Electricity Access

Power system planning covers a wide range of activities at a number of different scales, with the end goal of meeting the electricity demand of end users within a given area in the most reliable, cost effective and sustainable manner [29].

With the emergence of offgrid solutions for electricity access, new planning approaches and decision support tools to assist in the implementation of policy aims have emerged. These tools can roughly be divided into large geographic area planning tools.

3.4 Large Area Planning

The aim of large-area planning tools is to provide a top-down, joined up plan of how energy will be provided across a nation or region, detailing the system type, technologies and basic designs for all consumers in the area under investigation, while meeting an objective function, often system cost or LCOE.

It is acknowledged in [87] that a combination of both centralised and decentralised solutions are required to achieve universal electrification. Large-area planning tools for electrification generally address the need for both approaches, utilising a combination of geographical information on existing infrastructure, heuristics and optimisation techniques to divide a given geographic area and specify the system types at locations within that area, by selecting between SHSs, grid extension and minigrids. The solutions are devised to meet an objective function within defined constraints, usually to minimise LCOE over the chosen area and time horizon.

3.4.1 High Level Algorithm

All large-area approaches follow a similar general approach, although the level of sophistication and detail in the underlying model varies.

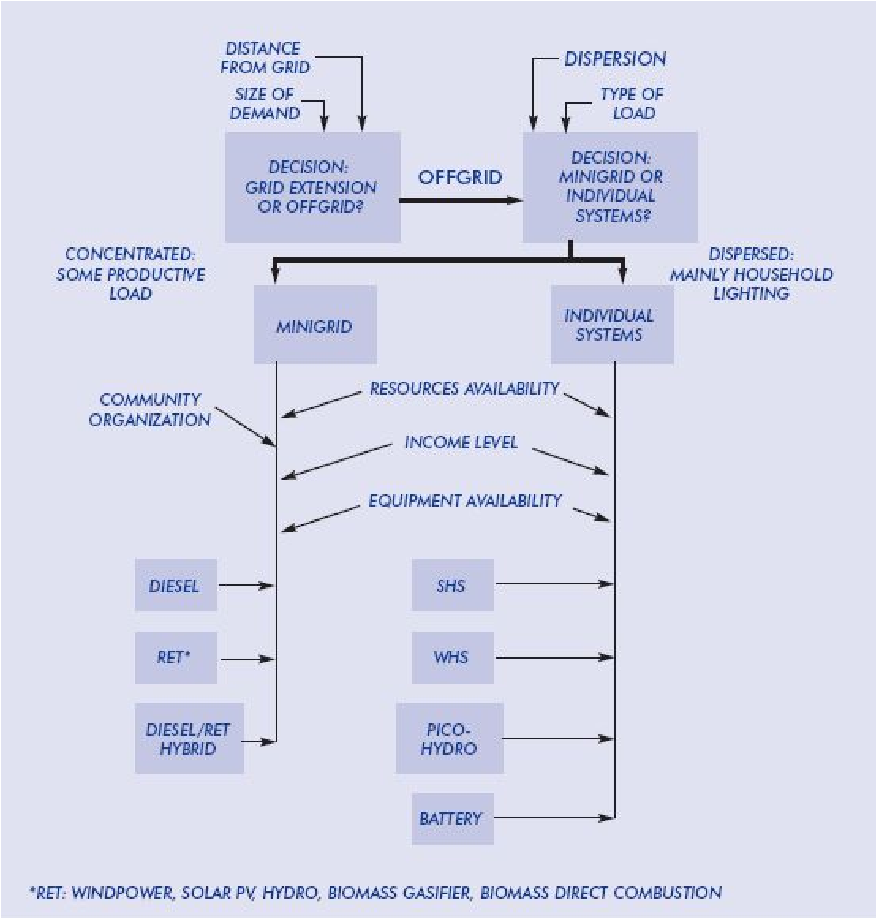

Figure 3.2: Decision process for energy access solutions [13]

Figure 3.2 details a simplified and generalised flow chart of a heuristic based approach for a specific location. The overall aim is to create a minimum cost plan for providing every consumer within the area under investigation access to electricity. This process is repeated across every location in the area under question to create complete plan of system type and basic design over the target area. For each location, a demand is calculated, based on estimated population data sources such as census data.

The first decision made is between extending an existing macrogrid or providing an offgrid solution. This depends on a range of factors, including distance from an existing macrogrid, the cost of extending the grid over a given distance and the size of demand present.

If offgrid solutions are chosen, the next choice is between minigrids or individual

SHSs, decided on the basis of dispersion of households and the presence of larger productive loads. For dispersed populations with only domestic demand, SHSs are selected. For more concentrated or clustered communities with larger loads present, minigrids are selected as the appropriate system type. The specific system level design then takes place, detailed below in section 3.5.

This approach requires a high level of visibility of both demand and renewable energy availability across the area in question, and the lack of high spatial and temporal resolution information, such as census data and weather station recordings, in particular for developing countries, has been cited as a barrier to this approach to large area planning [88]. Technologies such as satellite imaging and GIS are beginning to fill this data gap, particularly for measuring renewable energy resource from solar and wind [89], but the accuracy of population and other demographic data is lagging.

A number of tools have been created that utilise the same general methodology and include other features to produce more accurate and complete plans. They are detailed below.

3.4.2 Reference Electrification Model

Researchers at MIT have developed a tool called the Reference Electrification Model [90]. The tool defines a system type and design down to the granularity of individual customers for a given geographical area. A choice is made between grid extension, minigrids or standalone solutions and the tool specifies basic system designs for each location.

The working paper [91] on the tool details its capability. The tool first groups the user defined demands into clusters using a systematic bottom-up greedy algorithm in order to define the boundaries that will be considered.

This choice avoids the need for user defined clusters or population centres to be entered, but can potentially result in clustered populations that would not otherwise be grouped in practise, for example across administrative boundaries. Although this algorithmic implementation is bottom-up, from a planning perspective, this still considered a top-down approach, as the communities in question are not directly engaged in the planning process. Cost for grid extension and an optimally sized minigrid solution are then calculated for each cluster independently and the lowest cost option adopted. For clusters below 50Wp demand a standalone SHS is considered.

This approach does not use a heuristic threshold distance from grid beyond which extension will not be considered, but instead calculates the cost of each of the three possible modes of electrification independently for every cluster and compares them.

[91] also makes the point that any planning tool only exists to support decision making and give an initial overview of optimal approaches and the local factors such as cultural, political and legal factors should be taken into account in any case.

The Rwanda National Electrification Plan is an example of a country master plan for electricity access, following the top-down approach of dividing a country into grid and offgrid locations and was constructed with input from the REM tool [92].

This model considers demand growth over time as a fixed percentage increase, but does not mandate incremental investment in infrastructure and does not include any consideration of stochastic demand diversity or the requirement to upgrade network infrastructure downstream of the extended network to accommodate increased demand.

3.4.3 OpeN Source Spatial Electrification Toolkit (OnSSET)

OnSSET [93] is a another planning tool that uses geographic information and heuristics to decide between grid extension, minigrids and SHSs as the minimum cost solution for electricity access.

This tool offers more sophisticated consideration of electricity access quality, aligning its solutions with the ESMAP Multi Tier Framework, [19], but still uses the lowest LCOE as the objective function for each location in question. Notably the tool also considers hydro power along side solar PV and wind, unlike the other tools presented here.

The tool considers locations on a 1km by 1km resolution across Sub-Saharan Africa and calculates the cost of providing a given tier of electricity access for each location in question.

The tool makes no explicit attempt to address demand growth over time, other than setting population density in each unit to the projected population in 2030 to account for population growth, instead allowing the user to set the tier of electricity access desired at any given location, explicitly allocating the expected demand.

3.4.4 Network Planner

Network Planner [94] is an online tool developed by Colombia University. The tool takes user defined inputs for costs of infrastructure (generation, storage, grid extension cost, ect) and demographic information nodes on the system, including load types and demands and existing network infrastructure. Nodes are then defined as minigrids, offgrid or grid connected locations based on an aim to minimise cost.

The tool also attempts to account for demand growth over time, allowing users to define a fraction per year growth factor. Although costs are analysed over a chosen time horizon, the tool returns a system type to be installed at the beginning of this time, meaning that for large load growth scenarios, a highly oversized system will initially be installed to account for the eventual demand growth.

The tool simulates energy on a yearly resolution, using the metric of kWh/hh/year as the baseline for demand and varying this value based on a binary demographic definition of "poor" or "non-poor". A user defined "coincidence factor" is then used to define the peak demand seen on the system as a proportion of total demand, in order to size assets required on the system.

Network planner is now out of date and no longer supported, but presents the first significant attempt to create this type of tool and has influenced the development of future tools explored here.

3.4.5 Limitations

All of the top-down, geo-spatial approaches above have significant limitations in the scope of their implementation. The authors all emphasise the role of these tools as decision support rather than prescriptive planning tools, but there is still scope to improve how well they can fulfil this role.

All the tools consider distance to existing grid infrastructure and use that as a starting point for considering grid extension. In reality, a distribution line can not easily be connected to any point on a transmission line. The extension must take place from existing substations and transformers, which will only exist in a limited number of locations along a line. So called "under the grid" consumers, close to a transmission line but unable to connect to the national grid due to the lack of enabling infrastructure are symptoms of this [95]. The cost of a single secondary transformer in "under the grid" locations in Kenya is estimated to be $21,820, resulting in a cost per consumer of connection of $2427, even in locations already close to 11KV distribution lines. This means the cost of grid extension is being systematically underestimated in the above tools.

There is an inherent inequality in the quality of access provided to users and the quality of service provided by differing approaches, and it is clear that SHSs and mini-grid both provide lower tier of energy access in general than macrogrid extension. Those in more remote and rural areas will therefore benefit less from the human development impacts of electricity access.

Demand growth is also considered in a simplistic manner, not representative of the reality of offgrid energy systems. Due to the small size of systems, the inclusion of a single appliance can represent s significant step change in demand, far beyond the 8% growth per year used in the tools above. The aim of the UNSDGs is to create a fair and sustainable world for all, and it is difficult to envisage a world where these goals can be met without providing high tier electricity access to all people.

Therefore, there will be a requirement for households designated as SHS locations in the tools above to move up the energy tier ladder over time, representing significantly greater. This difference is particularly stark in the case of SHSs, where the introduction of a single new appliance such as a fridge can more than double the annual demand for a tier 1 SHS [96].

These techniques consider the cost of installing the most appropriate and cost effective assets in each location, assessed over a given time horizon, but without considering the full potential increase in demand that can happen over this time, or the option of incremental investment.

3.5 System Level Planning

System level planning takes a more local view, and provides detailed technical designs of systems to meet the requirements of local communities. This section will go into more detail on a number of planning tools and approaches, identify their limitations in the context of rural electricity access.

The challenge addressed by these tools and approaches is the optimal sizing of the storage, generation and other assets of the system to meet a predefined objective function, within the scope of the general system type already having been decided. As with large area planning, the function is most commonly LCOE, but the system will be modelled in more detail than in the large area approaches outlined above.

3.5.1 General Approach

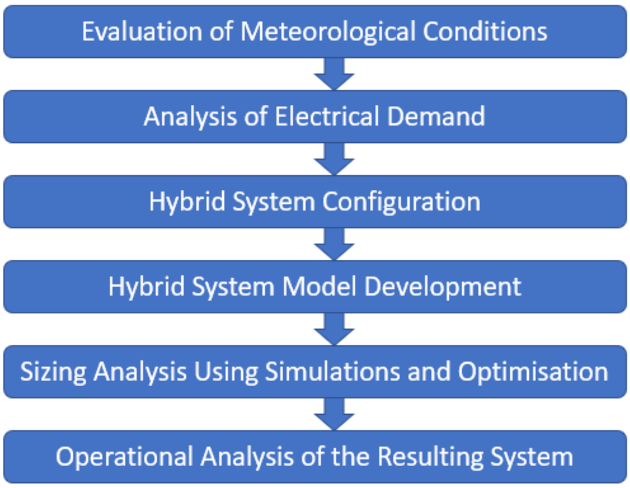

Figure 3.3: Generalised design flow for hybrid renewable minigrids

Figure 3.3 shows the high level design approach for system level design of offgrid energy systems. The first step is gathering of local data in the form of meteorological information on renewable energy resource. For solar demand, this can simply take the form of utilising publicly available global data-sets, but for resources that vary more drastically based on local condition, such as wind and hydro power, a campaign of ground measurements may be required.

This takes place alongside the gathering of data to establish demand and load profiles through community focus groups, surveys and other forms of bottom-up community engagement. This information can be used to synthesise load profiles. Where the load profiles in wide area planning are basic estimate based on population and demographic data, the load profiles used for system design should be informed by directly by the end user. In many cases the overheads required to fully engage communities is considered too significant and historic load data or indicative load profiles will be used instead.

Next is the application of the data into a model of the system. These underlying models can vary significantly in sophistication and are discussed in more detail in the methodology chapter 6.

The bounds of the system optimisation must then be set. This involves setting a number of constraints that must met, such as carbon emissions and reliability and the election of allowable technologies. This combination of technologies and constraints constitutes the solution space of possible systems that is then searched for a suitable or optimal system design.

[97] reviews the landscape of software for optimisation of offgrid renewable energy systems, reviewing the use of 19 different tools. The most commonly used are outlined below.

3.5.2 HOMER

HOMER (Hybrid Optimization Model for Multiple Energy Resources) is the industry standard software for the design and sizing of minigrids [97] featuring a range of energy sources. HOMER is designed for a range of applications, including mingrids in developed settings, such as for remote industrial applications like mines, it can also be used effectively utilised for rural electrification design It is a simulation and optimisation tool takes into account technical specifications, available technology and economic considerations to assess the viability of a range of solutions for the problem presented over a given time horizon.

It does this for a range of limitations, such as % share of renewable energy, reliability requirements and other factors. HOMER can also perform sensitivity analysis on a range of variables, giving some understanding of uncertainty. It outputs a range of designs, with LCOE and other metrics presented for the given location and constraints

Systems are simulated on an hourly basis in a time sequential manner, accounting for the effect of energy storage and will size converters, storage and generation assets and uses historic, location specific data for renewable generation resources like solar PV and wind.HOMER can assess both AC and DC systems as well as hybrid systems, making it suitable for a range of technologies and generation and storage types.

Functionality was recently added to assess minigrid to national scale grid interconnection, but does not currently feature the ability to assess interconnection between to islanded microgrids. The national grid is treated as an infinite buss, allowing the grid to buy power at a determined tariff.

There are a few significant limitations to HOMERs capability. The first is the time resolution of one hour which is too large to capture many of the dynamics of diverse consumer behaviour. Secondly, it can not model interconnection between grids, only connection by a minigrid to a national grid that is considered a perfectly reliable, infinite source of energy.

Although the tool facilitates the inclusion of user defined profiles, it defaults to a small number of 'indicative' load profiles, potentially reduced the users perceived need for end user engagement to develop load profiles.

3.5.3 Hybrid2

Hybrid2 [98] is another optimisation tool for hybrid energy systems with a focus on wind energy generation. The tool utilises a stochastic time series methodology to account for uncertainty and variability in wind energy. The tool offers detailed optimisation and investigation of dispatch strategies for generation and storage and a far more detailed technical system model than that of HOMER. While sophisticated, the tool is far less user friendly than HOMER and is no longer supported, resulting in its use in practical case studies being limited.

3.5.4 RETScreen

RETScreen is a tool developed by the Canadian government, focusing on the economic optimisation of energy systems. The tool is not specifically focused on offgrid or minigrid systems, so lacks much of the detailed technical specification offered by HOMER, but covers a wider rang of economic considerations, such as risk analysis and cost of carbon emissions. The key technical limitation for RETScreen is the analysis only considers monthly averages for demand and generation, rather than the hourly resolution of HOMER and Hybrid2.

3.5.5 Other Optimisation Approaches

There are many other academic papers exploring the optimisation of storage and generation assets utilising a range of differing optimisation techniques that are not currently intergrated into the tools above. Each is aiming to reduce the overall system cost over a prescribed time horizon, while meeting certain constraints for reliability. Investigating the relative merits of differing machine learning and AI techniques for system optimisation is beyond the scope of this work, but all of them aim to use an underlying model of the systems energy balance over time, with inputs from load profiles and historic weather data.

[99] presents a comprehensive review of different sizing and optimisation techniques as applied to offgrid renewable based energy systems. [100] uses neural networks to optimise parameters based on an underlining deterministic time sequential model. [101], [102] and [103] all make use of a genetic algorithm, a biologically inspired optimisation algorithm particularly suited to search-spaces with multiple local optimums [104], such as complexity multi-energy minigrids.

All of these approaches are dependent on the validity and relevance of the underlying model and the validity of the results is dependent on the search space of the optimisation.

3.5.6 Standardised Designs for SHSs

These design approaches are generally not applied for SHSs, with manufacturer preferring to offer a small number of standardised design. This is because the additional cost of designing bespoke systems to meet each users demand ends up being more expensive than using a few standardised designs, which can benefit from economies of scale minigrids are yet to achieve [75]. The exact sizing of theses systems is subject to an iterative process of consumer engagement to settle on the most suitable design.

The downside of this is that consumers will generally be sold the system that is the smallest in the range that will meet their needs, which could still be significantly larger than their exiting needs, upfront.

3.5.7 Limitations

The landscape of optimisation and design tools for offgrid energy systems is widely developed. The key limitations are in the underlying models and range of available choices that exist to form the search space.

One of the key limitations is that these tools are not designed to easily integrate collected date from direct community engagement, and make no consideration for incremental investment alongside demand growth, aiming instead to size the system optimal upfront for the given time horizon.

3.6 Who is Doing the Planning?

Any planning methodology can only inform decision makers, acting as a decision support tool. The person making the decisions still applies their assumptions, biases and motivations. Action will therefore be influenced by the goals and motivations of those decision makers.

We must therefore consider who is making these planning decisions, what motivations and incentives they may have and how this may affect the choices made. The three main stakeholders who are making choices are governments, the private sector and NGOs. The motivations are not monolithic in each case, but useful commonality can be established. It is worth noting that although the community in question is a stakeholder in each case, they are generally not the ones making the final decision.

3.6.1 Government

We will work under the assumption that the majority of countries we are interested in operate under a functioning representative democracy, as this is the most common form of government in Sub-Saharan Africa [105].

Under this model, elected representatives make choices on behalf of those they represent and are responsible for decisions pertaining to electricity infrastructure.

Politicians are generally motivated to make decisions leading to re-election, both to ensure that they keep their jobs and influence and to prevent an ideologically opposed government from taking power.

Election terms vary, but tend to be in the region of 3-6 years. This can result in shifted incentives, emphasizing projects that can result in visible results within the length of one term and can be seen by the largest number of people or most politically advantageous demographic to aid re-election.

In terms of electricity access, this incentive towards shorter term projects, combined with the potential lack of continuity leads to an increased emphasis on grid expansion to locations which can be quickly connected and quickly deployable offgrid solutions, but can result in solutions optimised for the short term, without capacity for long term growth.

Governments in developing countries are also incentivised by the international community, the UNSDGs and other data collecting campaigns towards quantity of electricity connections over quality, as these high profile tracking campaigns only consider binary figures for electricity access. Governments wish to be seen by the international community to be making progress, and the easiest way to do this currently is by focusing on number of connections.

Despite this, governments are not bound by direct financial profitability as the private sector is. The value of an intervention to the government can align with a number of goals, including education, health outcomes, economic development and more, meaning that even interventions that do not recoup their direct costs from tarifs can be considered if the benefits to the wider ecosystem are taken into account.

On the other hand, governments can have the most “joined up” or “top-down” view of the three main implementers, due to their ability to set policy and legislation for an entire country.

3.6.2 Private Sector

In many countries, such as Rwanda, the largest implementer of offgrid energy systems are private companies. The majority of existing large offgrid companies are “for good” enterprises, motivated to implement positive change through neoliberal economics, the key motivation of any private company must fundamentally be profit.

The offgrid sectors is a rapidly growing and companies are incentivised to achieve a high share of this emerging market, leading to an emphasis on rapid growth, favouring quickly deployable solutions such as mini grids and SHSs. Difficulty obtaining working capital and high interest rates in many developing countries additionally incentives systems with lower capital costs and shorter playback times, again incentivising short term thinking.

This growth focus can also result in companies overstretching and failing, such as Mobisol, whose German parent company, responsible for subsidiaries in Rwanda, Kenya and Tanzania, went into insolvency in 2019, in order to restructure [106], leaving significant questions regarding the continued maintenance and operation of the systems of their existing customers.

Many of the largest implementers are from outside the countries in question, which can lead to a range of issues.

The first issue is a potential lack of deep understanding of the end users needs - in particular long term changes in energy demand. A common trend in international development ’tech fix’ solutions, conceptualised in isolation from their context which have resulted in unsuccessfully interventions that could have been foreseen with engagement with end users as seen with the widespread challenges faced by the implementation of clean cook stoves [107]. Many of the most well established companies in the area do have strong and long term relationships with customers and a deep understanding of their needs, but there is potential, particularly in emerging markets, for less scrupulous actors to prioritise short term gains.

The second issue is the extraction of value from developing countries to companies in developed nations. The ethics of profiting from the rural poor and introducing a debt burden through private sector intervention are complex.

There is also a strong interaction between government and the private sector. The private sector is influenced and constrained by government policy, taxation and legislation to align with the incentives presented above. A lack of long term messaging from government about planned grid extension can lead to reduced private activity in locations close to existing grid infrastructure, for fear of being superseded by an expanding grid.

3.6.3 NGOs

The third implementer is the Non Governmental Organisation (NGO). The key motivations of these institutions vary from private companies: NGOs are driven by the positive community impact of an intervention rather than its profitability, although the aim of long term financial sustainability of an interventions is often a motivating factor.

Despite this mission for implementing positive social impact, NGOs rely on donor funding (individuals, corporations or governments) to operate, and are therefore accountable to these entities [108]. They are motivated to target interventions resulting in visible short term gain, even if the intervention may be less effective or even negative in the long term, as discussed in [108].

They are also subject to the same issues regarding lack of local perspectives outlined for private companies above.

3.6.4 Decision Making Implications

It is clear from this investigation that the three main implementers of power system planning in developing countries each have motivation to act in a short term manner. This can be best observed in the SHS market, where a one size approach for system design consider only the needs and demands at the time of installation, with no concession made for how the system can grow. The same behaviour short term focused can be observed in government led SHS deployment in Bangaldesh [109], with more than 4 million SHSs being installed under the government funded investment bank IDCOL.

The only plans for system upgrade are replacement [12] or grid connection. This can be explained by the lack of certainty within the sector regarding what the future of these systems looks like beyond the time horizon of their initial financial payback.

Selling consumers an entire new system to replace a SHS that has become unfit for purpose is in the direct interest of a private company, once the costs of an initial system have been recouped.

In order to realise the long term development benefits of offgrid energy, upgrade and growth plans must be built into the planning process. This could include considering larger inverters, batteries or cables to facilitate future demand growth, considered at the time of system design as in many of the approaches above, but this results in increased upfront cost.

3.7 Summary

In the future it is clear it will be necessary to reconsider electricity access provision in areas currently connected or planned to be connected to low tier electricity access.

None of the 19 tools outlined in [97] offer consideration of interconnection between islanded systems, but this work aims to outlining the motivation for integrating this approach into system level planning by developing a modelling framework for evaluating and quantitatively assessing its viability.

The contributions of this work aim to address many of the shortcomings with existing planning. Interconnection of existing SHSs to form nodes on a distributed minigrids, utilising the already installed assets has the possibility to provide a lower cost solution than rebuilding or installing new systems from scratch.

Despite this, little work has been undertaken to establish the quantitative value of this interconnection. Much of the published academic work, explored in chapter 4 focuses on a qualitative assessment of the value of interconnection. This work aims to outline the motivation for integrating this approach into system level planning by developing a modelling framework for evaluating and quantitatively assessing its viability.

This approach can be implemented into future iterations of the policy cycle for existing installed systems and integrated into future planning for new systems from the beginning of the process. This integration will be further examined with the benefit of the quantitative modelling results in chapter 7.

There is a huge opportunity in developing countries to re-contextualise the challenge of electricity access, not as a struggle to provide sub-par electricity access in the quickest and lowest cost way. Instead, we can reconsider how 100 years of technological advancement and experience can inform a more fit for purpose, modern, flexible and community driven energy system, ready for the modern challenges of climate change and DER.

Bottom-up electrification is one potential approach that may be capable of disrupting the current accepted approach to providing electricity access, by providing a credible and scale-able path to integrate both top-down grid extension and bottom-up offgrid energy deployment into a cohesive and synergistic strategy.

Chapter 4

Bottom-Up Electrification

This chapter introduces the concepts of bottom-up electrification as a possible approach to mitigate many of the issues with how electricity access is currently conceptualised outlined in chapter two.

In chapter two and three, it was established that there is a requirement for alternative conceptualisations of energy access, that account for the need for growth and move beyond a one size fits all, binary measure for electricity access. Existing planning approaches were demonstrated to be unsuitable for considering the incremental upgrading of off grid systems and bottom-up interconnection; one potential vector that could be integrated into existing planning to mitigate existing shortcomings.

It does not seek to present an entirely new way of operating, but a synergistic approach that can help existing energy infrastructure deployments move beyond a ”fit and forget” approach. This chapter will offer a quantitative and conceptual overview of bottom-up electrification, and explore its relative merits and challenges in terms of technical, economic and social impacts. The current work in both academia and industry on system interconnection will then be explored and the requirements for a planning tool or methodology to evaluate interconnection of systems established as the motivating context of the rest of the work presented in this thesis.

4.1 Bottom-up Electrification

Bottom-up interconnection is defined in this thesis as:

> The electrical connection of two or more offgrid energy systems currently operating permanently islanded

This can occur at a range of scales, from the interconnection of two SHSs, to a swarm of SHSs within a village or community, to the interconnection of multiple minigrids. At each scale, the intention is to increase aggregated demand and generation diversity. This can, in many cases, be shown to reduce the cost of energy, environmental impact of the systems and increase reliability, while facilitating demand growth.

The approach takes an evolutionary, bottom up view of energy access, utilising the resources and assets already present in community and assesses the specific needs of those end users, while acknowledging these needs change over time.

This has the potential to effectively mitigate many of the issues outlined in the previous chapter regarding the long term viability of offgrid systems. In particular, the ability to utilise SHSs already installed to mitigate the costs of upgrading a community's supply and move up the energy tiers can reduce the risk of stranding assets and form the basis for an alternative infrastructure investment strategy for off grid energy based on an incremental process of contextual, bottom-up growth.

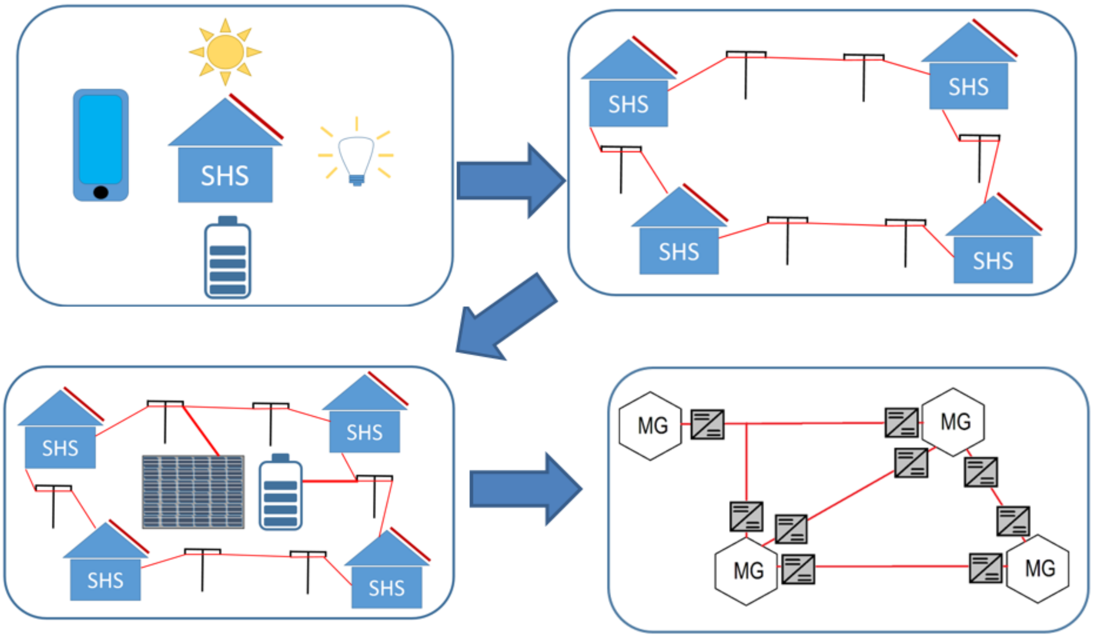

Figure 4.1: One imagined pathway for bottom-up interconnection

Figure 4.1 shows one possible progression that this approach could facilitate, gradually shifting users from energy consumers to prosumers - consumers who also produce and sell energy. Initially, SHSs are installed in a community to provide basic energy access. Over time, the electricity demand within the community grows, observed through remote monitoring technology and community engagement. The SHSs are interconnected to form a minigrid that can act as a peer-to-peer community energy market, allowing excess energy generated that would otherwise be dumped to be exported and used either to power other households loads or charge batteries in other SHSs that are not fully charged. This excess energy can also be used to connect new customers without an electricity connection, providing an income stream for SHS users and electricity access with less upfront cost for unconnected community members. Once a network has been built, the process of further upgrading the system becomes more simple, as new assets can be installed in a centralised, modular and scalable manner, rather than having to retrofit each SHS individually.

In locations with suitable demand and generation diversity, interconnection between minigrids, either formed of distributed SHSs or more traditional centralised minigrid can then be developed. This ready formed network can act as a single point of connection in the case of an extending national grid.

There are a number of high level potential benefits of this approach. These are explored qualitatively below from the perspective of technical, economic and social benefits. A quantitative assessment of many of these benefits will be developed in chapters 5 and 6.

4.2 Technical Benefits

4.2.1 Increased Demand Diversity

Diversity in power system arises from differing demand and generation profiles [110]. Demand diversity occurs when peak loads for individual households connected to the same system are not co-incident. The peak load seen at any given time is less than the sum of the peak load for each household. Diversity factor is the ratio of the sum of peak demands for each individual demand entity, such as a household or shop on the system, to the peak demand on the system taken as a whole.

$$DiversityFactor = \frac{\sum PeakSubsystemDemand}{PeakSystemDemand} \tag{4.1}$$

After Diversity Maximum Demand (ADMD), is another commonly used metric, often utilised for sizing wires in distribution networks and is defined as:

$$ADMD = \frac{peakSystemDemand}{numberofSubsystems} \tag{4.2}$$

Interconnection can therefore impact the Diversity Factor of the newly created system compared to the aggregate of individual systems. The newly interconnected systems become subsystems on the new larger system.

The diversity of the new system will depend on the co-incidence of the peak loads on the subsystems. If each subsystems peak demand occurs simultaneously, then the diversity factor will be 1. Due to the random, stochastic behaviour of electricity consumers, the probability of all peaks coinciding decreases with number of consumers connected and with variation in their patterns of energy use.

The load profile of a domestic dwelling in a given community will tend to be similar, but similar loads still result in improvements in diversity. Schools, healthcare centre, small industry, agriculture and other loads different from domestic dwellings further increase the demand diversity present if connected. By connecting a variety of loads to the system, each with different operating regimes, diversity can further increase. For example, an industrial application such as maize milling could utilize the excess solar energy during the middle of the day, reducing the need for energy storage.

Smaller demand peaks require less generation to be dispatched at peak times, reducing the need for backup generation such as diesel generation and battery storage and reduce power flows in a network, reducing the distribution losses.

4.2.2 Increased Generation Diversity

As well as demand diversity we must consider how interconnecting systems can increase the diversity of generation. This is particularly relevant for offgrid systems due to the prevalence of non-dispatchable renewable generation.

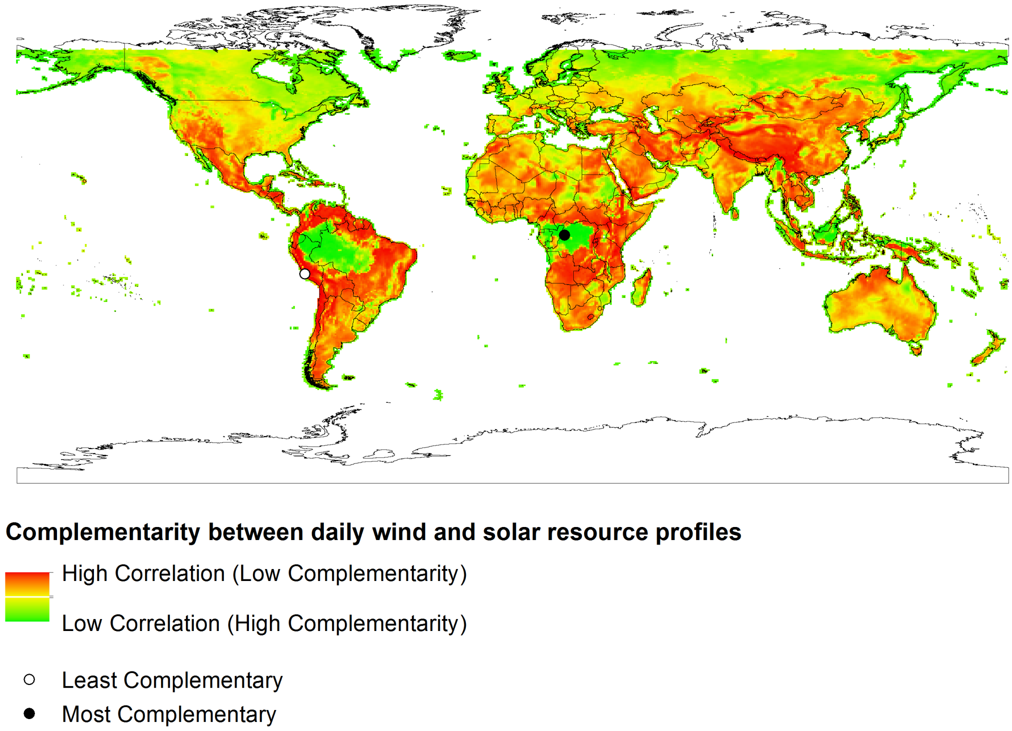

Figure 4.2: Global complementarity of solar insulation and wind [14]

If the interconnected systems have differing generation profiles, such as complementary wind and solar PV generation [111], interconnection for systems with these generation technologies can result in a mitigation of the variability of generation. This can result in reduced need for storage. Figure 4.2 shows a visualisation of the complementary of wind and solar globally, showing the extent to which they coincide. Effective utilisation of a complementary resource can depend on a number of other locational factors, for example surface roughness and elevations for wind generation or seasonal effects of rainfall for hydro power.

Additionally dispatchable sources of energy, such as diesel generation and battery storage can be utilised to further mitigate the variability of renewable and having many redundant sources of generation can increase system reliability.

4.2.3 Utilise Unused Energy

For a single SHS there is no benefit derived from diversity, as the peak subsystem demand and the peak system demand are the same.

The peak demand must be met by the panel and battery at all times to ensure constant operation. SHSs are therefore specified to have large generation and storage in order to satisfy this worst case peak. This results in a systematic over-sizing of generation as the most economic system design, considering the relative costs of solar PV and battery storage and as much as 65% of total generation being unused [78] [112].

Interconnection between systems can allow this excess energy to be utilized within the system in a number of ways. This energy can connect new consumers, increase the demand that can be drawn be existing users while maintaining reliability of supply, potentially enabling productive or income generating loads, provide income from exporting excess generation or it can reduce the required size of storage and generation in the overall system.

4.2.4 Increased Reliability

In the case of a fault on the system, an interconnected network of standalone systems could revert to islanded operation, providing at least limited functionality for basic loads such as lighting. This could significantly increase the reliability of systems compared to a minigrid with centralized generation and storage. A minigrid connected to the national grid could similarly intentionally island itself in the case of a fault on the system.

The system could also be configured to exhibit re-configuring or “self-healing” properties, the ability to autonomously identify and recover from faults [113]. This property is often found in communications networks [114] utilising redundant paths ensure connection even under conditions where some subset of the infrastructure is damaged. Self healing is increasingly explored in power systems, where complex and meshed topology, distributed generation and storage give opportunities to rethink how networks are operated [115] routing power to avoid faults in a manner similar to how the internet can reconfigure to route packets via a range of pathways to avoid faults and improve system performance [116].

There is increasing interest in operating energy systems with the possibility of intentional islanding [117], whereby microgrids or even distribution feeders can disconnect from a macrogrid and use their local generation and storage assets to operate autonomously under conditions where this is advantageous to either system.

Even in countries with high electrification rates and established national grids, distributed generation and storage is becoming more prevalent across every level of the grid, presenting opportunities to rethink how systems operate. A bottom up interconnected system could build in this functionality from inception, saving money and effort in the long term. The benefits of interconnection is examined analytically, with reference to a range of reliability metrics in chapter 6 and 7.

4.2.5 Increased Battery Lifetime

The capacity of a battery is impacted by environmental factors such as temperature and its operation, with the depth of discharge and number of charge cycles being the key factors impacting battery state of health. [118] develops a model for degradation of valve regulated lead acid batteries for SHSs and the impact of these factors on battery state of health.

Shared storage assets in an interconnected system can be dispatched in a coordinated manner. This could offer opportunities for dispatch strategies that can minimise the charge cycles and depth of discharge experienced by batteries over their lifetime. The capacity loss of most battery technologies is a function of the depth of discharge and number of charge discharge cycles, for example fully discharging one set of batteries before utilising others, can improve the lifetimes of these assets.

4.3 Economic Benefits

4.3.1 Financial Flexibility for Individuals

Many SHSs and minigrids rely on a "pay as you go" business model or microfinance to fund their operation [119] [120] [121]. The risk of failure to pay is a significant barrier to the commercialisation of this technology. The ability to sell excess energy can help individuals or systems to meet payments in difficult times by reducing their electricity demand rather than losing access altogether.

4.3.2 Flexible Investment

Investment in the required technology to interconnect systems can be undertaken incrementally, targeting locations with the greatest advantage to be derived, such as those with a varied demand or generation profiles located close together. Initially, access can be provided quickly and cost effectively with SHSs. There is a documented trend in growth of energy consumption over time as human development increases [38]. As such, this bottom up approach can offer a cost-effective method of ensuring the energy infrastructure evolves at a rate in accordance with growing demand. Incremental interconnection of SHSs or microgrids can be implemented to gradually increase minigrid capacity. Additional, centralized generation could then be added to the mini-grid and it could eventually be interconnected to other mini-grids, further increasing diversity of demand and supply. Where suitable, this network of mini-grids could then be integrated into a national grid. The key advantage is that these upgrades can be undertaken incrementally and can adapt to the changing consumption patterns and need of each community. Though not suitable in every situation, such as over large distances or between grids with low diversity, interconnection offers an additional path to grow and upgrade systems over time. In order to fully take advantage of the potential benefits offered by interconnection, a suitable planning methodology is required, involving detailed numerical modelling, real world experience and design tools.

4.4 Social Benefits

4.4.1 Equality of Access

Many of the poorest and most vulnerable are unable to afford the upfront cost or monthly payments associated with ownership of their own SHSs. Individuals who cannot afford to invest in a full SHS could instead install a cheaper controller and converter, connecting their dwelling to a network and allowing them to purchase excess electricity from other connected systems.

The quality of service may not be as good as a SHS, as there may be times when all systems of the network are unwilling to sell, but this first step may be an effective method to spread the cost and facilitate quicker and more cost effective electrification for those who cannot afford to purchase a complete SHS, one of the key barriers to uptake [122] [25].

In a location with many SHSs it may make sense for new customers not to buy a SHS at all and simply purchase an interconnection. This could also be used to connect new load centers without energy access to minigrids with excess energy. For example, small enterprises, who don't have the capital to invest in all of the components of an off grid system could utilize this pooled energy resource and unlock business opportunities within local communities, while also providing income generating potential for prosumers in the sale of energy to these small businesses.

4.4.2 Community Cohesion and Ownership

There is significant evidence to support the idea that strong spatial networks and infrastructure within the built environment can have a positive impact on social cohesion [123]. Creating a sense of joint ownership and participation within a community can lead to a greater sense of community, belonging and empathy. This can result in better stewardship of systems, resulting in higher reliability and reduced maintenance costs.

Many traditionally privately owned and operated assets, such as transport and accommodation have been disrupted by "sharing economy" models such as Uber and AirBnb [124] and this has democratised access to the benefits, allowing wider participation in the value stream. A well engaged and informed community participating in a community network facilitated by interconnection have the possibility of gaining direct control of the means of generation and more directly benefit from the wealth generated by their assets.

4.4.3 Energy Literacy and Capacity Building

Direct engagement in a community energy system, particularly in conjunction with capacity building and education activities, can facilitate a greater local understanding of energy use that can lead to more sustainable consumption [125] and a better understanding of modern energy services and productive uses of energy, leading to long term economic benefits.

4.4.4 Technical Continuity

For users already familiar with their existing energy provision ecosystem, this approach can guarantee that their existing appliances can continue to be used and can leverage existing positive consumer relationships with companies or other implementing organisations where these exist. This is in contrast to a scenario where a new minigrid is installed in a community to improve access, but possibly resulting in existing DC appliances designed for use in the SHS ecosystem being unusable on a new grid with different voltage levels or AC rather than DC distribution.

4.4.5 Environmental Impact

By potentially reducing the utilisation of diesel generation, interconnection can have a positive impact on carbon emissions and local air pollution [126], reducing the impact on climate change of the system and improving local health.

4.5 Technical Feasibility Challenges

4.5.1 Requirement for a Controller or Interface Device

In order to facilitate interconnection, there is a requirement for a controller to facilitate energy transfer between systems. This device must feature some form of communications to allow price signals to be sent between houses and a two way DC/DC converter to step up and down the voltage for distribution, as well as net metering to facilitate billing or other forms of payment. The design of such a controller is beyond the scope of this work, which will focus on the potential system level impact of interconnection rather than the detailed technical implementation.

4.5.2 Standards and Compatibility

Well defined and widely adopted standards for voltage levels, connectors, communications protocols and many other factors are crucial to the adoption of interconnection of systems. It is desirable that two systems can be connected as quickly and easily as possible, with the minimum technical expertise required, to reduce costs and allow individuals and communities to have more agency in their own energy. There are no internationally accepted standards for Low Voltage Direct Current (LVDC), although the IEEE Standards Association is developing a new standard for DC microgrids [127].

4.5.3 Losses

One of the key factors determining the viability of interconnection is the losses experienced while transferring power from one household to another. These losses are determined by three main factors:

- The losses in the power conversion stages stepping up and down the voltage
- The losses in the distribution lines determined by their length and impedance per unit length.
- The voltage level of distribution.

Converter Losses

Losses in DC/DC converters to step up and down the voltage for transmission must be considered. Cutting edge wide band gap devices can facilitate converters with greater than 98% efficiency [128], but the cost of these devices is currently prohibitive for this application.

Distribution Losses: Distance Between Systems, Voltage Levels and Cable Sizing

I^2R losses between two systems are a function of separation distance. For a given cross-sectional area of conductor the resistance of a line grows linearly with distance. The greater the voltage level, the lower the I^2R losses, due to the current reducing as voltage increases. This makes higher voltage levels more desirable to minimise losses, but there is a trade-off as higher voltage levels will require both more expensive converters and can have safety implications. It is often desirable in such systems to use DC voltages less than 48VDC where possible to ensure touch safety [129]. The other way to reduce distribution loses is to decrease the resistance of the line by increasing its cross-sectional area, but this will also result in increased cost as thicker cables are more expensive. The implications for the cost of these trade-offs require detailed techno-economic modelling to understand.

4.5.4 Requirement for Diversity

For interconnection to be viable, there must be some diversity of demand and/or generation present. Predicting this behaviour is complex and challenging. A clearer understanding of the required diversity to make interconnection worth considering would form a useful design heuristic.

4.6 Economic Challenges

In order to be wildly utilized the technology must not only be positive for consumers, but also financially viable. There are a number of potential business models for interconnection, including PAYG with a centralised pool operated by the network owner, Peer to Peer selling with a transaction fee, microfinance or a flat rate subscription. In order to ascertain the best approach, market research, pilot projects and detailed techno economic modelling are required, with an understanding that there will most likely be a range of suitable solutions depending on the specific social, economic and geographical context. This could build on market assessment methodologies used for other off grid technologies such as wind and minigrids [130].

There is currently no clear understanding of the lifetime cost of this approach in comparison to alternative approach. This thesis aims to develop some assessment of the required techno-economic metrics to perform a market assessment.

4.7 Social Challenges

4.7.1 Education and Energy Literacy

There is a risk that a more complicated system of energy trading can alienate users without proper education. Many consumers in targeted areas have limited literacy [131] and this must be carefully considered in the design of the user experience to ensure no users are left behind.

4.7.2 Equality of Access

This approach can facilitate consumers without SHSs connecting to energy at a lower cost, if improperly implemented, this approach could also allow a user with a larger amount of storage and generation to manipulate a local market. Potential commercial and ownership models for interconnected systems and their relative benefits and risks are explored in more detail in chapter 8.

4.8 Interconnection Literature

The concept of interconnecting decentralised off grid energy systems has been investigated in the literature under a number of different names, including bottom-up electrification, swarm electrification, power sharing, meshed microgrids and multi-microgrids. In this section, the work done in this literature will be outlined and compared.

4.8.1 SHS Interconnection

Academic interest in this work began in 2012. Before this time, the density of SHSs and other systems that could be interconnected was not present anywhere in the world to trigger academic interest in their interconnection. The concept of building a minigrid from a network of SHS is first mentioned in the masters thesis of Kurtis Unger [132] in 2012, "Organically grown microgrids: Development of a solar neighborhood microgrid concept for off grid communities". At this time, the market for cellular enabled SHSs with remote monitoring and payment was just beginning to emerge and the thesis outlines the potential of this technology to enable new models of peer to peer energy trading. The author identifies interconnection as a potentially disruptive technology and innovation that can facilitate the scaling up of electricity access.

The thesis develops a deterministic simulation in Matlab Simulink to model minigrids made up of SHSs focusing on the design of an appropriate DC-DC converter to facilitate power sharing in the system. The key contribution is the comparison of network topology, between a centralized bus and point to point interconnection of households. The model is applied to a case study in Mugumu, Tanzania, interconnecting 8 houses at 24VDC, modeling the switching characteristics and stability of such a system. The approach to economic modeling is of interest. The author identifies the possibility for consumers with SHS to sell electricity to solar lantern owners in order to charge their devices, creating some form of peer to peer market even before the introduction of physical interconnection between households.

"Identifying Hidden Resources in Solar Home Systems as the Basis for Bottom-Up Grid" by Hannes Kirchhoff et al [133] further develops the idea and sets a motivational foundation by using a simulation based approach to demonstrate significant unused energy present in SHSs. This excess energy is shown to be in the order of 50% of the energy generated by the system and could be utilized by nearby houses in an interconnected network. This excess is due to the lack of demand diversity present in the systems and the systematic over sizing of PV panels, issues that can be mitigated through interconnection as discussed in section 4.2.2.

The term Swarm electrification was established by Groh et al in 2014 [134]. The paper also establishes the idea of combining both top down and bottom up growth in power systems, with national grids being able to connect to a pre-made network. Reference is made to the concept of network theory and swarm intelligence, with the interconnected networks capability and value being greater than the sum of its constituent parts.

"Swarm Electrification: Investigating a Paradigm Shift Through the Building of Microgrids Bottom-up" [135] by the same authors in 2015 builds on these concepts, addressing the classical narrative of access provision being a comparison between on and off grid solutions, or the centralised and decentralised track established in [87]. The paper lays out the following challenges for traditional decentralised energy systems:

- Demand tends to grow once electricity is available;
- Pace of growth is hard to determine;
- Oversized systems are not economically viable;
- Undersized systems might fail to adequately perform and therefore hinder social acceptance and economic development;
- Productive use is enhanced with larger electrical loads.

It is proposed that interconnection in an incremental manner is a viable way to address these limitations, by reducing the initial investment risk with smaller systems that can wait and see what demand develops in a community.

"Against the odds: The potential of swarm electrification for small island development states" [136] presents the results of practical implementations of interconnection between SHSs in Bangladesh against the ESMAP multi tier framework, and elaborates on the resiliency impacts of a decentralised SHS network, when each house can default to islanded operation. The technology is analysed in the specific case of Small Island Developing States and their specific challenges.

The results from the trial of the ME SOLShare trail are presented, specifically relating the the ability of Swarm Electrification to improve battery health by reducing charge cycles. The interconnected SHS implemented had an average tier assignment if 1.52 across 106 systems investigated, compared to a tier rating of 1 for a traditional SHS, showing a small but significant benefit over islanded SHSs.

"Developing mutual success factors and their application to swarm electrification: microgrids with 100 % renewable energies in the Global South and Germany" [137] outlines further social benefits that could be derived from interconnection of SHS, including increased sense of community ownership and energy literacy among users.

The 2019 paper "Quantifying the Benefits of a Solar Home System-Based DC Microgrid for Rural Electrification" by Narayan et al [138] further investigates the use of interconnected SHSs to move up energy access tier and reduce loss of load probability. The paper is of particular interest as it addresses the tier 4 and 5 services (using SHSs with much larger panels and batteries than regular SHSs 4kWp solar and 6.6kWh of batteries) and utilizes 380Vdc distribution between houses to achieve the higher power transfers required to facilitate this higher tier access. The paper proposes a power management algorithm used to decide the operational priorities of the SHS model for a standalone system.

The paper then proposes a number of ways of establishing the power sharing priorities of interconnected SHSs. Each system will first attempt to meet its own demands locally, and in the case of additional excess, the energy from other system batteries will be utilized in order, beginning with the battery with the greatest SoC. Any surplus energy must then be shared between the batteries on the system. The paper presents three options for priorities of use for this energy; DOD-Based Proportional Excess Energy Sharing, where the energy given to each battery is proportional to its depth of discharge, with more discharged batteries prioritised; Priority Excess Energy Sharing, where the battery with the highest DOD is charged fully followed by the battery with the new lowest DOD and Equal Excess Energy Sharing, where each battery simply receives an equal proportion of the excess energy. Each approach here assumes centralised visibility and control of the distributed system.

The expected Loss of Load Probability (LLP) for each approach is presented for a case study of homogeneous tier 4 and 5 SHSs for clusters of between 2 and 50 systems over a 1 year time horizon. In the case presented of between 2 and 10 SHS systems interconnected with all three different battery sharing approaches, Priority Excess Sharing resulted in the highest chance of lost load, with both other methods performing identically in this particular case. After diversity mean peak demand for a network of interconnected systems is also presented in the work, but the use of such large batteries and panel sizes for the tier 4 and 5 SHSs makes it of limited interest for practical systems in most remote rural communities.

In [139] the results of simulation case-studies on interconnected SHSs using field data gathered from SOLShare system in Bangaldesh is presented. The paper presents evidence for the presence of excess energy due to solar panel over-sizing in three of the four systems under investigation and a basic simulation demonstrates reliability benefit derived from interconnection of four households.

[140] presents another approach to simulating a swarm grid, again utilising a deterministic simulation, although the systems under investigation in the distributed swarm grid each feature individual diesel generation and no investigation of battery degradation is made. The simulation demonstrates that swarm grids are less financially viable than traditional minigrids in the case-study investigated.

4.8.2 Minigrid Interconnection

There has also been significant investigation of interconnection between systems at the minigrid scale, focused mostly on hydro grids in Nepal.

"Interconnected mini-grids for rural energy transition in Nepal" by Koirala et al [141], published in 2013, considers the specific case of Nepal for interconnection of microgrids. The case of Nepal is interesting, as there are a large number of Hydro powered mini grids in the country, due to its mountainous location, but many of these experience severe planned load shedding and unplanned blackouts, due to reaching the limit of usable water resources. In addition, the mountainous terrain makes diesel generation an unappealing approach to mitigate this, due to the significant costs of transporting the fuel.

The motivation behind interconnection is to mitigate these blackouts by increasing diversity of generation availability and add the option to install shared generation or storage assets. The paper does not make consideration of the benefits of increased demand diversity.

In 2011, 6 hydro plants in Nepal were interconnected by 11KV AC over a distance of 8km via a synchronisation unit, providing 107kw of energy for a total of 1200 households. The grid was then interconnected to the national grid and it has been reported that reliability and quality of service improved, although the paper offers no quantitative analysis of the impact.

"Micro Hydro Interconnected Mini Grids in Nepal: Potential and Pitfalls" [142] expands on this work, presenting results of a case-study where 4 hydro grids were interconnected.

"Nepal: Scaling Up Electricity Access through Mini and Micro Hydropower Applications A strategic stock-taking and developing a future roadmap" [143] published by the World Bank in 2015 further considers the viability of interconnecting micro hydro grids in Nepal. It refers to these larger, interconnected networks as mini grids, but only considers the case of AC interconnection. This is seen as a potentially viable approach, but only in situations where some of the grids have an energy excess and some a deficit.

Benefits identified include the ability for one grid to support the other under some failure cases, but identifies a number of challenges with AC interconnection including the need for coordinated frequency, phase and voltage level between interconnected systems and the requirement for load controllers with dump loads to maintain energy balance between the system and an increased need for protection devices to ensure safety. Distance between grids and number of grids connected is also identified as a key factor, as the CAPEX cost cost of interconnection will scale with these factors.

The report specifically states that no benefit in demand diversity can be derived by interconnection during peak times, although this merits further quantitative investigation using stochastic approaches to model the behaviour of consumers and is addressed in chapter 4 and 5.Results of feasibility case studies are presented in the report, all for 11KV AC interconnection under the assumption that productive uses of energy will be adopted for 75% of utilised energy between 9:00-17:00, when the domestic demand is low.

The financial analysis concludes that while some of the case studies can make enough income to cover operational costs, maintenance and salaries, none of the mini grids are expected to make a net profit, even with the generous assumption of 75% of excess energy being utilised.

Business and operational models are mentioned, and it is considered by the AEPC and other stakeholders that the best model of operation is for each micro hydro plant to be operated as independent power producers, and a distribution operator be formed with membership from each of these bodies to operate the distribution network. The report does not consider DC interconnection, which could mitigate many of the issues of load flow and synchronisation needs, or consider installing or utilising other generation technologies to increase diversity, such as small wind, battery storage or solar PV.

Interestingly, there is no published work investigating the interconnection of non-hydro based islanded minigrids, representing a particular gap in the literature.

4.8.3 Multi-microgrids

The concept of multi-microgrids developed from exploration of smart grids and the problems of integration and control of DER. This concept details the control and operation of multiple microgrids connected to the low voltage distribution network. [144] establishes a multi microgrid as :

> "Formed at the Medium Voltage (MV) level, consisting of several LV microgrids and DG units connected on adjacent MV feeders."

[145] uses particle swarm optimisation to solve an economic dispatch problem for a case-study of three minigrids all connected to the same MV feeder. [146] investigates the reliability benefits of coordinated operation of multi-microgrids and [147] similarly investigates how multi-microgrids can provide reliability benefit and resilience to distribution networks.

Although of tangential interest, the work undertaken on multi-microgrids focuses on the control and operation of microgrids connected to a macrogrid, rather than islanded as investigated in this work. Additionally, no work has been published exploring the planning and decision making process for installing and evaluating these systems.

4.8.4 Existing Interconnection Activities in the Private Sector

In addition to the academic interest in interconnection of power systems, a number of businesses are working in this area. This section offers a summary of the current cutting edge of implementation in the area, in relation to the wider field of offgrid energy.

Brooklyn microgrid are a company operating in Brooklyn, New York. They operate a local energy market that facilitates the real time trading of energy over the existing AC distribution network owned by conEd in a 'virtual microgrid' [148]. The system net meters the flows of energy within the system and utilises the block-chain cryptocurrency ethereum for billing, allowing consumers and small businesses to buy and sell excess energy from rooftop PV.

The organisation operates as a Distribution System Operator, using price signals to manage and balance local demand. LO3 and their parent company Centrica are also working towards a similar project in Cornwall, UK.

Okra Energy have a solution they call modular off grid energy [149]. This approach differs slightly from swarm electrification. It is not primarily intended to utilize the already existing assets of SHS installed, but instead to create a distributed, smart microgrid with storage, generation and demand at each household level.

They take advantage of the controllability and efficiency of DC meshed networks to effectively route power between households and provide a microgrid at lower cost (they claim 1/2 the cost) of a traditional AC microgrid. Their solution is providing a range of tiers of energy access, including some productive use applications such as incubation of crickets, rice driers and water pumps.

SOLShare was founded by a number of researchers from TU Berlin involved in the initial inception of the idea of swarm electrification. They operate in Bangladesh and have investigated networks of interconnected SHS there, using a peer-to-peer trading platform called CELLbazaar to facilitate a local energy network. This platform allows SHS users to sell excess energy and non-SHS users to buy that energy.

Their system works natively at DC, using a bi-directional DC/DC converter module and claims to interface directly with existing SHS hardware in the customer's house and features integration with a mobile app and mobile money payment. They have the ambitious aim of installing 10,000 microgrids by 2030 in Bangladesh, taking advantage of the countries proliferation of SHSs [150]. They also identify the limitations of this approach, being limited to areas with high density of SHS users located close to each other and mention the transformative impacts on community dynamics that could occur by turning the village into an energy market of producers and buyers. Finally, they identify that one of the most valuable assets generated from a commercial standpoint is the data on the usage patterns and behaviour of the consumers, which raises interesting business model and ethical questions.

4.9 Summary

It is clear from chapter three that there is a need for adapting existing process of off grid energy planning to adopt a more incremental approach. Interconnection of off grid systems has gained interest as a vector for improving electricity access, but the work undertaken does not place the process effectively in this wider context and focuses on individual case studies, rather than investigating the underlying factors that impact the viability of this approach. Understanding the wider impact of factors such as present diversity of demand and generation and distance between systems in an empirical fashion is vital to the further development of this potentially transformative approach.

Additionally, the existing work is not effectively placed in the wider context of electricity planning, simply presenting individual, system level examples. Interconnection can be integrated into existing planning both at a wider area and system level, but a robust underlying model must be created and more robust evidence of the relative benefits of interconnection quantitatively evaluated.

In order to fully evaluate the value of this approach, a stochastic rather than deterministic model is required to effectively simulate the diversity exhibited by agents acting unpredictably, in contrast to the deterministic, case study based work undertaken in literature to date.

The next chapter will present one of the key contributions of this thesis, a detailed methodology for simulating interconnected systems utilising time-sequential Monte Carlo, as the basis for model that can more effectively investigate and quantitatively address a number of the questions raised in this chapter, such as the cost and reliability impacts of interconnecting systems and the level of demand and generation diversity present.

Chapter 5

A Methodology for Monte Carlo Simulation of Interconnected Solar Home Systems

5.1 Introduction

The requirement for a quantitative methodology to investigate bottom-up interconnection and its role in electricity access planning has been established in previous chapters. In this chapter, a methodology utilising a time sequential Monte Carlo method is proposed as a non-deterministic approach to evaluating uncertainty and modelling the stochastic behaviour of agents.

First a model of the systems under investigation is developed, consisting of blocks modelling generation, storage, demand and losses. Then these are combined to form a whole system model to act as an underlying model for the Monte Carlo simulation with system constraints and dispatch evaluated.

The use of a Monte Carlo methodology is then justified and the integration of the developed model into the methodology outlined. This model is then used to evaluate a number of case studies in chapter 6.

5.2 Programming Language and Tools Used

All work presented in this thesis was coded from scratch using Python 3. A number of libraries were utilised, including NumPy, SciPy, Seaborn and MatPlotLib.

5.3 Methodology Selection

The requirements for a planing approach for bottom up electrification are informed by a number of factors explored in previous chapters.

- Systems under investigation are storage dominated. A time series method is required to appropriately model the system [151]. A time sequential simulation simulates a number of time-steps and passes state data from one time-step to the next to model the impact of temporal effects such as storage of energy, deferred investment and asset ageing.
- The methodology is required to have some method of capturing the uncertainty and capturing the effects of demand and generation diversity. For this reason, a deterministic simulation is deemed unsuitable, as it would only investigate one set of demand profiles with a given diversity factor, making deep investigation of the effects of varying diversity challenging.
- The model needs to operate over a large time horizon with a fine temporal resolution in order to capture the impact of transient and low probability events that could have a large impact on the system operation.
- The model must contain the ability to model additional infrastructure investment at any time in the simulation or when specific conditions are met.

To meet these requirements, a time sequential Monte Carlo approach was adopted.

5.3.1 Approaches to Stochastic Modelling

5.4 Monte Carlo Simulation

A Time Sequential Monte Carlo methodology was adopted. Monte Carlo simulation is a stochastic simulation methodology based on randomly sampling a variable from a probability distribution. This method is commonly used in power systems reliability analysis, as the analysis of impact of component failure and repair has an impact over time [152].

For each time-step t, the energy balance of the system is evaluated and performance metrics recorded, with unknown values being simulated as independent random events. This is repeated for each time-step of the simulation in chronological order, with relevant information such as storage state of charge passed from one time-step to the next.

Once the entire time horizon has been evaluated, the desired metrics are recorded and the process is repeated for a number of runs. By running a simulation a large number of times, with variables associated with unknown or uncertain behaviours drawn randomly from a defined probability distribution on each run, a distribution of possible results can be obtained.

Each metric can then be presented as a range of possible results, with confidence intervals placed around those results.

A key advantage offered over deterministic methods of simulation is the ability to capture a range of possible "worlds" containing not only the most likely simulation result, but also a range of lower probability but possible results. Many high impact power systems events, such as failure of key assets occur rarely, but have a significant impact on system performance. A Monte Carlo simulation can give an indication of the risk of these low probability, high impact events, making it an invaluable tool for planning under uncertainty and evaluating the benefits and cost of mitigating such risks.

5.4.1 Time Based and Condition Based Changes to Simulation Parameters

A limitation of existing methodologies is the lack of ability to model investment being made during a simulation. Under this model, both time based and state based changes can be made to the simulation, such as increasing the installed generation or battery capacity after three years or if reliability or another metric falls below a predetermined threshold.

At the beginning of each time-step, the simulation checks to see if any of the conditions have been met and if so, the relevant values are changed for future time-steps.

5.5 Solar Photo-Voltaic Model

The aim of the solar PV model is to model the energy generated by solar PV panels at a given location and over a given time. The model used is adapted from [153], which has been validated against over 1000 ground weather station measurements.
The inputs to the model are:

- The MEERA 2 satellite data-set
- Location latitude and longitude of the system under investigation
- PV_{Size} in Wp
- Conversion efficiency of the PV array
- Tilt and azimuth angles of the installed PV array
- Temporal resolution of data required
- Desired time horizon

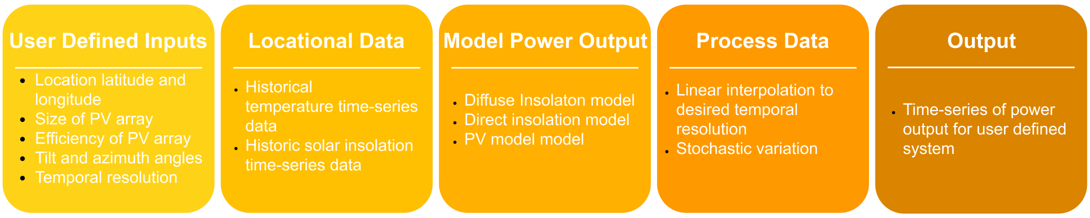

Figure 5.1: Flow diagram of solar PV model

5.5.1 Data Selection

In order to capture the locational variation in solar insolation, the model takes historical solar insolation data for the location under investigation as an input.

There are two main sources of historical data, ground measurements from weather-stations or data captured from satellite observation. Ground measurements can offer an accurate and high temporal resolution data-set for a given location, but are contingent on systematic data collection campaigns. This measurement process is expensive and time-consuming, so has not been conducted for most locations in the world.

Satellite weather data is recorded globally and historical data can be accessed for the entire earth. Data sets vary in both temporal and spatial resolution.For locations further than *37km* from a ground weather station, satellite data is considered to be a more accurate alternative [154] to ground recordings. Due to the requirement for a complete global data-set, satellite data is used in this work.

The selected data-set used is MEERA II [155], a database of historic satellite weather data reanalysis provided by NASA. This data-set offers temperature and energy flux at a resolution of 0.5 lat x 0.625 lon and a temporal resolution of 1 hour. Unless otherwise stated, all solar data used is for 2007 at latitude -2, longitude 30 in Kigali, Rwanda.

In order to account for random variations in weather, normally distributed noise with a normal distribution and a standard deviation of 5% of the magnitude at the given time. This standard deviation was chosen to represent the stated uncertainty in the MEERA 2 data [155].

Solar resource data with a temporal resolution finer than an hour for solar insolation

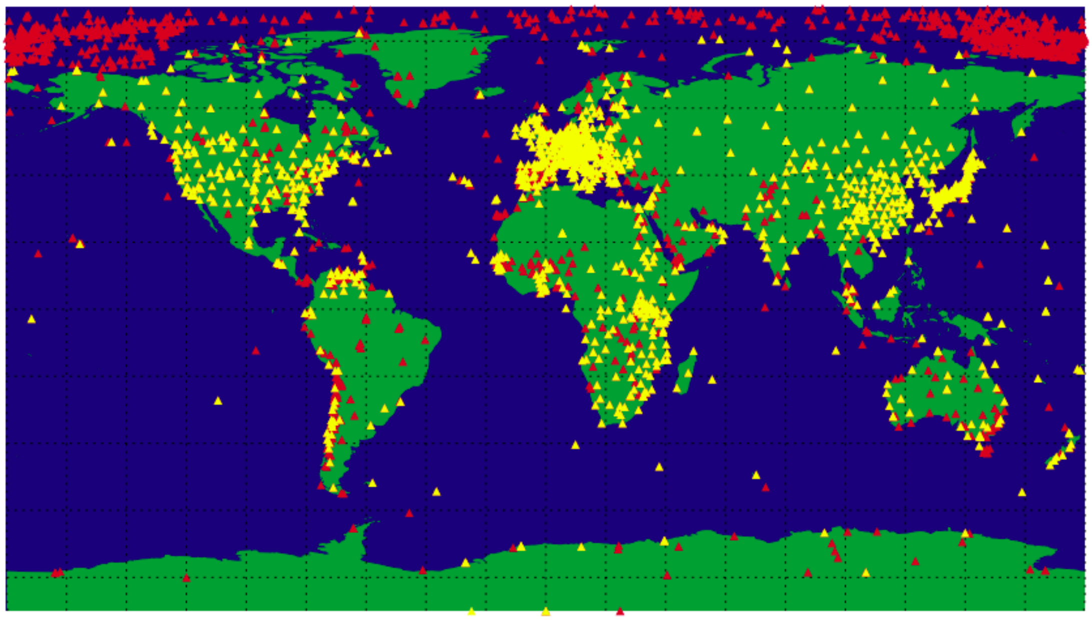

Figure 5.2: Locations of ground recording weather stations from [15]

is not available globally. It is necessary to modify the available data in order to provide the required data of any simulation with a temporal resolution of less than an hour.

This is achieved through linear interpolation of the existing data, an approach commonly used for smoothing data distributions [156]. Linear interpolations is a method used to fit curves by creating new data-points between know discrete data values. Linear interpolations is the simplest method of data interpolation.

5.5.2 Limitations of Solar Model and Further Work

A number of factors are not considered in this model for the purpose of simplicity, but could be expanded in future work.

Shading of solar PV panels can have a significant impact on both their performance and lifetime [157]. Shading can be caused by clouds or by terrestrial objects such as trees, and will change over the course of a day and this effect could be more significant in a distributed system, with a large number of smaller PV panels compared to a single centralised generation location, due to individual households possibly being less likely to appropriately maintain the system than a centralised operator. The could impact the modelling by causing a systematic overestimate of the outputs of the PV panels

In addition, not all panels in a real distributed minigrid of SHSs will have the same azimuth and tilt angle, as each household and installation will differ. This effect could have beneficial smoothing effects on solar demand compared to centralised installation or sub-optimal installations could result in reduced output. The optimal setup may depend on latitude, demand profiles, system design and many other factors and merits investigation [158].

Finally, the long term impact of climate change can increase the likelihood of rare weather events and impact seasonal variations in weather such as the cycles of dry and rainy seasons observed in many equatorial locations [159]. Detailed investigation of the long term viability of any solar based power system should consider these factors.

5.6 Demand Model

A key factor in the evaluation of interconnected systems is the need to understand and investigate demand diversity in very small systems. In order to achieve this, a stochastic, bottom-up, appliance level model was selected. This approach models the demand of each appliance individually, based on expected usage across the day. This approach was chosen due to the flexibility of data sources that can be utilised and its compatibility with bottom-up community engagement approaches and the fact the modelling can easily scale to consider the addition of new loads over time.

5.6.1 Data Availability

Planning and simulation for any energy system requires understanding of load profiles for the system in question. For many conventional power system simulations, there is a wealth of high temporal resolution historic data available. Well recorded historic changes in usage patterns can be used to inform future demand in a well understood manner.

For minigrids and other off grid energy systems, this wealth of experience and historical data does not exist. There are a few key factors contributing to this systemic lack of data.

The first is how recent wide scale deployment of minigrids is globally. The number of installed islanded minigrids has rapidly expanded in recent years, but is still short of the full market potential. The consequence of this relatively recent development is that systems have not been installed for long enough to gather a large volume of load data over a number of years.

The second reason for this lack of data from mini grids is financial. Most minigrids are currently installed by private developers or third sector organisations with a focus on the repayment of capital and operational costs. The payback time for such systems varies, but tends to be in the region of 5-20 years. There is significant pressure for developers to lower costs and recoup investment. Installing remote monitoring devices incurs additional costs in hardware for data loggers and other monitoring devices, software for the direct collection of data, and costs for transferring the data from the system in question to those who can make use of it either by GSM or other mobile data systems or though manual collection of memory cards from data loggers, requiring additional staff hours.

Some organisations, particularly in the off grid Pay As You Go sector such as BBOXX and MobiSol have made sophisticated metering and monitoring of data a core component of their business, using the information to inform preventative maintenance, identify problem customers and design future product offerings but they are in the minority. The data is also a key component of these companies competitive advantage in a fast moving sector, making them understandably unwilling to share the information widely.

5.6.2 Modelling Demand

This approach models the demand for each individual appliance on each system, allowing for realistic and modular understanding of demand growth, both driven by changing use of existing appliances and connection of new appliances. For each time-step in the simulation, each appliance is assigned a probability value associated with it being in the on state, informed by surveys and load data.

The model represented the probability of an appliance being switched on at a given time step as independent from previous timesteps in the simulation, depending only on the predefined probability of use during that time of the day.

Demand profiles used to generate the initial load profiles are based on usage data for BBOXXs standardised SHS topology and data on the available appliances taken from [30].

Table 5.1: Probability of use for an LED light in a small SHS

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Probability	0.1	0.05	0.05	0.05	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	0.6	0.5	0.3	0.25	0.2

Table 5.2 shows the appliances present in a standard (tier 1 or 2) SHS and a constant self consumption load associated with the charge controller and communications. Chapter 6 details all case study systems and their respective appliance.

Table 5.2: Loads in BBOXX bPower50 SHS

	Number	**Power Consumption**	**Unit**
LED Bulb	4	1	W
USB Port for Phone Charging	2	1	W
TV	1	11.2	W
Self Consumption	1	1	W

For each appliance at each time step a random number between 0 and 1 is generated from uniform distribution and compared to the probability distribution displayed in 5.1 for the given hour of the day, where the hour of the day is calculated by:

$$Hour = tmoduloResolution \cdot 24 \tag{5.1}$$

Therefore, for appliance x at time-step t

$$AppliaceState_{xt} = \begin{cases} 1 & \text{if } PApplicance_{xt} > R_{at} \\ 0, & \text{otherwise} \end{cases}$$

5.6.3 Two State Markov Chain Load Estimation

This does not realistically capture the behaviour of customers for most appliances. The chance of a given appliance being switched on is dependent on a number of factors, key among these is the history of the use of the load.

A two state Markov chain model is used to represent each appliance at the household level. For each timestep, each appliance will have a probability to turn on if currently off and a chance to turn off if currently on.

For example, a light that is on may have a large probability to be switched off if it is on during the middle of the day, when much of the lighting demand can be met by sunlight (in many cases). In contrast, a light left switched on overnight, either by accident or as security lighting, has a much lower probability of being switched off at 3am as most of the residents of the house are likely to be asleep.

A two state Markov chain model can be represented mathematically for each appliance. Three components describe the Two State Markov chain model: The distribution of initial states, the state space and the transition matrix.

In the case of a two state model describing and appliance that can either be on or off, the state space consists of these two states, off and on, referred to as S0 and S1 respectively.

A 2x2 matrix can then be constructed. The values in the matrix are:

- T_{00}: the probability of being in S_0 and remaining in S_0
- T_{01} the chance of being in S_0 and transitioning to state S_1, given by 1-T_{00}
- T_{11}, the probability of being in S_1 and remaining in S_1
- T_{10} the chance of being in S_1 and transitioning to state S_0, given by 1-T_{11},

$$\begin{bmatrix} T_{00} & T_{01} \\ T_{10} & T_{11} \end{bmatrix}$$

1/T_{01} The mean number of rolls before transition from S0 to S1 (or the mean number of time steps spent in in S0 before moving to S1) is given by:

$$TransitionTime_{01} = 1/T_{01} \tag{5.2}$$

Similarly, the mean time taken to move from S1 to S0 is:

$$TransitionTime_{10} = 1/T_{10} \tag{5.3}$$

So the probability of being in S1 across all time is:

$$Time_{\text{on}} = (1/T_{10})/(1/T_{01} + 1/T_{10}) \tag{5.4}$$

Which simplifies to:

$$Time_{\text{on}} = (T_{01})/(T_{01} + T_{10}) \tag{5.5}$$

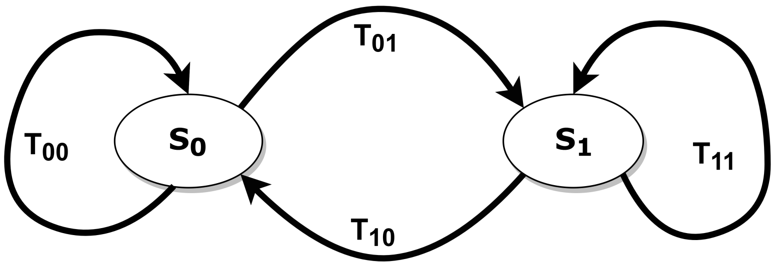

Figure 5.3: State diagram for a two state appliance model

There are therefore a family of solutions for T_{01} and T_{10} which give the same mean probability, but will transition between states more or less often. This allows the user to create load profiles where the averaged mean and variance can be controlled for the same appliance utilisation per day.

This is shown in figure 5.4, the profile for 10 LED bulbs where both profiles have the same mean when averaged over 1000 runs, but exhibit different variance.

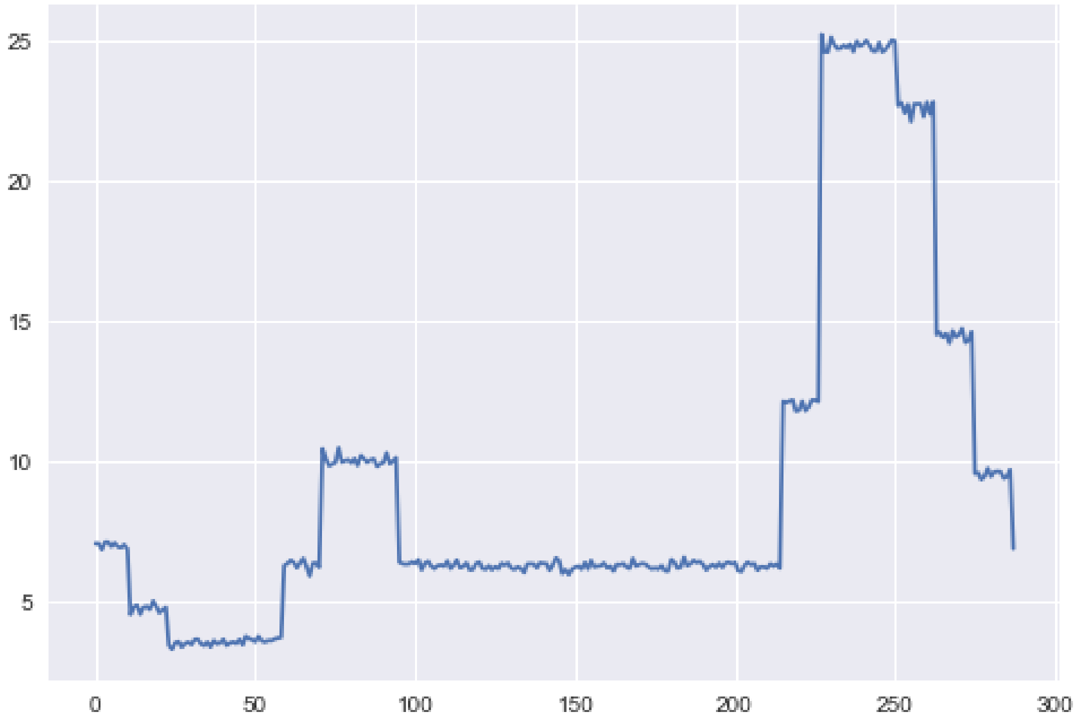

Figure 5.4: Averaged load profile for 10 LED bulbs showing comparison of variance for differing values of T_{01} and T_{10}

This can be used to fit an appliance level model to an existing load profile as described in section 5.7.

5.7 Battery Model

Battery storage is included in off grid systems to mitigate the uncertainty and variability associated with renewable generation and unknown demand profiles. Batteries are used to store excess energy when generation outweighs demand and to meet demand at times when it is greater than generation, such as overnight in solar dominated systems.

Each battery had the following properties defined at the beginning of the simulation:

- Capacity (kWh)
- Maximum power output (W)
- Maximum charging power (W)

- Charging losses
- Discharge losses
- Standing losses (%/day)
- Initial SOC (%)
- Minimum allowable SOC

5.7.1 Battery Model

A storage device is a fundamentally time dependant component, with the state of charge at a given time a function of the history of the state of charge and load experienced by the battery. The charge at timestep t is dependent on if the battery is being dispatched, left in its existing state of charge or charged. This is represented by the variable $Excess_t$ determined, with the magnitude of $Excess_t$ positive if there is a surplus of energy and negative otherwise. The historic state of charge from the previous timestep is represented by SOC_{t-1}.

The State of Charge (SOC) at timestep t =

$$SOC_t = SOC_{t-1} + Excess_t \tag{5.6}$$

The initial state of charge is determined at random, uniformly distributed between 0% and 100% SOC.

Charge and discharge efficiency denote the losses undertaken in converting from electrical to chemical energy and back to electrical energy. This is determined to be 5%.

A battery can also experience standing losses, which occur over time if the battery is charged. For each day that the battery is utilised, but this is ignored in this model as high battery utilisation make this phenomenon negligible.

5.7.2 Battery Types

A wide range of battery technologies are available. The two most commonly used in off grid applications are Lead Acid and Lithium Ion Batteries and will be the focus of the modeling in this section. Models for other battery technologies could easily be included due to the modular nature of the model. Lead acid batteries have lower capital costs than lithium ion batteries, but in many applications lithium ion can have a lower lifetime cost due to their longer lifetime

5.7.3 Battery Degradation

The capacity of batteries degrades over time. This degradation can lead to reduced quality and reliability of service and replacement represents a significant operational cost. For this reason, understanding and modelling battery degradation is vital to planning the long term sustainable operation of systems. Degradation rates differ for battery technologies, but are a function of the number of charge/discharge cycles experienced, the depth of discharge experienced and the temperature of the battery.

This battery behaviour is of particular interest to modelling interconnected networks of systems with distributed storage resources, as the range of options for dispatch allow the optimisation for battery charge and discharge cycles and the evaluation of this on the selected objective function for the simulation.

5.7.4 Battery Degradation Model

The model for degradation is adapted from [16] and uses average depth of discharge $\overline{DOD}$ and temperature $\overline{T}$ to calculate the proportional damage done to the battery, based on degradation information provided by the battery manufacturer. This table gives the number of cycles until the battery capacity reaches 80% of its rated capacity.

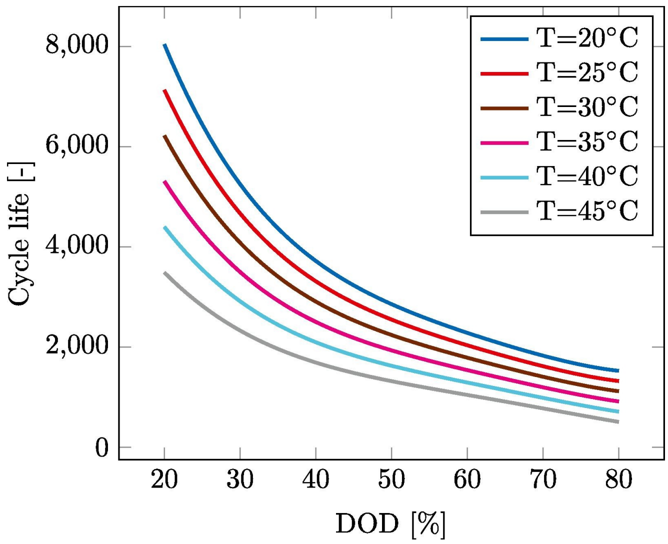

Figure 5.5: Battery degradation curves for flooded lead acid batteries [16]

This is adapted to a polynomial lookup table and used to evaluate the remaining battery capacity dynamical thought the simulation.

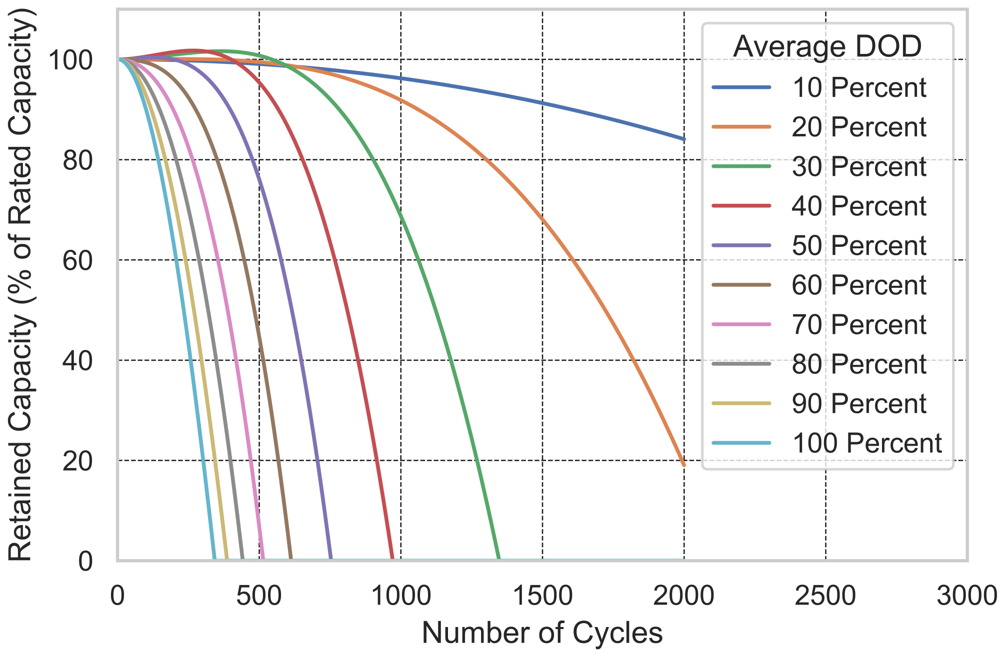

Figure 5.6: Remaining capacity curves for flooded lead acid batteries [16]

5.8 Interconnector

The physical model of the interconnection between systems must take into account the losses associated with both the converter station and resistive losses in the line.

5.8.1 Line Losses

The converter station is modelled as a black box that allows sharing of power between the two interconnected systems with a fixed percentage power loss. This loss is made up of I^2R losses and converter losses.

Each interconnector has a maximum power rating, voltage, length, cross sectional area of the line and a defined converter loss.

The power rating constraint is dependent on the thermal limits of the line and the rating of the converter station. This rating can not be exceeded and forms the main constraint for the interconnector.

The resistive losses are due to the energy lost as heat in the resistance of the line or cable forming the network component of the interconnector. These losses are proportional to the resistance of the line and the square of the current being transferred, governed by the equation:

$$P_{loss} = I^2R \tag{5.7}$$

The resistance of the line or cable is dependant on a number of factors: its material, the cross sectional area and its length. Each material has a resistance per unit length value, which can be found in standard data-sheets.

The selection of material and cross sectional area will impact on the cost of the cable, outlined further in section 5.10.

The current flowing in the line is a function of the power being transferred and the selected voltage level. Therefore the overall loss is given by:

$$P_{loss} = (V_{converter}/P^2_{connector})(L_{line}R_{PerUnitLength}) \tag{5.8}$$

5.8.2 Step-Up and Step-Down Losses

It is assumed that the losses associated with stepping up the voltage for transmission and back to household voltage is 5%, established in [160].

5.9 SHS Model

The PV, battery, load and charge controller models are combined to form a SHS system model.

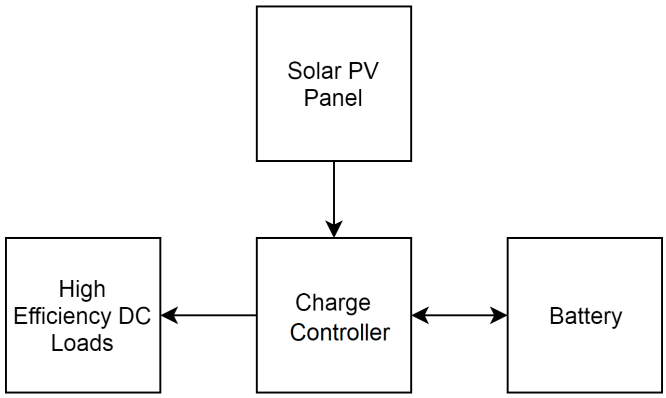

Figure 5.7: SHS block diagram

Figure 5.7 shows the block diagram for a SHS used in this model.

5.9.1 SHS Model Simulation Process

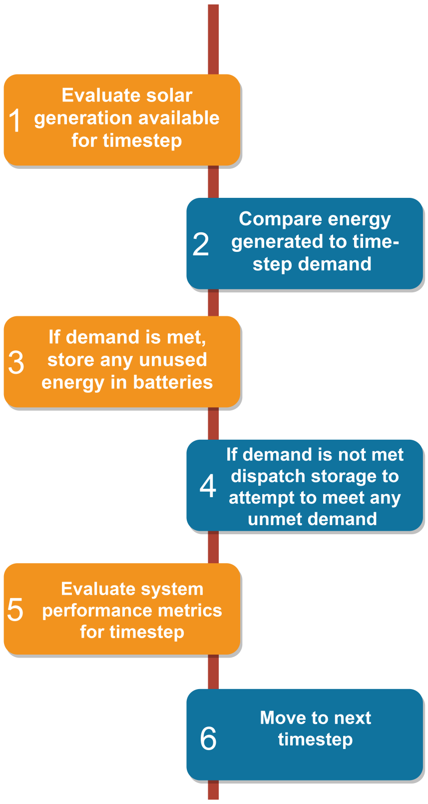

Figure 5.8: Generalised process for each simulation time-step for a SHS

For each time-step of the simulation, the decision process shown in figure 5.8 is followed. First the system will attempt to meet demand from any PV generation. If demand is met, any excess energy will be stored in the batteries. If the batteries are fully charged, excess energy is dumped.

If the generation is insufficient, energy stored in the batteries will be utilised if the energy is great enough and the battery SOC is above its sharing threshold. If demand is still not met, the unmet demand is recorded as $EENS_t$.

5.9.2 Dispatch Decision Tree

Figure 5.9 offers a more detailed breakdown of the dispatch choice for each timestep.

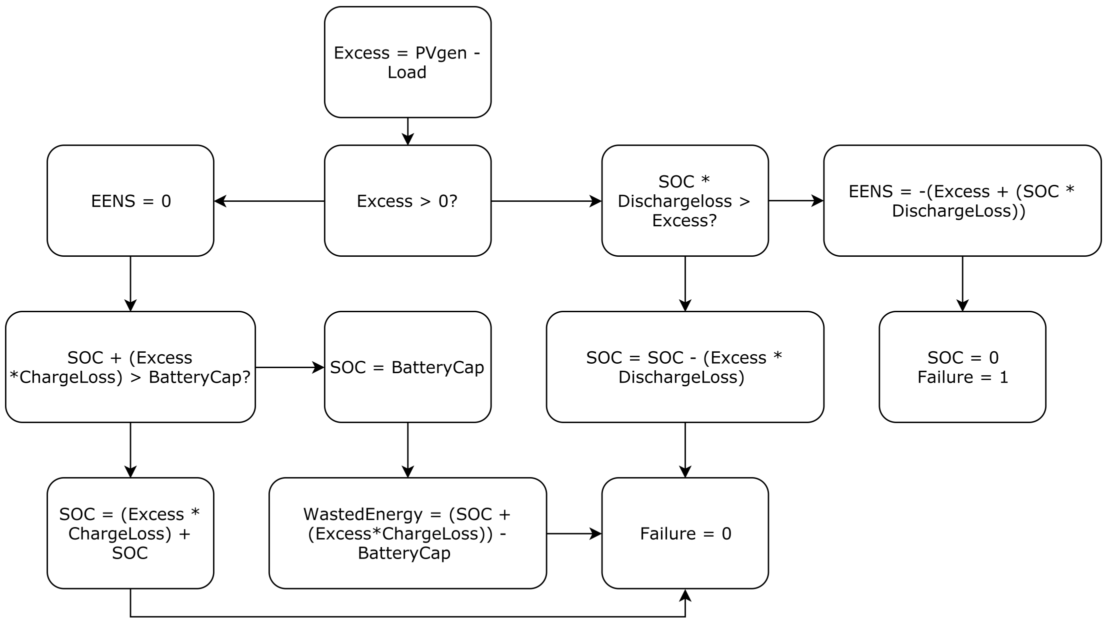

Figure 5.9: Dispatch Decision Tree for SHS model

5.10 Cost Model

The cost model combines three sources of cost, CAPEX, OPEX and external costs not captured by these. These are combined below to calculate Levelised Cost of Energy (LCOE), to facilitate like for like comparison of differing solutions. All costs are given in USD.

5.10.1 CAPEX

The costs are presented here are reflective of 2016 prices. Prices for these components, particularly PV panels and batteries, can change rapidly and differ based on locational factors such as transport distances, import taxes and local manufacturing.

The CAPEX (Capital Expenditure) associated with the system is the sum of the costs of all components of the system. Capital costs for generation plant are taken from [22] and are shown in table 5.3.

Component	Cost per Unit ($/ kWp)
Solar PV Minigrid	4341
Diesel Generator Minigrid	721
Solar PV SHS	5209
Diesel Generator SHS	938

Table 5.3: Generation plant capital costs (2016 prices)

Costs for LV distribution network are given in table 5.4

Component	Cost per Unit ($/ km)
LV Network	5000

Table 5.4: Distribution network capital costs

Costs of batteries are given in table 5.4 from [161] and [162].

Component	Cost per Unit ($/ kWh)
Sealed Lead Acid	160 [161]
Lithium Ion	600 [162]

Table 5.5: Battery storage capital costs

5.10.2 Net Asset Value

In order to calculate the LCOE at a given time, the discounted value of assets in the system must be calculated. A discount rate of 8% per year was adopted for all assets.

$$NetAssetValue = \frac{CapitalCost}{(1 + DiscountRate)^{Year}} \tag{5.9}$$

5.10.3 OPEX

Operational expenditure is modelled and proportional to capital investment, from [22]. At the start of each year a cost is incurred for each unit of installed capacity based on the value of each asset, shown in table 5.6.

Component	O&M Costs (% Capital /year)
Solar PV Minigrid	2
Diesel Generator Minigrid	10
Solar PV SHS	2
Diesel Generator SHS	10
LV network	2

Table 5.6: Operations and maintenance costs

No O&M costs are modelled for the batteries, this is instead included in the replacement cost. The battery replacement costs are based on the capital cost of the battery plus a labour charge taken from [163].

5.10.4 Externalities

The value of lost load (VOLL) is a cost associated with the negative utility of a system failing to meet energy demand. It is an attempt to quantify the financial benefits of reliability.

A dis-utility cost per unit time for each kWh of energy not served can be established and used to quantify the financial impact of reliability in order to compare the value of actions impacting the reliability of the systems, such as investing in additional battery storage, to the end user impact.

The value of lost load can vary depending on the nature of interruptions and the user. The value of lost load for high value manufacturing or failure of a fridge that forms part of the vaccine cold chain in a healthcare centre could have a different utility to the loss of a radio for the same length of time, even when aggregated over a large number of radios so the lost kWhs are equivalent.

In the UK VOLL is calculated as the money that a customer would be willing to pay in order to not be disconnected for a unit of use. The value of VOLL for domestic users was £6,957/MWh to £11,820/MWh [164] in 2013, which is around 1000 times higher than the domestic tariff. . One simple method for calculating VOLL in off grid applications would be to assume the same relationship between tariff and VOLL, but a number of factors make this assumption oversimplified, as outlined in [165].

The concept was established in countries with developed energy infrastructure and is dependent on a market view of energy.

Off grid energy systems tend to have significantly higher tariffs per kWh than grid supplies in many locations. The ability to pay of consumers is generally lower. There is also less of an incumbent expectation as exists in developed countries of a 100% reliable energy supply. Consumers may be willing to accept a far more unreliable grid if it results in overall lower tariffs.

For the purpose of this model:

$$CostofLostLoad = EENS \cdot VOLL \tag{5.10}$$

Where

$$VOLL = 100 \cdot LCOE \tag{5.11}$$

Which can then be used to calculate Levelized Cost of Supplied and Lost Energy

$$LCOSLE = LCOE + (EENS \cdot VOLL) \tag{5.12}$$

5.11 Performance Metrics

A number of reliability metrics are evaluated for each simulation.

5.11.1 Performance Metrics

Unused energy is the sum of energy generated but unable to be used or stored due to lack of demand and battery capacity. This excess energy is dumped through a load resistor as heat.

$$UnusedEnergy = \sum_{t=0}^{t_{tot}} ExcessEnergy_t \tag{5.13}$$

DumpRatio is the ratio of unused energy to total energy generated.

$$DumpRatio = \frac{UnusedEnergy}{TotalEnergy} \tag{5.14}$$

5.11.2 Reliability Metrics

Expected Energy Not Served (EENS) is the sum of all unmet demand over the simulation

$$EENS = \sum_{t=0}^{t_{tot}} EnergyUnserved_t \tag{5.15}$$

Loss of Load Probability (LOLP) is the probibility averaged over a given time horizon of any amount of required energy not being provided at any given timestep.

$$LOLP = \frac{\sum_{t=0}^{t_{tot}} Failure_t}{t_{tot}} \tag{5.16}$$

Where

$$Failure_t = \begin{cases} 1 & \text{if } EnergyUnserved_t > 0 \\ 0, & \text{otherwise} \end{cases}$$

5.11.3 Cost Metrics

The net present value is the current discounted value of the assets in the system, where y is the number of years the asset has been installed in the system.

$$NPV = \sum_{0}^{NumberOfAssets} \frac{CapitalCost}{(1 + DiscountRate)^y} \tag{5.17}$$

Levelised Cost of Energy (LCOE) is the cost per KWh of energy over the lifetime of the system, accounting for capital and operational costs [166].

$$LCOE = \frac{\sum \frac{CAPEX + O\&M + Fuel}{1 + DiscountRate^t}}{\sum \frac{Energy}{1 + DiscountRate^t}} \tag{5.18}$$

5.12 Validation

The model components have been validated independently and as a system. This section presents the approach and results of validation for each section.

5.12.1 Load Profiles

The load profile coefficients for each appliance are fitted to existing load profiles from BBOXX SHSs from [30]. Although disaggregated profiles are unavailable, the number and type of appliances is known. The output of the model is compared to the load profiles from these systems both in terms of mean and variance and the variation is shown in table 5.7.

Metric	Deviation(%)
Mean Demand	7.3%
Standard Deviation	10%

Table 5.7: Validation Results for SHS load profiles

Table 5.7 shows the resulting match between these measured and simulated load profiles, with mean and standard deviations being less than 10% different from the provided load profiles.

5.12.2 System Model

The SHS model was validated by comparing to the design created in HOMER an identically sized system and by comparing the wasted energy metrics to recorded data from [26]. Across all system types there is a maximum variation of 15% variation from the results and those in this paper.

The results for Minigrid simulations are similarly validated against HOMER pro simulations for four case study systems. In each case, the results obtained for identical systems from the commercial design software are within 10% of the results obtained from the system model.

Table 5.8: Validation results for the large SHS systems

System Type	**HOMER Simulated LCOE ($/kWh)**	**Model Simulated LCOE ($/kWh)**
Large Domestic	1.47	1.36
Large Commercial	1.01	0.95

5.12.3 Battery Degradation

The model used for battery degradation from [16] is validated directly to physical measurements of battery capacity degradation. Utilising this model which has been lab validated against experimental data under a range of temperature conditions allows us to be confident of the model results.

5.12.4 Solar PV model

The solar PV generation model from [153] is validated against over 1000 ground measurement from weather stations. By utilising real historical data taken form these measurement, at locations close to these weather stations, accurate solar insulation values can acquired. The chosen location of Kigali, Rwanda was chosen for its proximity to the Kigali weather station.

5.13 Further Work

Further work has been outlined in each section, but there is also some overall extensions to this work that could be undertaken. Firstly, this model could be directly validated against a greater range of data-sources and case studies.

5.13.1 Optimisation

In chapter 4 a number of optimisation techniques and their application to designing off-grid energy systems are outlined. These techniques all require an objective function and search space to operate. The model developed here can be utilised with any of combination output metrics as an objective function and a search space including component sizing and interconnection presence and layout to design optimal systems.

5.13.2 More Complex Network Typologies

For this work it was chosen to only investigate the impact of minimum spanning tree network typologies of interconnection. In practice, these layouts may not be practical and consideration can be made of local geographical features, such as hills and other obstacles and the practical desire to follow roads and other terrain features with networks.

In addition, evaluation could be made of more complex, meshed network typologies, which could yield increased reliability and resilience and minimise losses, despite requiring more CAPEX than a simple spanning tree.

5.13.3 Component Level Reliability Modelling

A key barrier to the performance of offgrid energy systems is downtime caused by the failure of components. The downtime of a component is a function of the time between failures - influenced by its environment and the expected time to repair a failure. The time taken to repair a failure is of particular interest in the off grid applications investigated in this work, as many offgrid systems are far from components and expertise required to perform repairs, or do not have the financial mechanisms in place to pay for unplanned failure of components. Fully understanding factors influencing the potential failure of the system are vital in evaluating the long term cost and reliability of any system. There is therefore a desire to create a time series of availability for each component that is reflective of the real world distribution of failures on the system.

Each component that could fail will exhibit different expected times to failure and distribution of failures, based on the component in question, its rate of utilisation, environmental factors such as temperature and wind speed and a range of other factors. Similarly, expected time to repair will be different for each component and location, influenced by the remoteness of the location in question, availability of replacement parts and technicians with the required skills to perform the required repair work.

For any given component in any system, there exists a theoretical distribution of times to component failure f and repair r. We can create an estimation of these distributions In order to achieve this, we can then create a two state Markov chain model for each component, as was done with each load in section 5.6.3, where S1 is when the component is operational and S0 is when the component has failed and is awaiting repair. A probability of transitioning between states can then be modelled by sampling from the relevant distribution for each time-step.

5.14 Summary

This chapter outlined a time-sequential Monte Carlo simulation methodology for evaluating a range of performance metrics for interconnected systems and traditional isolated systems to facilitate comparison.

The novelty of the approach is in its transferablity to evaluate a range of scenarios the stochastic approach to simulation and the ability to evaluate conditional or time-based changes in system parameters in order to model contextual, incremental investment in infrastructure as demand changes and grows.

In chapter 6 this methodology is applied to a range of case studies to first establish the limitation of the SHS then investigates under what conditions interconnection of SHS offers the optimal solution to upgrading electricity access.

Chapter 6

Simulation of the Limitations of Solar Home Systems

6.1 Introduction

This Chapter presents results from the simulation methodology outlined in the methodology section in chapter 5 applied to a range of case studies. These studies explore quantitatively the limitations of SHSs and form a baseline against which to compare the simulations of interconnected systems that will be presented in chapter 7.

Section 6.2 establishes the case-study systems that will be investigated, presenting their specification and load profiles. The reliability of SHSs over time and the impacts of battery ageing on LCOE are then established. The unused excess energy generated by SHSs is quantified for each system type and demand diversity of SHSs is then investigated.

This combination quantified excess energy and demand diversity, as well as the potential to reduce battery ageing through different dispatch strategies in an interconnected network of SHSs all motivate further investigation of this strategy

6.2 Case Study Systems

4 different Solar Home System types are presented as case studies in this section. Each system type is designed for a differing uses and are intended to be indicative of the existing and future SHS market in East Africa. The methodology can be easily adapted to simulate systems with differing specifications.

The systems are defined by load profiles and PV and battery sizes resulting in differing capital cost. Where possible, real world data sources for system specifications are used, but the methodology and results can be adapted for a range of other system specifications and these case studies are intended to be indicative of overall trends rather than direct studies of implemented systems.

Loads for each system are simulated using the Monte Carlo simulation approach presented in chapter five. For each system type, a mean averaged over 500 Monte Carlo simulation runs is shown, with the error bar showing one standard deviation from the mean simulated result.

The energy demands appear small in comparison to those in domestic situations in developed countries. This is due to the utilisation of efficient DC appliance, specifically designed for their low power consumption.

Each system features a smart meter, dealing with net metering and billing and the self consumption load is the power draw of this meter.

6.2.1 Small Domestic SHS

The Small Domestic SHS is based on the BBOXX bPower50 system [167]. The data sheet for the system can be found in [168]. The product features either a 17Ah Sealed Lead Acid (SLA) battery or a 12Ah Lithium Iron Phosphate battery. This work will focus on the SLA version of the system, due to this being the more established technology.

Table 6.1: Generation and Storage specification for Small Domestic SHS

	Type	**Value**	**Unit**
Generation	Solar PV	50	Wp
Storage	Sealed Lead Acid	17	Ah

The loads in the small domestic SHS are those provided in the bPower50 [167], providing lighting, phone charging and entertainment.

Table 6.2: Loads in standard BBOXX bPower50 SHS

	Number	**Power Consumption**	**Unit**
LED Bulb	4	1	W
USB Port for Phone Charging	2	3	W
TV	1	11.2	W
Self Consumption	1	1	W

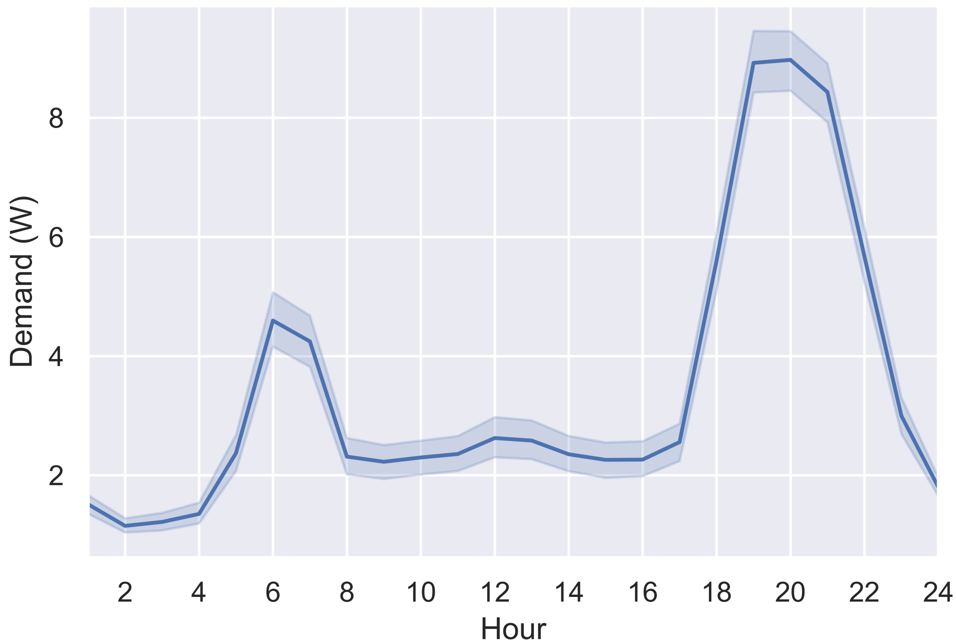

Figure 6.1: Simulated load profile for the Small Domestic SHS

Figure 6.1 shows a simulated demand profile for the system. The profile of loads for the small domestic SHS features a higher incidence of lighting being used in the morning and evening, the TV being used in the evening, with phone charging demand spread evenly across the day. The mean daily energy demand is 82.662 Wh with a standard deviation of 19.306 Wh.

6.2.2 Small Commercial SHS

The small commercial SHS has the same generation and storage specifications as the small domestic system, shown in table 6.3, but used to run a barbers shop rather than power domestic loads. This is a common productive use application of SHSs [169] [170]. The system features the same appliances as the small domestic SHS as well as hair clippers.

Table 6.3: Loads in a small commercial SHS

	Number	Power Consumption	Unit
LED Bulb	4	1	W
USB Phone Charging	2	2	W
TV	1	11.2	W
Hair Clippers	1	10	W
Self Consumption	1	1	W

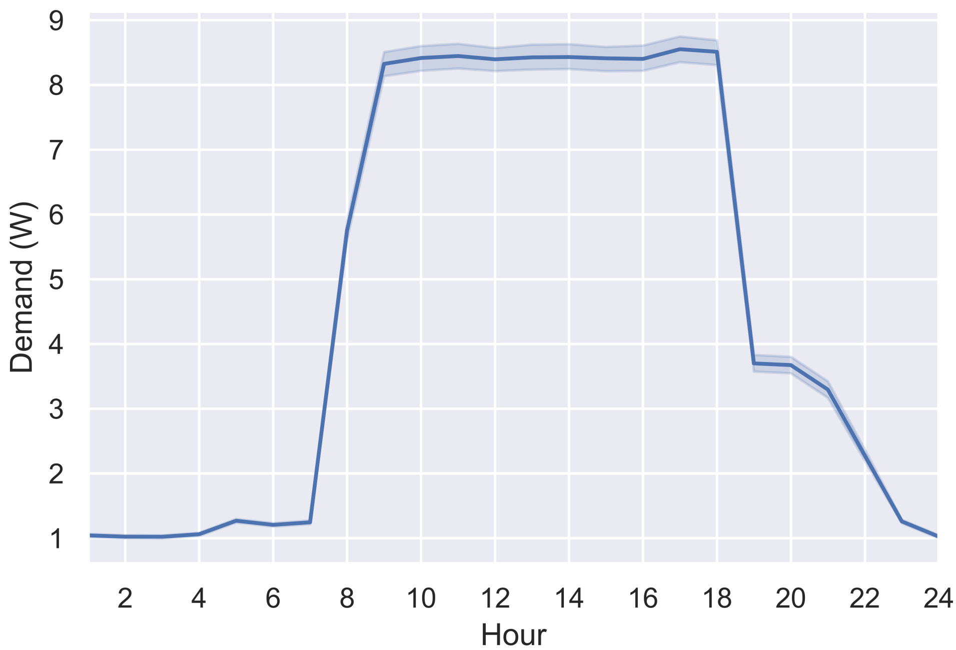

Figure 6.2: Simulated load profile for a small commercial SHS

The bulk of the system demand is in the daytime when the business is in operation.

The hair clippers have a high power but low duty cycle when in use. The knee in the load profile from 1900h to 2300h is caused by the occasional use of the system for entertainment purposes in the evening. The mean daily energy demand is 111.72 Wh with a standard deviation of 23.04 Wh.

6.2.3 Large Domestic SHS

The specification for the large domestic SHS is based on the bPower300, designed for powering larger households and small businesses.The system has a larger solar PV array and larger battery than the small domestic SHS. The predominant use case for this systems is currently as backup in locations with an unreliable grid connection but they represent an aspirational technology in off grid locations and a potential way to provide higher tier electricity access than the small SHS.

Table 6.4: Generation and Storage specification for the Large SHS

	Type	**Value**	**Unit**
Generation	Solar PV	300	Wp
Storage	Sealed Lead Acid	60	Ah

In addition to phone charging and lighting services found in the smaller system, the large domestic SHS also has a fridge for food preservation and a larger a 40" TV.

Table 6.5: Loads in a large doemstic SHS

	Number	**Power Consumption**	**Unit**
LED Bulb	6	1	W
USB Phone Charging	3	2	W
TV	1	35	W
Refrigerator	1	9.4	W
Self Consumption	1	1	W

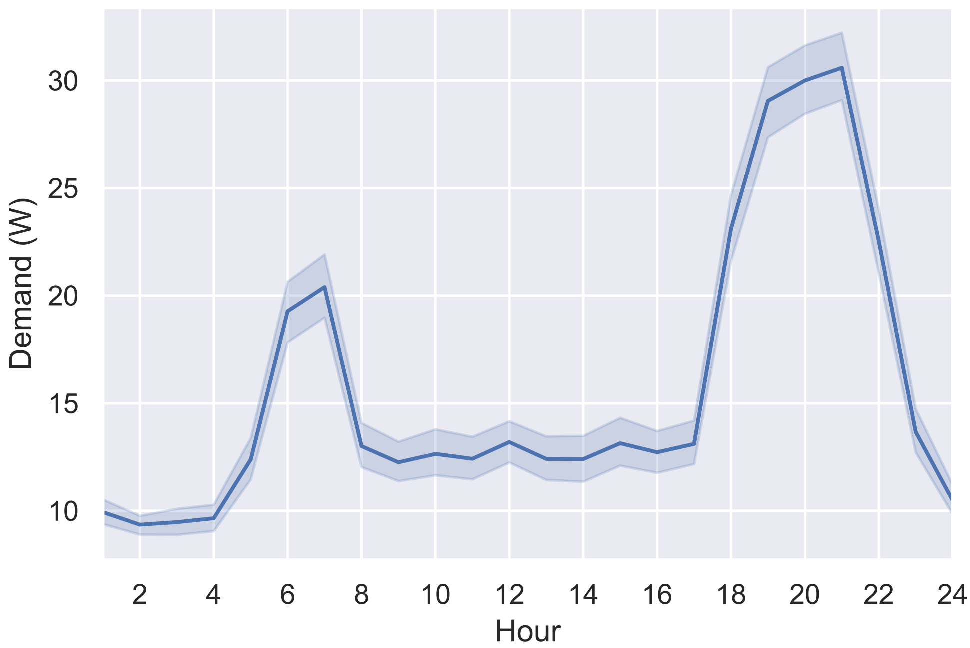

Figure 6.3: Simulated load profile for the Large Domestic SHS

The load profile displays similar morning and evening peaks found in the small domestic SHS, but with greater magnitude. This is shown in Figure 6.3. The mean daily energy demand is 377.147 Wh with a standard deviation of 60.472 Wh. The distribution is shown in figure 6.3.

6.2.4 Large Commercial SHS

The large commercial SHS is used to run a shop, utilising a fridge to sell cold drinks. The system has the same battery capacity and PV array as the large domestic SHS, shown in table 6.6.

Table 6.6: Loads in a large SHS

	Number	Power Consumption	Unit
LED Bulb	6	1	W
USB Phone Charging	3	2	W
TV	1	35	W
Refrigerator	1	18.4	W
Self Consumption	1	1	W

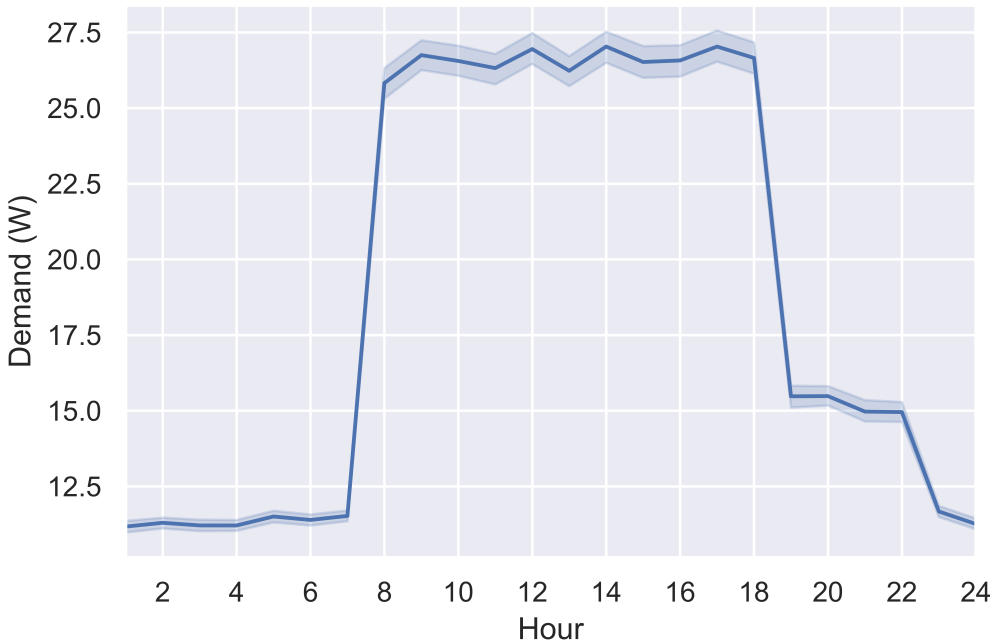

Figure 6.4: Simulated load profile for a large commercial SHS

The large commercial SHS has the same loads as the large domestic SHS, shown in table 6.4, but with different usage profiles shifted towards the centre of the day similar to the small commercial SHS. When utilised in a shop rather than a domestic setting, the refrigerator will experience increased demand, due to being opened more often.

6.2.5 Household Without SHS

Some of the presented studies will connect households without SHSs as energy importers. In these case studies, basic energy access is provided consisting of two lights and phone charging, smaller than the Small Domestic SHS, minis the TV.

Table 6.7: Loads in a tier 1 energy importing household

	Number	**Power Consumption**	**Unit**
LED Bulb	2	1	W
USB Port for Phone Charging	2	1	W
Self Consumption	0.5	1	W

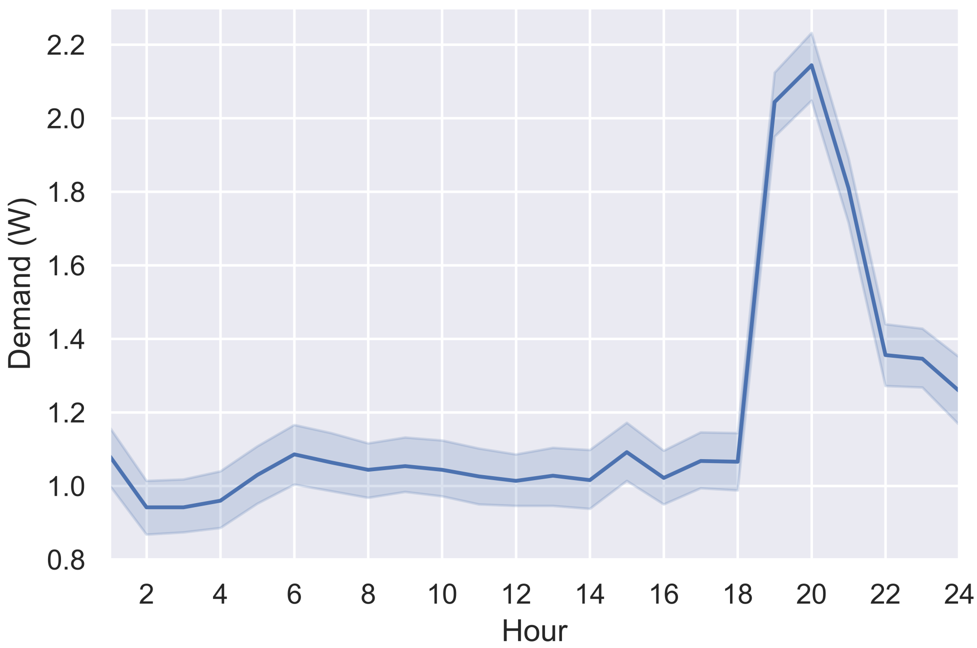

Figure 6.5: Simulated load profile for a tier 1 energy importer

The load profile displays similar morning and evening peaks found in the smaller bPower50, but with greater magnitude. This is shown in figure 6.5. The mean daily energy demand of the system as simulated is 28.050 Wh with a standard deviation of 4.721 Wh. The self consumption of the energy importing system, averaging 12 Wh a day represents a significant proportion of the demand.

6.2.6 Energy Demand Comparison

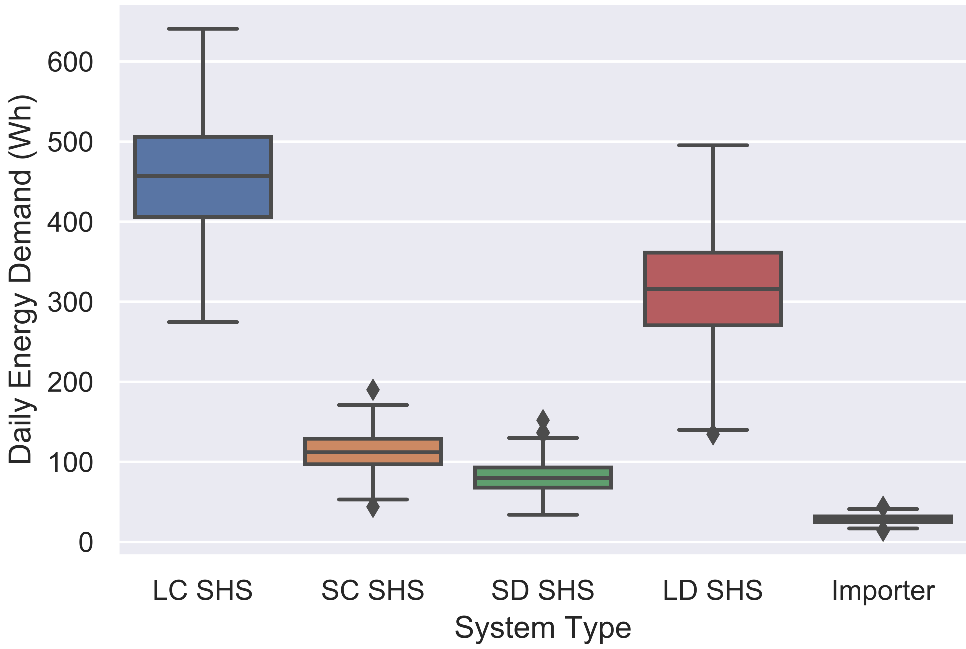

Figure 6.6: Comparison of energy demand of the 5 system types

Figure 6.6 compares the daily energy demand of the 5 system types and shows the distribution of these demands. It can be seen that the commercial systems have a large energy demand per day on average than the domestic systems. This is due to their demand being focused during the daytime, when direct consumption from the PV panels is possible without the losses incurred utilising the battery. This facilitates increased energy usage while maintaining system performance.

6.3 Reliability and LCOE Under Demand Growth

In this section, the LCOE and reliability of SHSs is investigated over time, both in conditions of no demand growth and in cases with demand growth present.

6.3.1 Battery Degradation

First, to demonstrate the effect of loading on battery degradation, a simulation was run for a small domestic system with no demand growth and without battery replacement to establish the effective lifetime of the system without maintenance intervention for a single system.

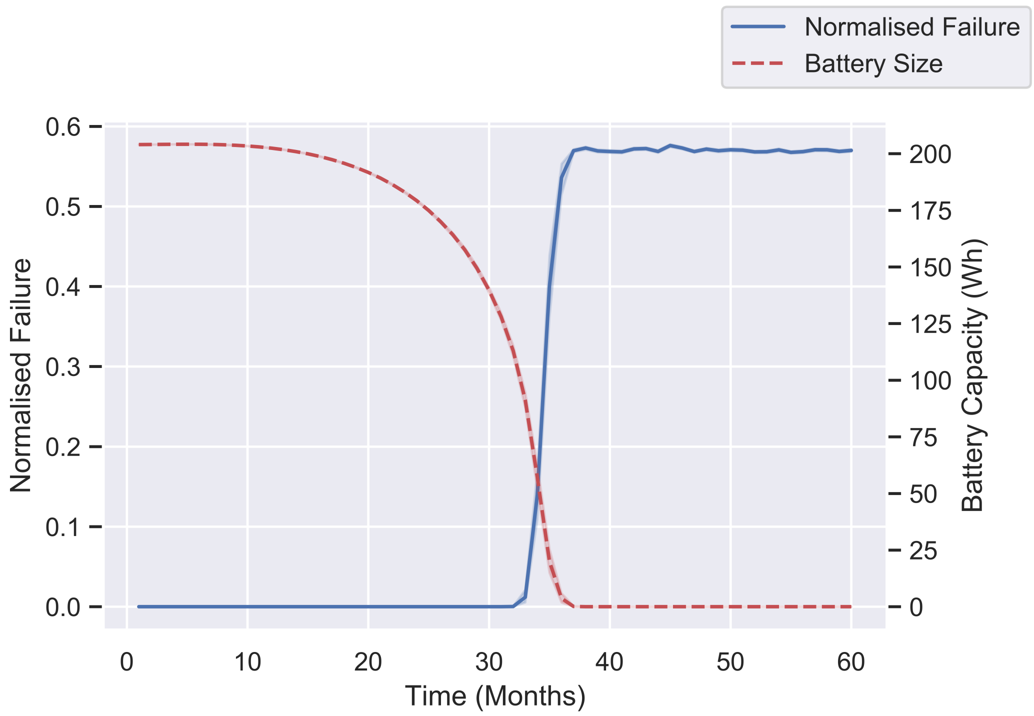

Figure 6.7: Normalised failure and battery capacity rate for a small domestic SHS over time without battery replacement

Under this use case, battery degradation is observed quickly and after 36 months as the battery condition reaches 60% of its original capacity. The battery capacity diminishes exponentially due to to two mechanisms. The battery capacity is a function of DOD and the number of cycles experienced. Over time, both of these increase. The capacity reduces with number of cycles and this reduced capacity in turn results in a lower DOD in future cycles as the same average energy is being extracted from a battery with less capacity. The only demand being met once the battery has reached its end of life is the daytime demand directly fed by the solar PV array.

Under the battery sizing presented, failures begin to occur when the battery capacity has reached 60% of its original rated capacity. This occurs after roughly three years, a common time frame for contracts under a rent to own business model.

6.3.2 Conditional Battery Replacement

In practice, batteries in a SHS would be replaced after reaching their end of life. For all remaining simulations in section 6.3, the battery is replaced after reaching a defined end of life when it has reached 60% of its original rated capacity, commonly considered to be the end of life for batteries [26]. As shown section 6.3.1, the capacity of the battery fades at a significant accelerated rate once the capacity has reached this level.

The time between battery replacements is recorded for each simulation. When LCOE is later calculated, the battery replacement rate will be a key contributing factor, due to the capital cost of the batteries and costs associated with their replacement.

6.3.3 LCOE for Small SHSs

A larger battery under the same utilisation will experience a lower DOD and its capacity will therefore fade at a reduced rate. This will reduce replacement rate, but will increase the capital cost associated with each replacement event. In addition, if the battery size selected is too small, then it will be unable to meet demand under some conditions of high demand, resulting in unreliable service. For each system type under investigation, the LCOE over 10 years was calculated for a range of differing battery sizes, accounting for the differing costs of battery replacement and replacement rates.

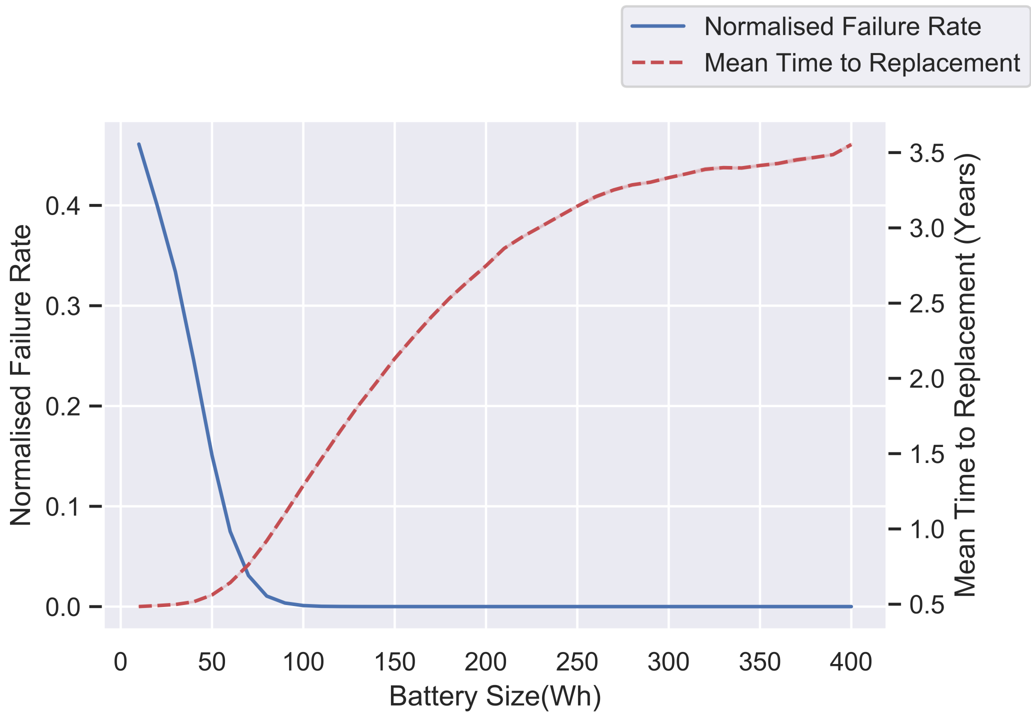

Figure 6.8: Battery replacement and failure rates for a small domestic SHS with varying battery sizes

Figure 6.8 shows how this varying battery size affects the replacement rates and reliability of energy delivered by a small domestic SHS over a 10 year time horizon. For a battery size less than 100 Wh, the system experiences failure under high demand conditions, even with battery replacement. This is due to the battery being small enough that it can not meet overnight demand on some days even with minimal capacity degradation. With larger batteries, the system reliability reaches 100% and the rate of replacement decreases with battery size.

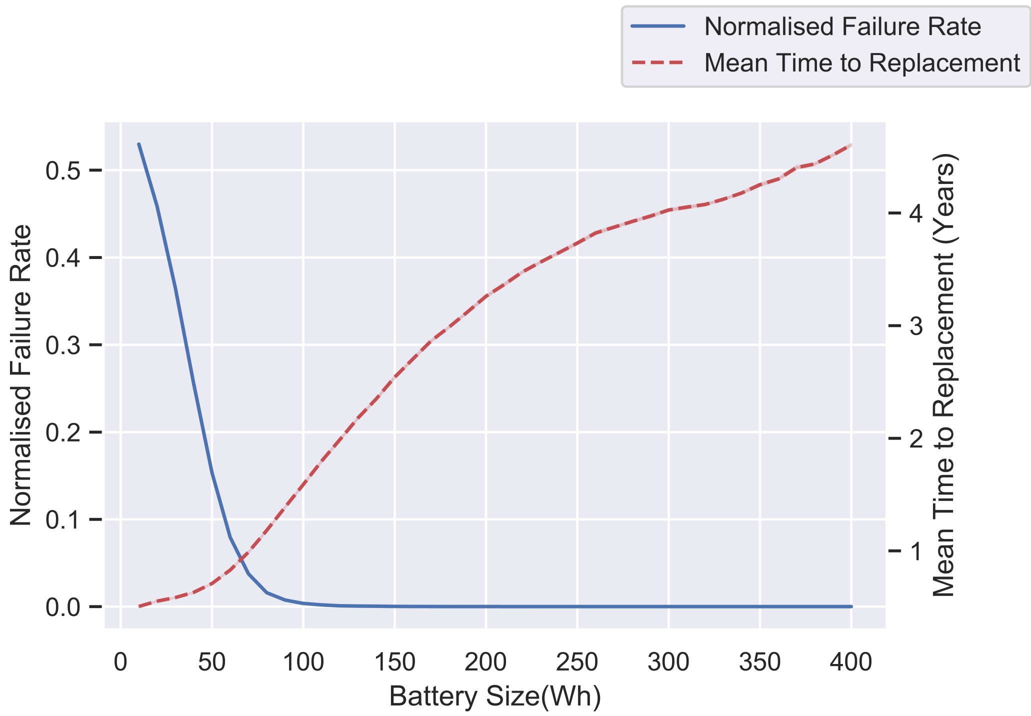

Figure 6.9: Battery replacement and failure rates for a small commercial SHS with varying battery sizes

Despite having greater daily demand, the small commercial SHS exhibits lower rates of battery replacement for a given size of battery compared to the small domestic system, as shown in figure 6.9. This is due to lower battery utilisation. A greater proportion of the generation is concentrated in the daytime and met directly by the solar PV array.

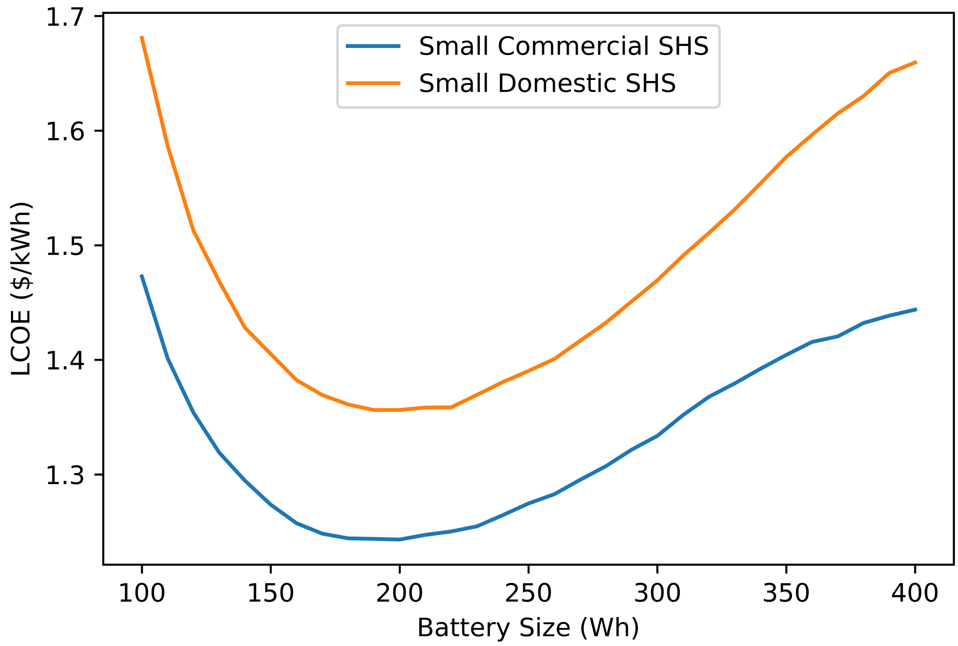

Figure 6.10: LCOE for both small SHS cases with varying battery size

Figure 6.10 shows the variation in LCOE for a range of battery sizes for both use cases. Both systems have the same initial capital cost, but differences in replacement rates for batteries due to their different utilisation. This result in different costs of energy when accounting for the costs of battery replacement. The lower battery utilisation of the commercial SHS is reflected in its lower average LCOE.

For both system types, the optimal sizing of battery occurs at around 200 Wh. The sizing of the battery in the case study small systems is 204 Wh, demonstrating that for a fixed demand and panel size, the battery is optimally sized. Beyond this size, the increased cost of the battery is outweighed by the additional capital cost.

6.3.4 LCOE for Large SHSs

The process undertaken in section 6.3.3 was repeated for the large domestic system type, with battery replacement rates and failure rates plotted against the battery size.

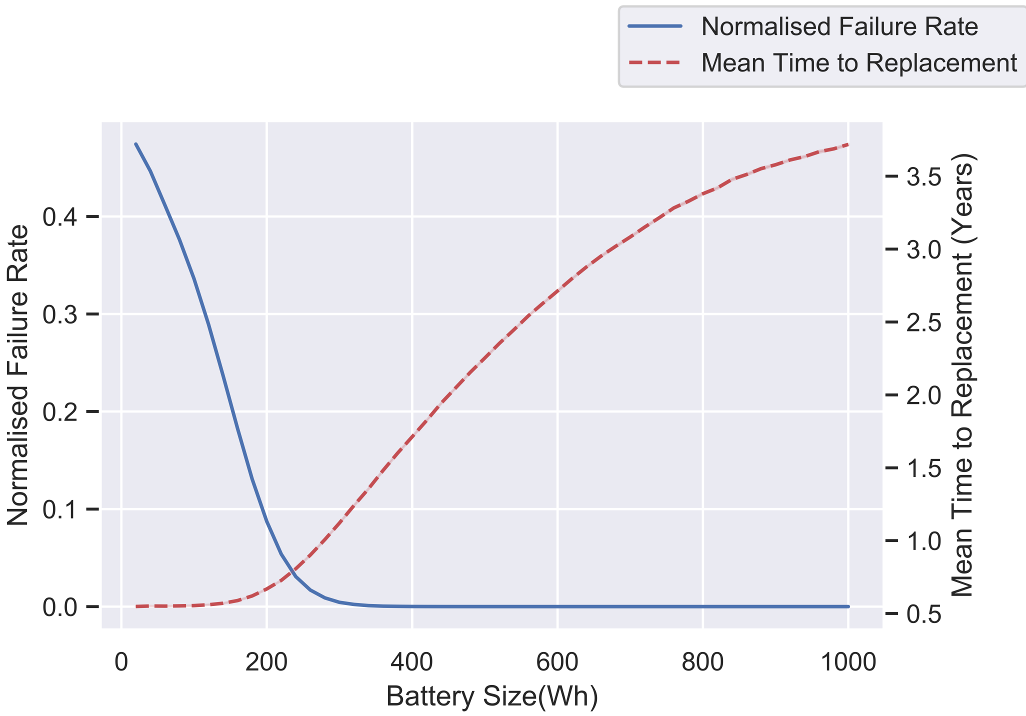

Figure 6.11: Battery replacement and failure rates for a large domestic SHS with varying battery sizes

This process was then applied to the large commercial SHS.

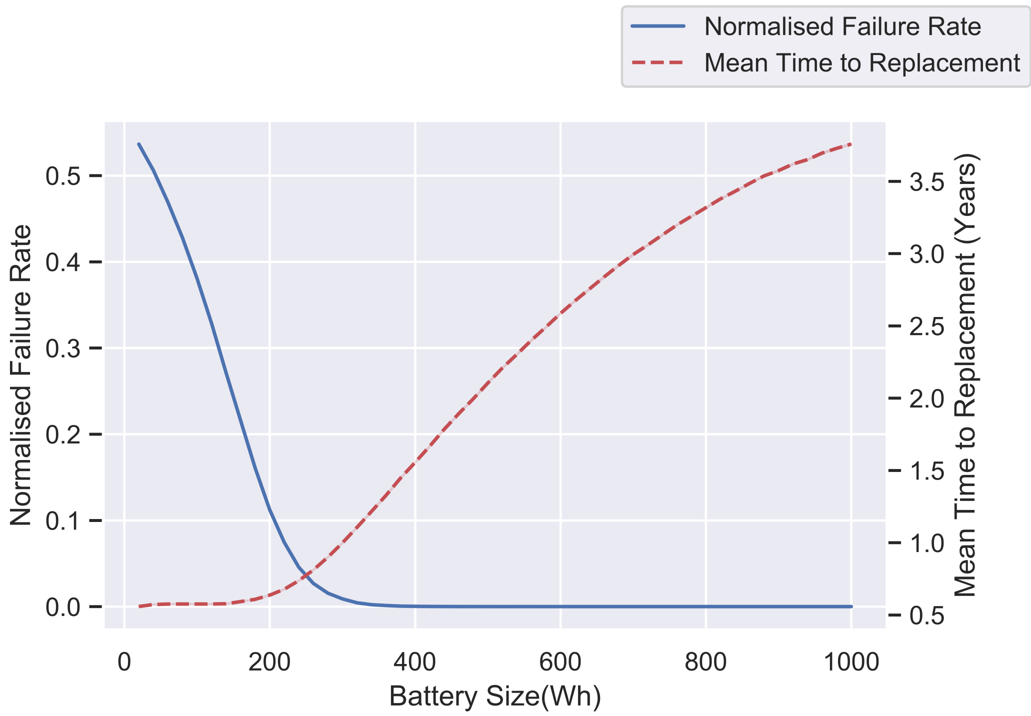

Figure 6.12: Battery replacement and failure rates for a large commercial SHS with varying battery sizes

For both systems, shown in figures 6.11 and 6.12, a failure rate of zero is achieved when batteries are sized at 300 Wh or larger. As with the small systems, the commercial system has a slightly lower battery replacement rates, despite having a larger overall demand, as more of the demand is direct consumption from the solar generation during the daytime and less is consumed from the batteries.

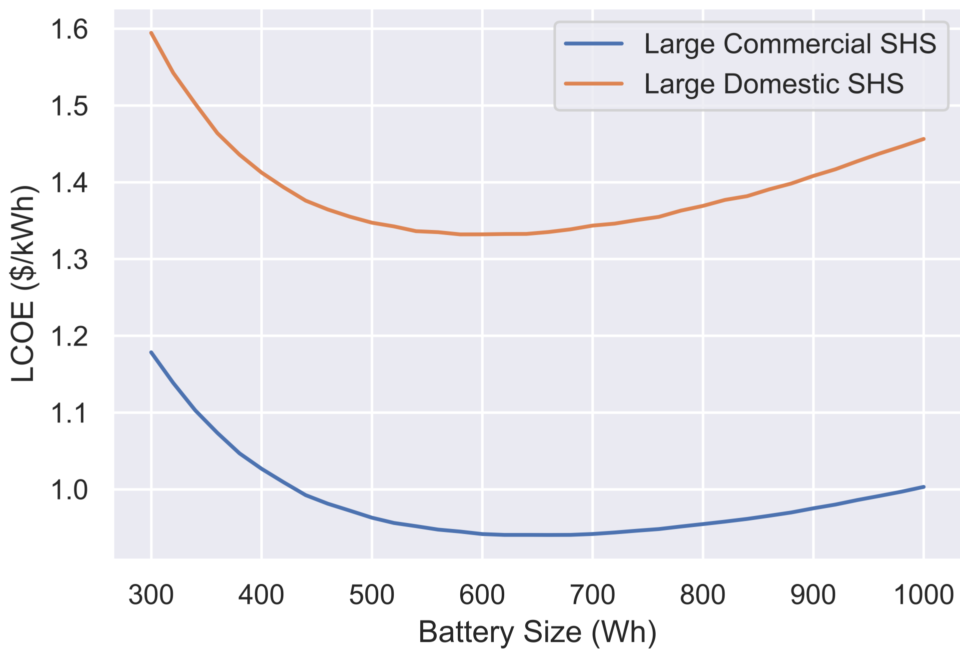

Figure 6.13: LCOE for both large SHS cases with varying battery size

Figure 6.13 shows the repsective LCOE, again over a 10 year time horizon, for the large SHS systems. The optimal sizing of battery occurs at around 700 Wh, again aligning with the case study system sizing.

As with the smaller systems, the lower replacement rate exhibited by the small system type results in a lower LCOE. Overall, the larger systems have a lower LCOE than the small systems, exhibiting a microcosm of the effects of economies of scale and diversity in power systems.

6.3.5 Costs as a Proportion of LCOE

For all system types, battery replacement contributes more than 60% of overall costs. There is therefore a strong motivation for any intervention that can reduce the degradation effects seen by batteries by reducing either their average depth of discharge or number of charge cycles, as this would result in a lower LCOE for a given system.

6.3.6 Demand Growth

If the human development potential of energy interventions is being fully met, we would expect to observe rising energy consumption. A number of the wide area planning methods assume a percentage per year demand growth for each SHS and assume that the solution will be appropriate to provide electricity access to consumers as demand grows.

For each system type, the rate of battery replacement and resulting LCOE was calculated over a 10 year time horizon with differing yearly % demand growth.

Table 6.8: Battery replacement rates for each system type under different demand growth rates

Demand Growth (% per year)	**Small Domestic SHS Battery Replacement Rate (Years/Replacement)**	**Small Commercial SHS Battery Replacement Rate (Years/Replacement)**	**Large Domestic SHS Battery Replacement Rate (Years/Replacement)**	**Large Commercial SHS Battery Replacement Rate (Years/Replacement)**
0	2.73	3.140	3.07	3.02
3	2.35	2.42	2.76	2.64
5	2.09	1.70	2.41	2.30
8	1.56	0.93	1.95	1.71

Table 6.8 shows the replacement rate for different growth rates. Greater demand growth results in higher rates of battery replacement as average depth of discharge increases.

Table 6.9: LCOE over 10 years for each system type under different demand growth rates

Demand Growth (% per year)	**Small Domestic SHS LCOE ($/kWh)**	**Small Commercial SHS LCOE ($/kWh)**	**Large Domestic SHS LCOE ($/kWh)**	**Large Commercial SHS LCOE ($/kWh)**
0	1.89	1.24	1.36	0.95
3	1.38	0.97	1.24	0.88
5	1.39	1.20	1.21	0.86
8	1.57	1.81	1.17	0.87

This increased replacement rates has an impact on the LCOE observed by the systems. For small increases in demand, the LCOE actually drops for all system types. The greater rates of energy consumption outweigh the additional costs of battery replacement. As demand growth increase, the cost of battery replacement begin to outweigh the additional energy being sold, resulting in a trend towards increase in LCOE for all cases.

The LCOE calculations above do not account for the value of lost load. In order for the system to be fit for purpose, a minimum threshold of reliability must be met by a system. Table 6.9 shows the reliability of each system type in year 10 with differing demand growth rates. It can be observed that for a demand growth of 5% or greater, more than 10% of demand is unmet, with failure rate rapidly growing with demand growth.

This clearly demonstrates the unsuitability of SHSs for the long term provision of electricity access. There is a need to either increase the generation capacity of the systems, replace them with a minigrid, macrogrid connection or instigate other options such as interconnection.

6.4 Excess Energy

As discussed in chapter 2, SHS tend to generate more energy than they use. After any loads have been met and the batteries have been charged, excess energy remaining is dumped. This energy could potentially be shared and utilised in a number of ways in an interconnected system. To facilitate further investigation, this section will first aim to quantify the excess energy generated aggregated over 10 identical system types. First the results for the small SHS are presented:

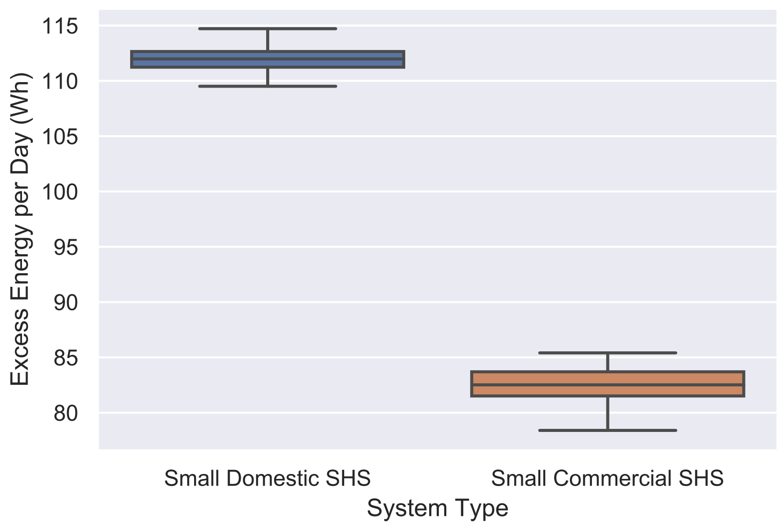

Figure 6.14: Daily excess energy for small SHSs

The hour by hour profile of this excess energy can also be shown for each system type, with error bars showing the range of daily result from the stochastic simulations.

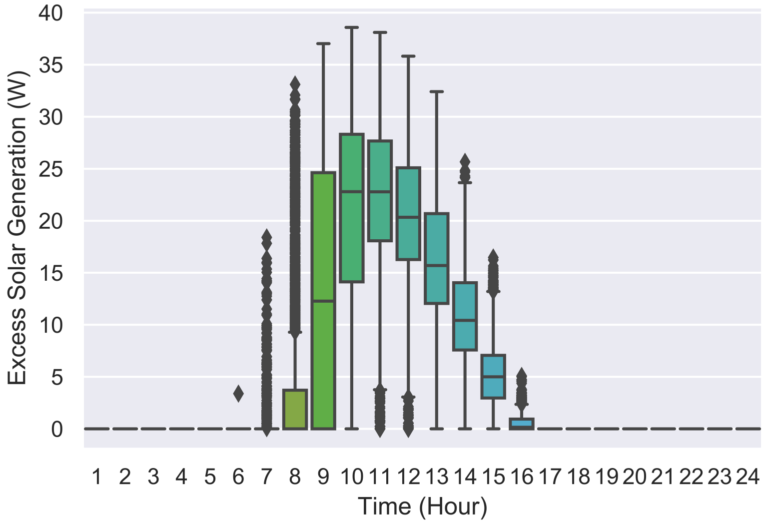

Figure 6.15: Daily excess energy profile for a small domestic SHS

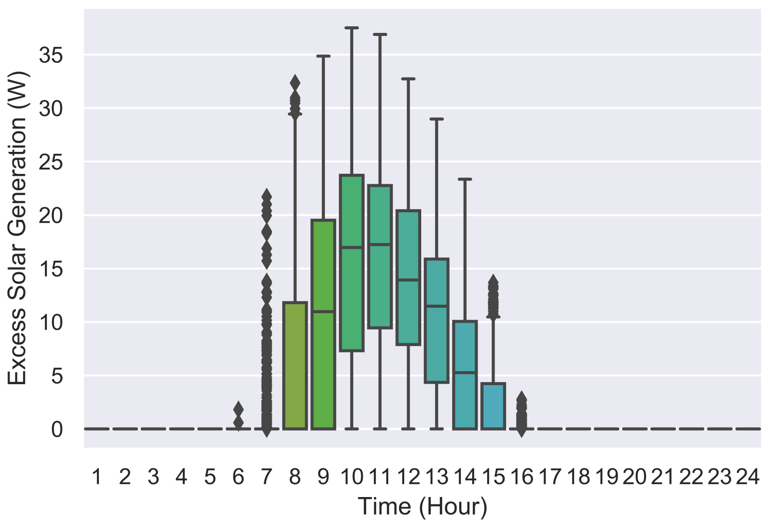

Figure 6.16: Daily excess energy profile for a small commercial SHS

Figures 6.15 to 6.16 show the averaged daily profiles of this excess energy. For both system types, average excess energy matches up with the solar generation profile, but slightly skewed towards times later in the day. Excess is lower in the morning than the evening, as generally batteries will have been discharged over night.

The same process can be undertaken for clusters of 10 large systems of both the commercial and domestic type.

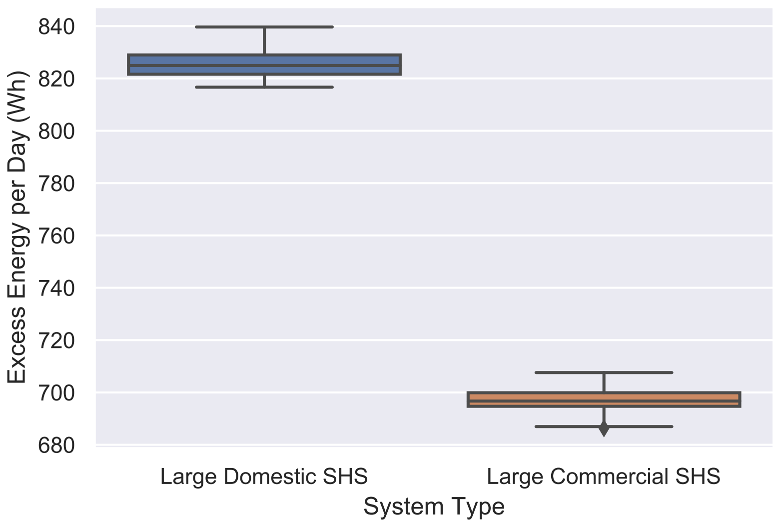

Figure 6.17: Daily excess energy for large SHSs

Similarly the hourly profile of this energy can be plotted and has the same skew towards the evening as the smaller systems, with a larger overall magnitude reflective of the large generation assets.

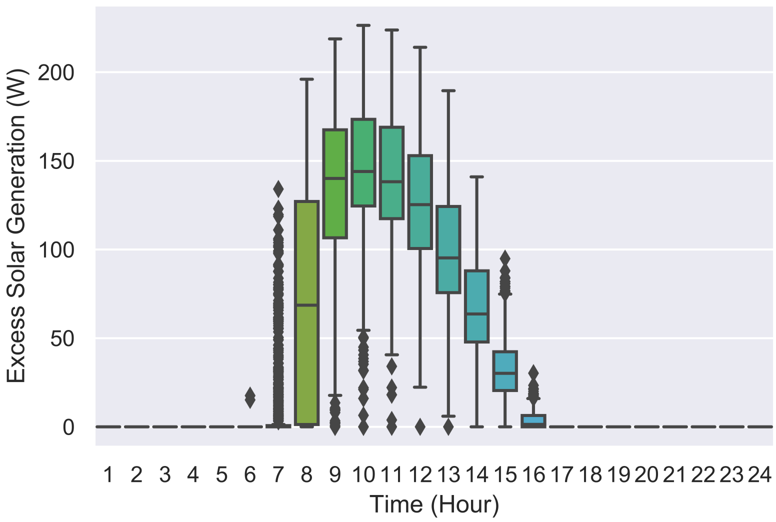

Figure 6.18: Daily excess energy profile for a large domestic SHS

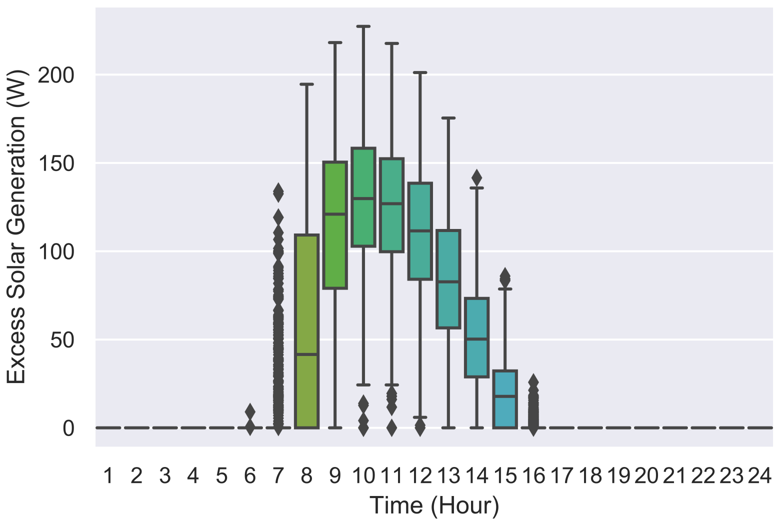

Figure 6.19: Daily excess energy profile for a large commercial SHS

Considering the LCOE for these systems is in the order of \$1/kWh, this excess represents significant potential value and possible uses for this energy will be investigated in chapter 7.

6.4.1 Excess for Varying System Sizes

The excess energy for a given demand varies with the size of the panel, which could be specified to be larger or smaller than the case study systems under investigation.

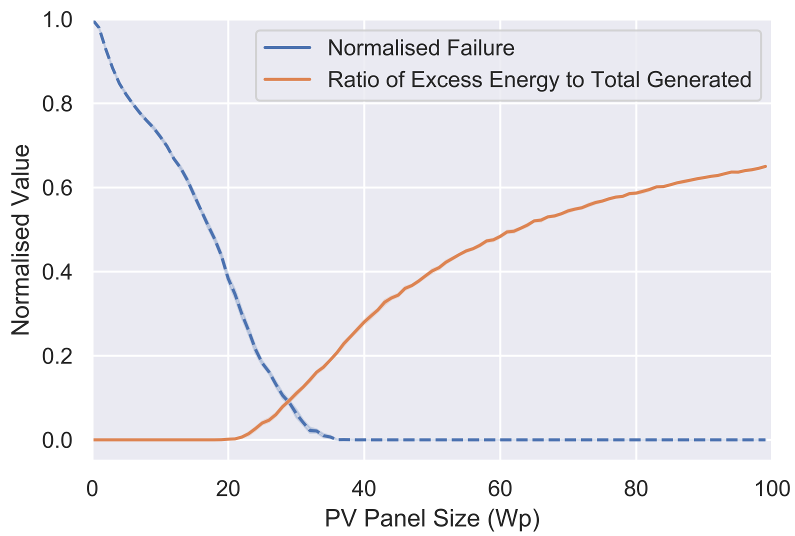

Figure 6.20: Excess energy and loss of load probability for a small domestic SHS with varying panel size

Figure 6.20 shows how the excess energy varies as a proportion of total generation for a system with a varying PV panel size. For systems with a PV panel smaller then 38 Wp, the system experiences some loss of load, but even under this condition, 20 % of generated energy is wasted. For the system as specified in the case study, with a 50 Wp panel, around 40% of the total generated energy is wasted.

6.5 Demand Diversity

The presence of demand diversity is one of the prerequisites for interconnection, but the conventional wisdom is that significant diversity requires heterogeneous demands.

In order to investigate this, the After Diversity Peak Demand was calculated for a day for a range of aggregated demands. This can be used to inform the cluster sizes of interconnected systems that could offer the most cost effective solution.

6.5.1 Homogeneous System Types

For each system type, including the demand only energy importing household, the Normalised ADPD was calculated for between 1 and 50 households aggregated demand.

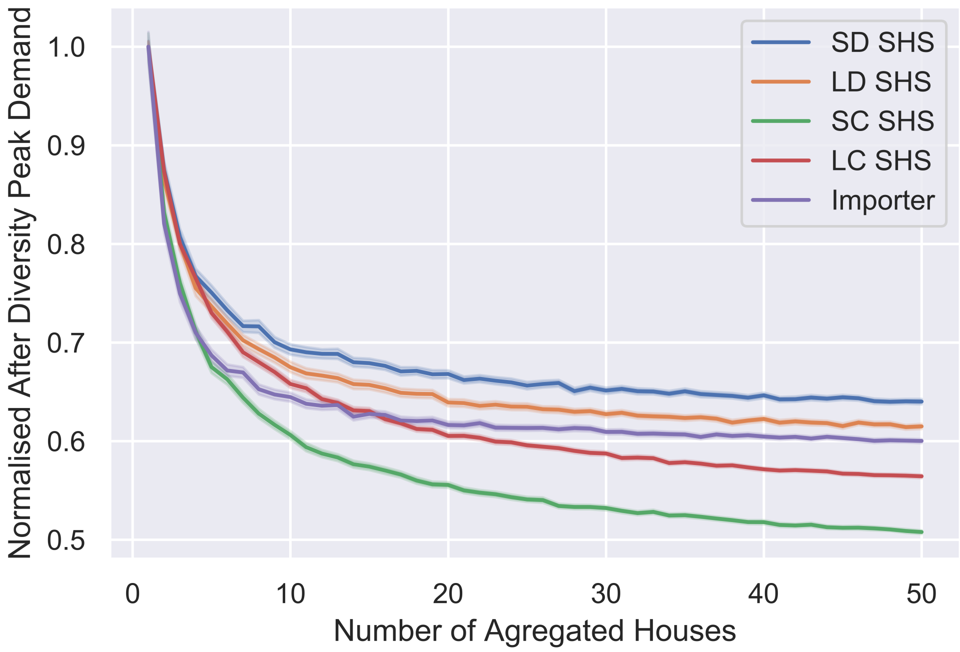

Figure 6.21: After diversity normalised peak demand for a range of system types

Figure 6.21 shows the result of these simulations. For all system types, ADPD reduces as the number of aggregated houses increases, with diminishing net benefit for each additional house. The greatest reduction observed for the small commercial system, but all systems see a reduction in ADPD of greater than a third for clusters of more than 20 households. This diversity of demand is observed even in homogeneous system types due to the stochastic behaviour of each household user. This contrasts a common belief that identical SHSs are too similar in their usage for there to be any significant diversity of demand present.

6.6 Summary

The investigation in this chapter allows us to establish a robust motivation for investigating the interconnection of SHSs.

- Significant excess energy in the order of 100 Wh a day for the smaller systems and 1000 Wh a day for large systems
- Battery replacement is the dominant cost over the lifetime of a SHS
- SHSs are unfit for purpose without retrofitting within 10 years under reasonable demand growth assumptions used in commonly adopted wider area planning tools
- Significant diversity of demand exists between SHSs, even for relatively small cluster sizes of less than 20 household. This is exacerbated by diversity of use, when both commercial and domestic SHSs are aggregated.

From a techno-economic perspective, there are two key value streams that can be utilised by interconnecting systems in comparison to continuing to operate each system in isolation. The sum of this value needs to be greater than the capital and operational cost of the infrastructure to enable interconnection in a given situation in order for it to make economic sense to pursue. The two value streams are:

- Utilising the excess energy generated by SHSs, either in other households or to power new loads.
- Reducing the average utilisation and DOD of the batteries in each SHS in order to extend their lifetime.

The next chapter will model the interconnection of SHSs to quantify the value of interconnection in comparison to other upgrade paths for SHSs.

Chapter 7

Interconnection of SHSs

7.1 Introduction

In chapter 6 it was shown that SHSs generate excess energy that can not be utilised due to limitations in system sizing and battery size. It was proposed to create a minigrid of electrically interconnected SHSs. This would allow this excess energy to be utilised to facilitate the connection of new demand and balance battery depth of charge across the system to optimise battery lifetime. To further investigate this approach, analytical evidence of the operation of such a system are required.

This chapter will investigate the benefits of interconnecting SHSs, using the methodology outlined in chapter 6 to quantify the changes to battery lifetime and system lifetime cost for a range of modes of operation. First, three dispatch methodologies for allocating excess energy will be outlined, representing different ways that energy users may interact with such a system. Then the impact on battery replacement rate and LCOE differing combinations of system types of these dispatch approaches will be analysed, both for fixed demand and for systems with growing demand. Possible additional productive uses of excess energy on these systems, such as water pumping, are then introduced and it is shown that they can utilise excess energy not used by SHS nodes to further reduce the LCOE of the system.

7.2 Dispatch Approaches

There are a range of different approaches that can be taken when dispatching generation and storage. The dispatch methodology will determine the use of the generated and stored energy in each time-step of the simulation and how this energy is allocated between the interconnected systems. Three novel dispatch methods developed during this work are proposed:

- Greedy random allocation of excess energy
- Non-greedy random allocation of excess energy
- Battery depth of discharge minimisation

7.2.1 Greedy Random Allocation of Excess

Each system will aim to meet local demand using local installed generation. Any excess generation will then be used to charge the battery on that system. If this battery is full, the excess will be added to a pool of available energy for other systems to use. This pool of energy does not represent stored energy, but rather the available excess within each time-step across all systems that is available to be flexibly allocated according to dispatch rules.

This process is repeated for each SHS. Then energy is allocated from the shared pool to any system that has a shortage of energy. The energy is allocated to these households with energy shortages at random, attempting to fully meet any shortage before selecting another random household that has not met its demand. Any remaining excess is then allocated to any batteries of systems with remaining battery capacity, again at random.

7.2.2 Non-Greedy Random Allocation of Excess

As with the dispatch outlined in 7.2.1, each system first attempts to meet its own demand. Then any excess energy is then used to meet the demand of other households that can not meet their demand from their own installed generation. The choice of which house gets the excess energy first will be made at random.

Once all demand has been attempted to be met by generated energy, any surplus will be used to the charge batteries on the system. The excess energy will again be allocated at random, this time between all batteries with remaining capacity.

If any households do not meet demand, then stored energy in local batteries is used. This methodology aims to reduce the utilisation of batteries on the system while remaining fair and equitable for all agents.

The key difference between this method and 7.2.1 is that systems will not prioritise their own batteries to receive excess energy above other houses with a generation shortage.

7.2.3 Battery Low State of Charge Prioritisation

This dispatch operates similarly to 7.2.2, but aims to prioritise systems with batteries in the lowest SoC when allocating excess energy, rather than allocating randomly. Each system will first meet its own demand then use pooled energy to meet the demands of other systems. The demands of systems with the lowest battery state of charge will be prioritised both when using any excess energy to meet demand or to charge batteries.

7.3 Interconnection of Homogeneous SHSs

In this section, interconnection of SHSs of the same system type into clusters of varying size is investigated for each of the dispatch approaches outlined above. The result on average battery replacement rate and subsequent impact on LCOE is calculated in each case and compared to the base case of an individual system with no interconnection.

7.3.1 Greedy Random Allocation of Excess

Figure 7.1 to Figure 7.4 show the change in battery replacement for networks consisting of between 1 - 10 identical systems from the four case study archetypes. Each simulation was run for 10 years and repeated for 10 runs.

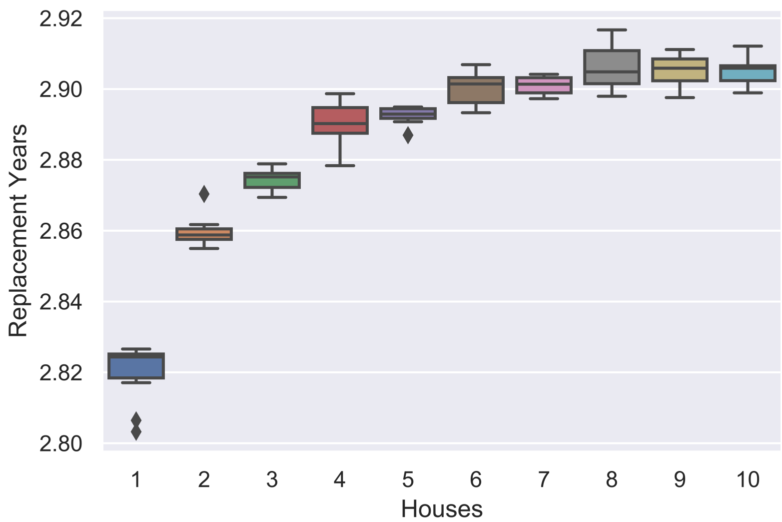

Figure 7.1: Battery replacement rates for interconnection of between 1 - 10 small domestic SHSs with "greedy" dispatch

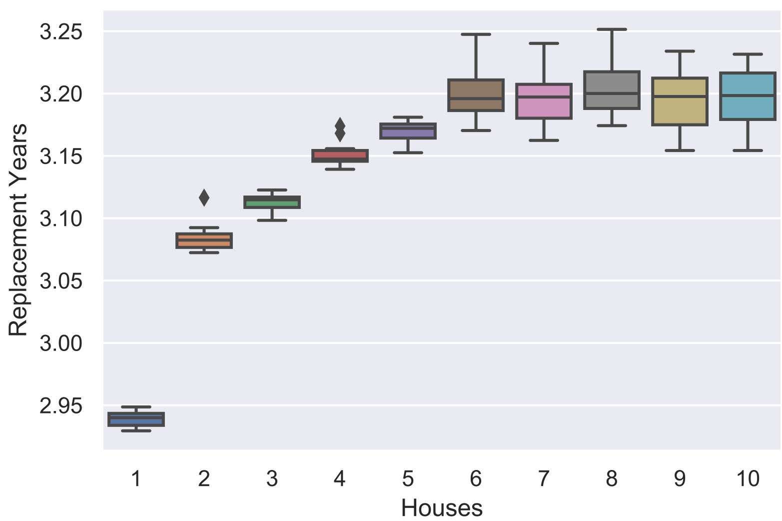

Figure 7.2: Battery replacement rates for interconnection of between 1 - 10 small commercial SHSs with "greedy" dispatch

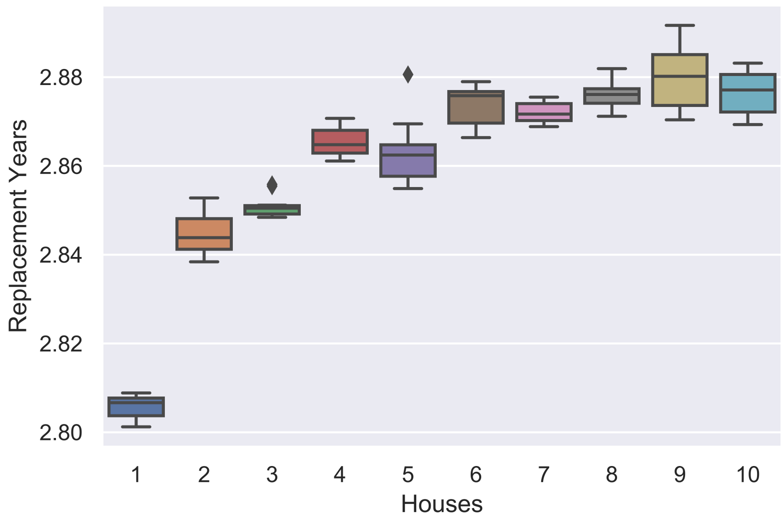

Figure 7.3: Battery replacement rates for interconnection of between 1 - 10 large domestic SHSs with "greedy" dispatch

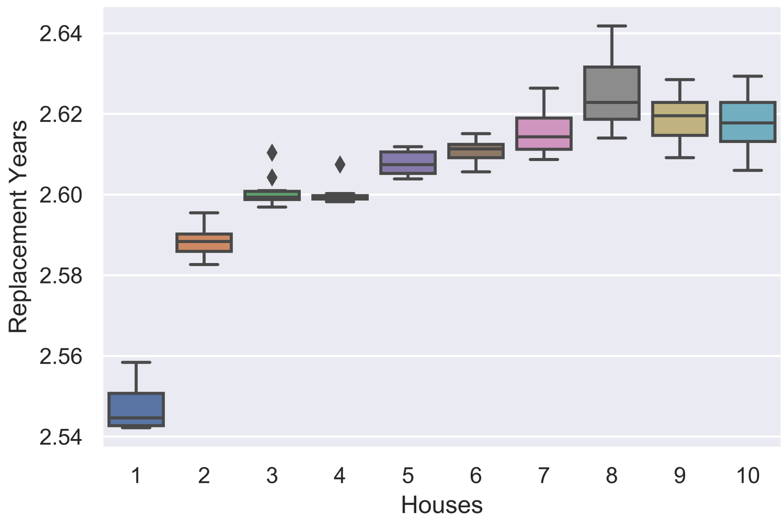

Figure 7.4: Battery replacement rates for interconnection of between 1 - 10 large commercial SHSs with "greedy" dispatch

A small improvement in replacement rates is seen in each case. The largest improvement in replacement rate is observed in the transition from a single standalone system to two systems interconnected, with the improvement diminishing exponentially as additional SHSs are added to the network. Beyond 10 systems, this extension in battery lifetime showed negligible improvement, so has not been included.

Levelised Cost of Energy and System Cost

For each system type, LCOE can be calculated based on the differing battery replacement rates and the average energy delivered, as outlined in chapter 5.

Table 7.1: LCOE and system cost over 10 years for individual small SHSs and cluster of 10 identical large systems with "greedy" dispatch

	SD Single System	**SD 10 Systems**	**SC Single System**	**SC 10 Systems**
System Cost over 10 years ($)	477.07	469.74	465.36	445.53
LCOE ($/kWh)	1.61	1.58	1.13	1.08

Table 7.2: LCOE and system cost over 10 years for individual large SHSs and cluster of 10 identical large systems with "greedy" dispatch

	LD Single System	**LD 10 Systems**	**LC Single System**	**LC 10 Systems**
System Cost over 10 years ($)	1630.72	1611.37	1708.07	1683.18
LCOE ($/kWh)	1.412	1.395	1.026	1.011

Tables 7.1 and 7.2 show the impact on LCOE for each system of interconnection. The costs associated with connecting systems in this manner is uncertain, so the costs presented are the costs without the network. The reduction in total cost over 10 years offers an indication of the target cost of the network in order to make the system financially viable.

In each case a small reduction in LCOE is observed, as the battery utilisation is slightly reduced as excess energy from other systems can be used to meet demand under some conditions. Opportunities to utilise excess energy are relatively low, as each system will prioritize charging its own batteries first.

This reduction is greater for the commercial systems than the domestic systems, as more of their demand is during the day, giving more opportunities to utilise excess solar generation. The majority of the domestic demand takes place at night, for lighting and entertainment, so there is less opportunity to utilise excess solar energy. The introduction of additional flexible and productive loads such as water pumping would make use of this excess energy.

The observed LCOE reduction is likely not enough to justify the expected financial cost of creating, maintaining and managing the network under this dispatch methodology. This is discussed further in chapter 8.

7.3.2 Non-Greedy Random Allocation of Excess

Figures 7.16 to 7.12 show the resulting battery replacement rate for the non-greedy dispatch methodology for each system type.

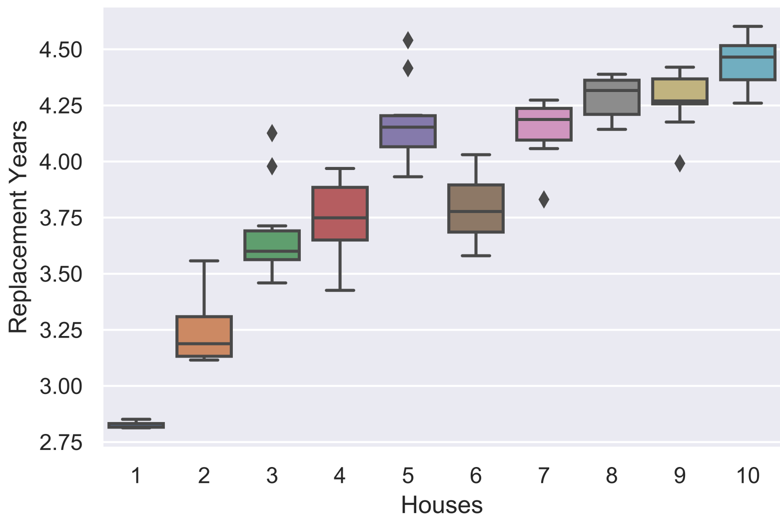

Figure 7.5: Battery replacement rates for interconnection of between 1 - 10 small domestic SHSs with ”non-greedy” dispatch

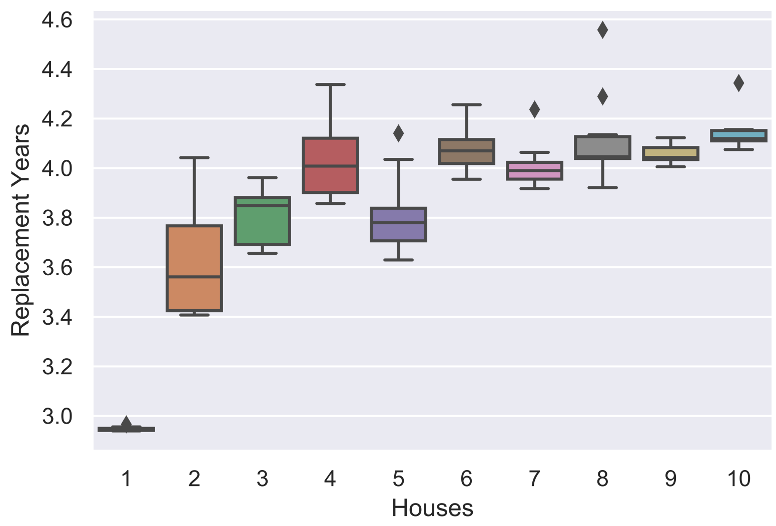

Figure 7.6: Battery replacement rates for interconnection of between 1 - 10 small commercial SHSs with "non-greedy" dispatch

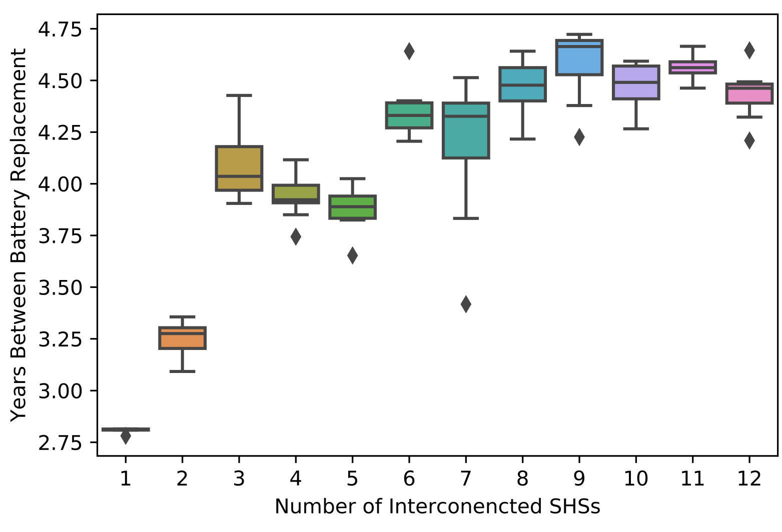

Figure 7.7: Battery replacement rates for interconnection of between 1 - 10 large domestic SHSs with "non-greedy" dispatch

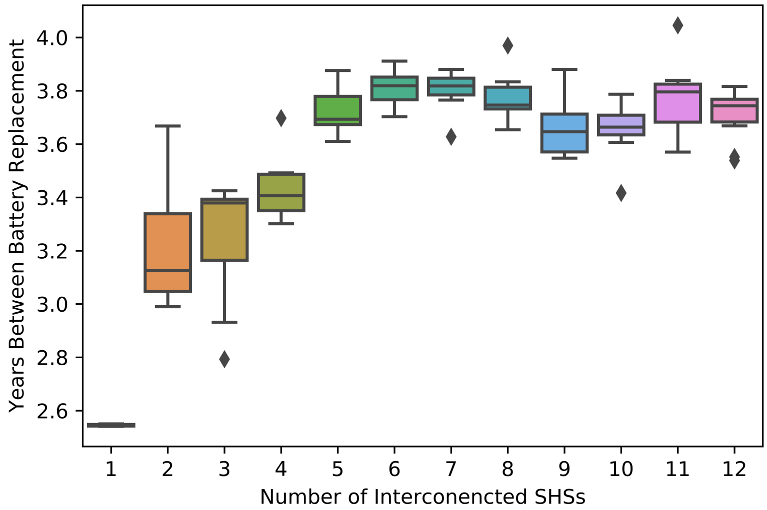

Figure 7.8: Battery replacement rates for interconnection of between 1 - 10 large commercial SHSs with non-greedy dispatch

The results show a clear reduction in battery replacement rates that scales with the number of systems connected for each SHS type. The increase in battery lifetime is significantly greater under this dispatch methodology than the "greedy" dispatch methodology. This improvement is caused by reduced battery charge/discharge cycles, as each demand shortage is attempted to be met through generated energy in each time step before resorting to using the battery. In contrast, the "greedy" dispatch methodology, each system will charge its own battery with excess before sharing, leaving less opportunities to utilise excess energy to reduce the need for a battery discharge, minimising the frequency of battery discharging (number of discharge cycles over time), and so extending battery lifetime.

LCOE

As above, LCOE for each system type was calculated for a cluster of 10 systems and compared to the LCOE and lifetime system cost of single systems.

Table 7.3: LCOE and system cost over 10 years for individual small SHSs and cluster of 10 identical large systems with "non-greedy" dispatch

	SD Single System	**SD 10 Systems**	**SC Single System**	**SC 10 Systems**
System Cost over 10 years ($)	486.18	379.80	465.36	391.87
LCOE ($/kWh)	1.64	1.28	1.13	0.95

Table 7.4: LCOE and system cost over 10 years for individual large SHSs and cluster of 10 identical large systems with "non-greedy" dispatch

	LD Single System	**LD 10 Systems**	**LC Single System**	**LC 10 Systems**
System Cost over 10 years ($)	1630.72	1350.87	1708.07	1443.50
LCOE ($/kWh)	1.412	1.170	1.026	0.867

A significantly greater reduction in LCOE can be observed in all cases compared to the greedy methodology. This is driven by reduced battery replacement costs. For the small domestic system, the lifetime cost per system drops by $106.38. For the large domestic system, this reduction is even greater at $279.85.

In order for interconnection to be a cost effective proposition, additional capex/opex costs over 10 years associated with SHS interconnection would need to be kept below this saving of $279 made on battery replacement over 10 years to justify interconnection.

For both the small and large system types, the domestic systems derive greater benefit from interconnection than the commercial systems. This is due to the domestic systems having less demand during the day, and overall lower demand, resulting in more available energy to charge the batteries on each system.

7.3.3 Low SoC Prioritisation

The same simulations as above were run for the dispatch methodology designed to prioritise charging batteries with low state of charge (SoC).

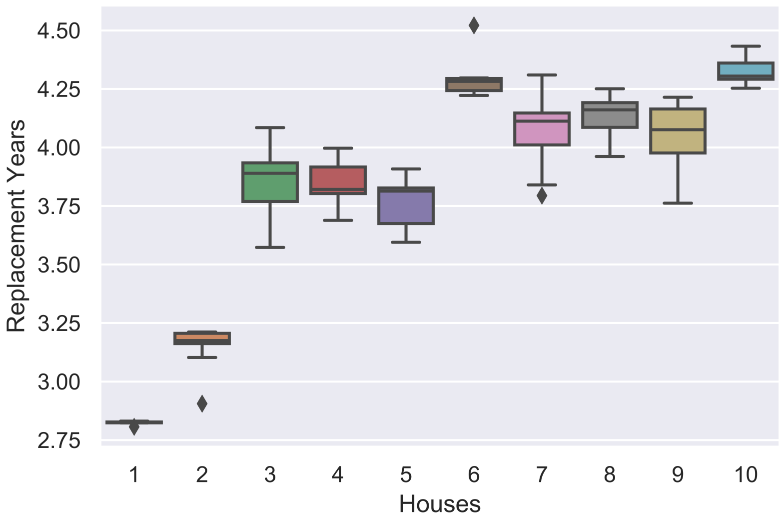

Figure 7.9: Battery replacement rates for interconnection of between 1 - 10 small domestic SHSs with Low SoC prioritising dispatch

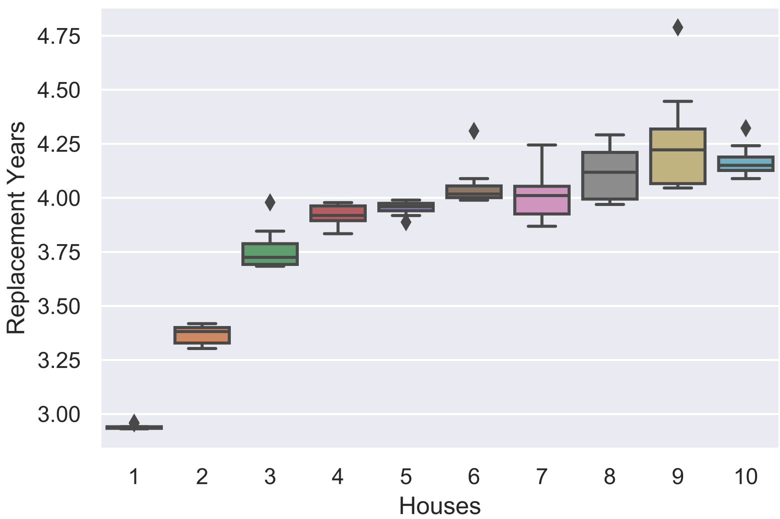

Figure 7.10: Battery replacement rates for interconnection of between 1 - 10 small commercial SHSs with with Low SoC prioritising dispatch

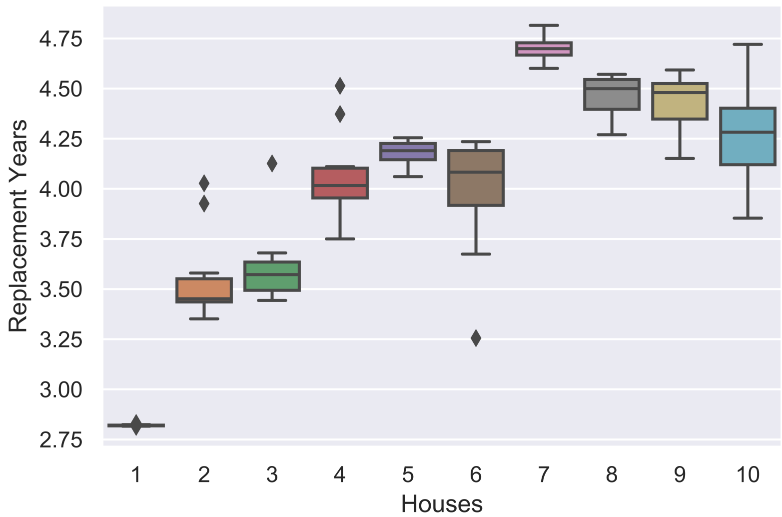

Figure 7.11: Battery replacement rates for interconnection of between 1 - 10 large domestic SHSs with Low SoC prioritising dispatch

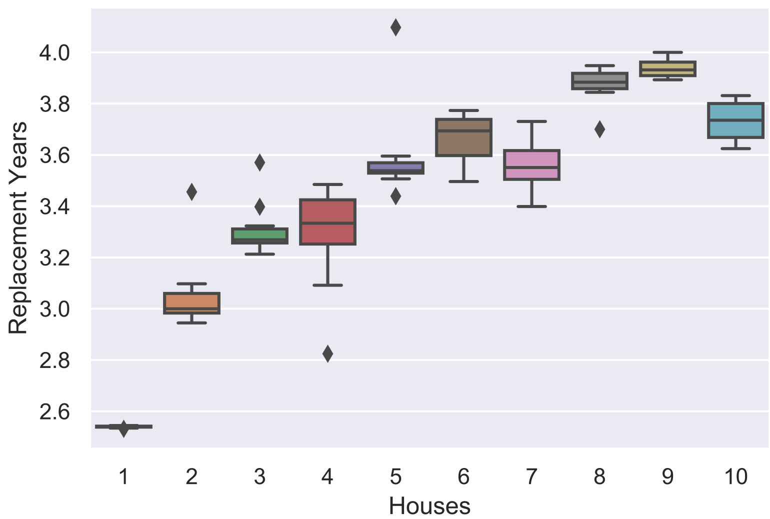

Figure 7.12: Battery replacement rates for interconnection of between 1 - 10 large commercial SHSs with Low SoC prioritising dispatch

LCOE

Table 7.5: LCOE and system cost over 10 years for individual small SHSs and cluster of 10 identical large systems with low SoC prioritising dispatch

	SD Single System	**SD 10 Systems**	**SC Single System**	**SC 10 Systems**
System Cost over 10 years ($)	486.18	386.90	465.36	391.10
LCOE ($/kWh)	1.64	1.30	1.13	0.95

For the third dispatch methodology, prioritising the supply of energy to systems with a low battery SoC, we observe an improvement in battery lifetime when compared to the greedy dispatch approach and results very similar to the "non-greedy" dispatch methodology.

A small improvement is observed over the "non-greedy" method for the commercial SHSs and a small reduction in battery lifetime is observed for the domestic systems.

This is due to the battery replacement rate being a function of both average depth of discharge and number of charge cycles experienced. Although this methodology reduces the average DOD experienced by the batteries, it also causes the batteries to experience a greater number of charge/discharge cycles, causing the replacement rate to be higher than in the case of random allocation of energy.

Table 7.6: LCOE and system cost over 10 years for individual large SHSs and cluster of 10 identical large systems with low SoC prioritising dispatch

	LD Single System	**LD 10 Systems**	**LC Single System**	**LC 10 Systems**
System Cost over 10 years ($)	1630.72	1372.71	1708.07	1387.04
LCOE ($/kWh)	1.412	1.189	1.026	0.833

7.4 Interconnection of Heterogeneous Systems

In chapter 6 it was shown that the aggregated demand of different system types from the system archetypes exhibit greater diversity than homogeneous systems. In this section, we will investigate the impact of heterogeneous networks of systems. Both different number of connected systems and different ratios of commercial and domestic systems will be investigated. For the case studies selected, it is assumed there will generally be a greater number of domestic systems than commercial systems in any network, although investigating the impact of larger concentrations of commercial systems, for example in commercial hubs would be valuable further work.

In this section we will investigate only the non-greedy dispatch methodology, as the results have been shown to give the largest improvement in LOCE for domestic systems.

For each simulation a "Cluster Size" was defined, as the sum of the ratio between domestic and commercial systems. The maximum number of systems was selected as 12 due to its ease of divisibility allowing a like for like comparison of 1:1, 2:1 and 3:1 ratios of systems while maintaining the overall number of systems being interconnected.

7.4.1 Heterogeneous Small System Interconnection

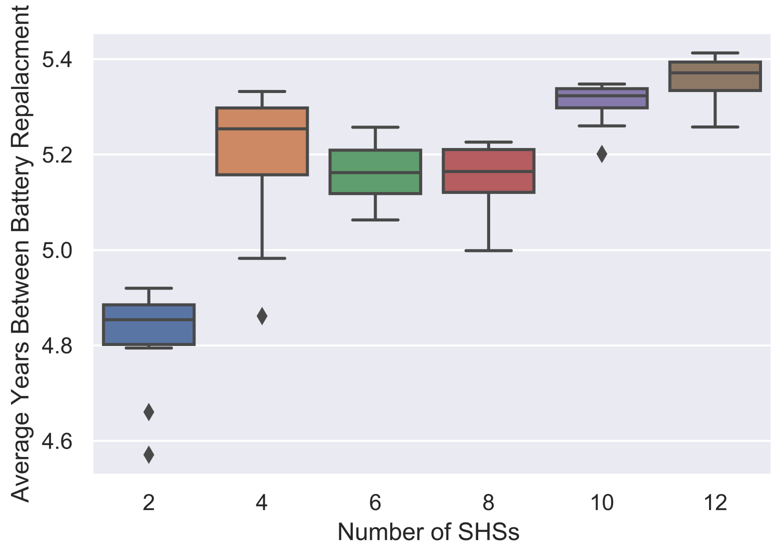

Figure 7.13: Battery replacement rates for networks formed from small domestic and commercial SHSs in a ratio 1:1

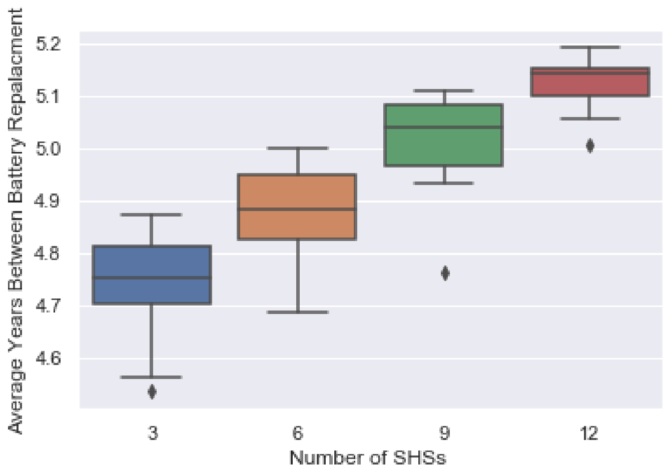

Figure 7.14: Battery replacement rates for networks formed from small domestic and commercial SHSs in a ratio 2:1

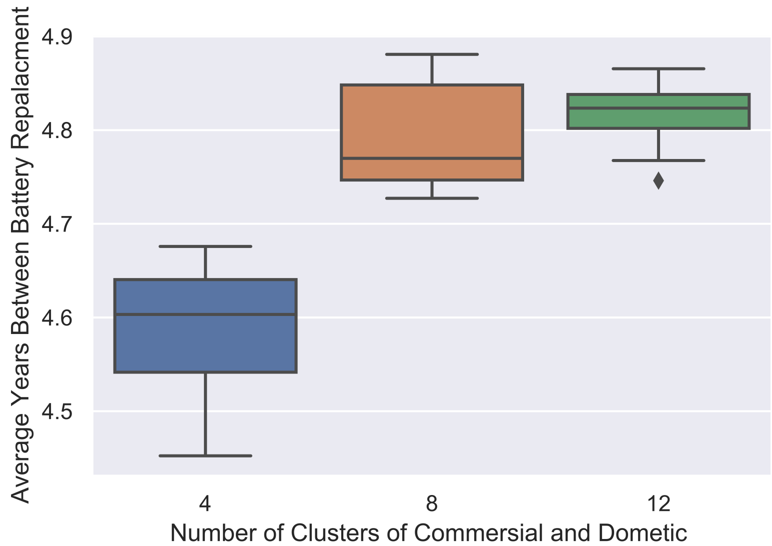

Figure 7.15: Battery replacement rates for networks formed from large domestic and commercial SHSs in a ratio 3:1

For each ratio of systems, the average battery replacement rate is an improvement over homogeneous systems. The greatest improvement is seen in a 1:1 ratio with a mean battery replacement rate of once per 5.37 years across the systems, compared to the expected average taking the homogeneous system simulations of 4.35 . The replacement rate drops as more domestic systems are introduced, but in all cases remains greater than the replacement rate for either homogeneous system type.

This improvement is caused due to the diversity of energy demand. The domestic systems have a greater proportion of excess energy during the day, due to their morning and evening peaks, and this energy can be utilised by the commercial systems.

7.4.2 Large System Interconnection

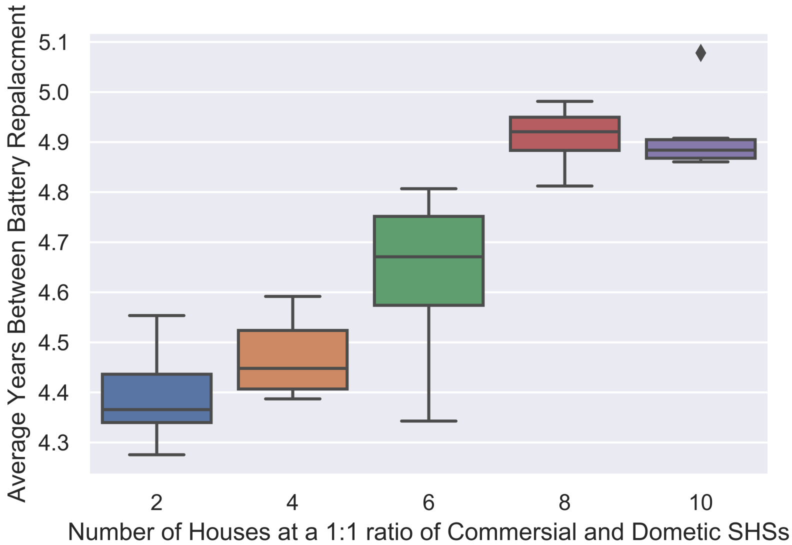

Figure 7.16: Battery replacement rates for networks formed from large domestic and commercial SHSs in a ratio 1:1

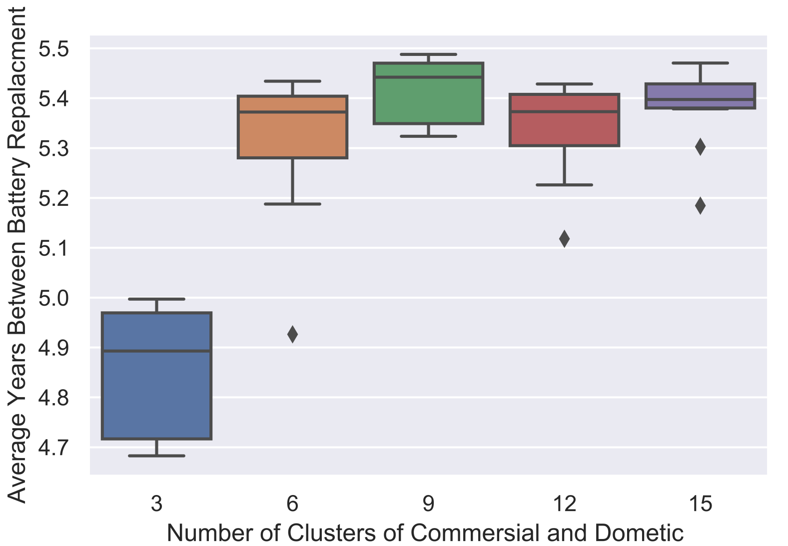

Figure 7.17: Battery replacement rates for networks formed from large domestic and commercial SHSs in a ratio 2:1

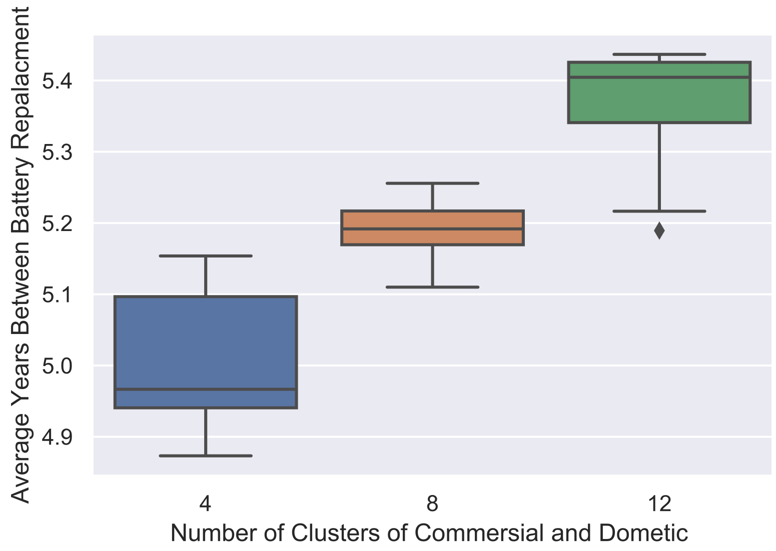

Figure 7.18: Battery replacement rates for networks formed from large domestic and commercial SHSs in a ratio 3:1

For the large system types, improvements in LCOE can also be observed for over homogeneous systems for every cluster size. This improvement remains consistent at an average of 1 replacement per 5.4 years for each cluster size, compared to a replacement rate of 4.43 12 homogeneous large domestic systems and 3.75 for 12 large commercial systems.

7.4.3 LCOE Improvement

Tables 7.7 and 7.8 show the LCOE comparisons for interconnection of 12 SHSs and the average LCOE for those 12 systems without interconnection over 10 years.

Table 7.7: LCOE comparison for 6 small domestic and 6 small commercial SHSs without and with interconnection over 10 years

Average LCOE for 6 SD SHSs and 6 SC SHSs Without Interconnection (\$/kWh)	**Average LCOE for 6 SD SHSs and 6 SC SHSs With Interconnection (\$/kWh)**	**Percentage Reduction in LCOE**
1.57	0.86	44.86%

Table 7.8: LCOE comparison for 6 large domestic and 6 large commercial SHSs without and with interconnection over 10 years

Average LCOE for 6 LD SHSs and 6 LC SHSs Without Interconnection ($/kWh)	**Average LCOE for 6 LD SHSs and 6 LC SHSs With Interconnection ($/kWh)**	**Percentage Reduction in LCOE**
1.219	0.76	37.65%

In both cases a significant reduction in LCOE is observed. This reduction is over 40% for the small systems and 37.65% for the larger systems.

7.5 Demand Growth

As established in chapter 6, the performance of SHSs under demand growth is vital to assessing their long term viability. In order to investigate the impacts of demand growth on interconnected systems, simulations were run for 0%, 2%, 5% and 8% annual demand growth for a range of scenarios. For both large and small systems, a network of 12 domestic, 12 commercial and a combined network of 6 domestic and 6 commercial systems were simulated for each demand growth scenario.

These results can also be compared to the average expected LCOE for 12 systems of the given specification operating without interconnection.

7.5.1 Small SHSs

Table 7.9: LCOE and system cost per SHS for a network of 6 small domestic SHSs and 6 small commercial SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	5.38	0.86	305.84
2	4.6	0.85	329.44
5	3.41	0.86	386.24
8	2.32	0.95	489.41

Table 7.10: LCOE and system cost per SHS for a network of 12 small domestic SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	3.925	1.21	357.43
2	3.615	1.15	373.79
5	2.63	1.21	451.37
8	2	1.26	541.05

Table 7.11: LCOE and system cost per SHS for a network of 12 small commercial SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	4.12	0.84	348.40
2	3.7	0.82	369.03
5	2.47	0.90	469.81
8	1.935	0.93	553.63

In each of the three cases shown in tables 7.9 to 7.11 case, there is an initial reduction in LCOE at 2% annual demand growth, due to the additional energy usage outweighing the impact of reduced battery lifetime, driven by greater average depth of discharge.

For every level of demand growth, the average system cost for the 1:1 commercial and domestic system is lower than either of the other system types.

Table 7.12: LCOE comparison for 6 small domestic and 6 small commercial SHSs without and with interconnection over 10 years

Demand Growth per Year (%)	**Average LCOE for 6 SD SHSs and 6 SC SHSs Without Interconnection ($/kWh)**	**Average LCOE for 6 SD SHSs and 6 SC SHSs With Interconnection ($/kWh)**	**Percentage Reduction in LCOE**
0	1.57	0.86	44.86%
2	1.17	0.85	27.61%
5	1.30	0.86	33.22%
8	1.69	0.95	43.68%

Table 7.16 compares the LCOE for 12 standalone SHSs to a network of 6 commercial and 6 domestic SHSs under each demand growth scenario. The greatest improvements in LCOE are seen for 0% demand growth, but begin to increase again under more extreme demand growth scenarios.

The changes in LCOE with demand growth are much less extreme and more consistent in all cases for interconnected systems than isolated systems. The improvement in LCOE with initial demand growth is seen in isolated systems under demand growth is not observed, as more of the excess energy is utilised in the interconnected systems already.

7.5.2 Large SHSs

Table 7.13: LCOE and system cost per SHS for a network of 6 large commercial SHSs and 6 large domestic SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	4.86	0.93	1316.57
2	4.24	0.90	1379.85
5	3.06	0.89	1568.81
8	2.14	0.91	1861.59

Table 7.14: LCOE and system cost per SHS for a network of 12 small domestic SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	4.72	1.15	1329.57
2	4.08	1.11	1398.55
5	2.95	1.10	1594.20
8	2.16	1.11	1852.58

Table 7.15: LCOE and system cost per SHS for a network of 12 large commercial SHSs over 10 years

Demand Growth per Year (%)	**Mean Battery Replacement Time (Years)**	**Average LCOE ($/kWh)**	**Total System Cost Over 10 Years ($)**
0	3.91	0.84	1403.60
2	3.05	0.83	1519.28
5	2.38	0.85	1772.69
8	1.80	0.85	2052.01

Table 7.16: LCOE comparison for 6 large domestic and 6 large commercial SHSs without and with interconnection over 10 years

Demand Growth per Year (%)	**Average LCOE for 6 SD SHSs and 6 SC SHSs Without Interconnection ($/kWh)**	**Average LCOE for 6 SD SHSs and 6 SC SHSs With Interconnection ($/kWh)**	**Percentage Reduction in LCOE**
0	1.219	0.93	23.40%
2	1.06	0.90	15.51%
5	1.035	0.89	14.37%
8	1.01	0.91	10.48%

For the larger systems, the reduction in LCOE is less than for the small systems. This is due to the large systems having a large number of loads, already exhibiting a greater diversity of demand. The battery replacement rate benefits of interconnection also diminish more quickly with increased demand growth for the larger systems.

7.6 Excess Energy

As well as improving battery life time, interconnection between SHSs allows an outlet to utilise any excess energy. This excess energy could provide another value stream to increase the viability of these networks. Potential uses include light industrial applications or loads where the majority of energy is used in the day, such as schools and health care centres.

For both the small and large SHSs interconnected network of 12 systems, with a ratio of 1:1 between commercial and domestic, the excess energy generated in each day, after all excess energy has been utilised to charge other systems and meet demand in other systems was recorded.

There is a significant average generation energy which could be utilised by a range of non-time sensitive loads. The most obvious of these is agricultural water pumping which requires a certain input of energy over a given time but does not generally result in reduced utility if that energy use is spread over a few hours or days. In these cases the use of this energy needs to be supplemented with battery storage to ensure the required reliability but could mitigate a significant amount of the system cost.

For the small solar home system network the mean excess energy generated by 12 systems in a day is 1.166 kWh. The range is large with 3 kWh energy maximum and many cases with no energy generated at all.

The distribution of energy in figure 7.20 shows the majority of this energy is available between 8 a.m. in the morning and 13:00 peaking at 11 and not extending into the evening hours. This is from 4 due to increased domestic demand during this time from the domestic systems.

For the network of 12 large systems, 6 commercial and 6 domestic solar systems, mean excess energy per day is 8.73 kWh. As expected this is significantly larger than the small systems. figure 7.21 shows the distribution of daily energy generation presenting a significant range from 0 kWh per day to almost 20 kWh per day.

Over the ten-year lifetime of these systems we can calculate the total and used excess energy generated and calculate the potential additional revenue that could be derived from this energy. We have assumed a tariff 20 cents per kWh for this energy, roughly 25% of the cheapest levelized cost of energy for the SHSs. Its lower price accounts for the unreliability of the energy.

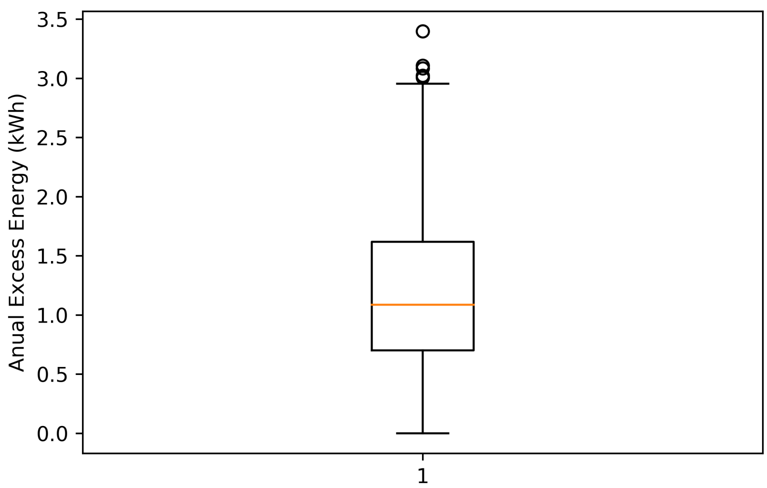

Figure 7.19: Range of daily excess energy generated by an interconnected network of 6 small commercial and 6 small domestic SHSs

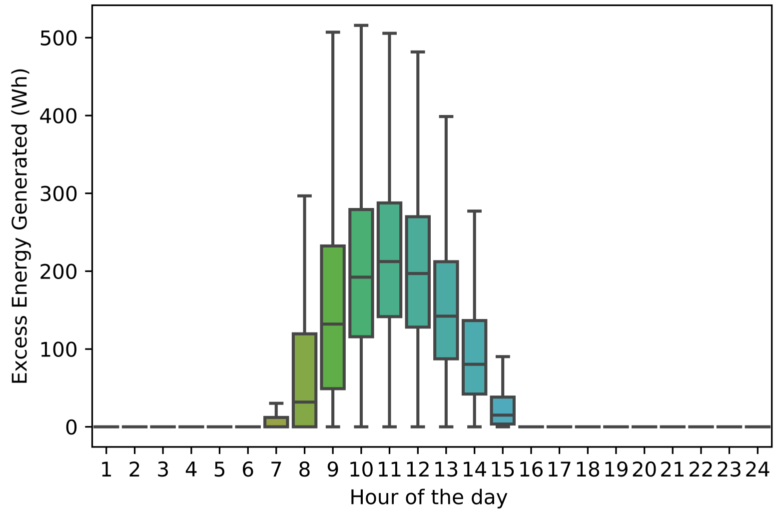

Figure 7.20: Range of hourly excess energy generated by an interconnected network of 6 small commercial and 6 small domestic SHSs

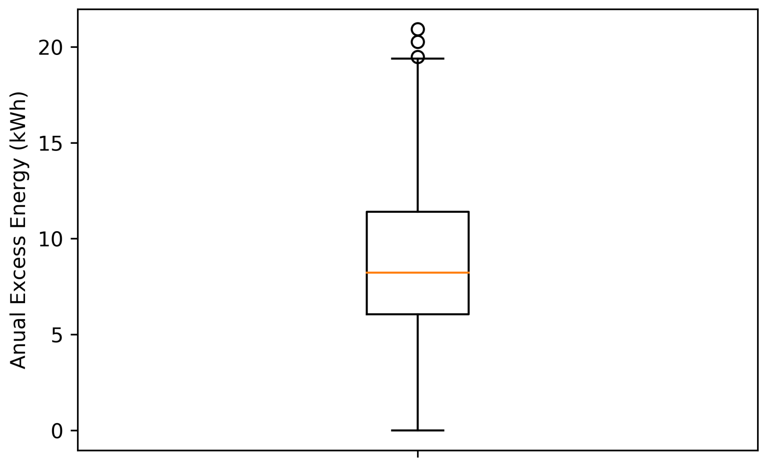

Figure 7.21: Range of daily excess energy generated by an interconnected network of 6 large commercial and 6 large domestic SHSs

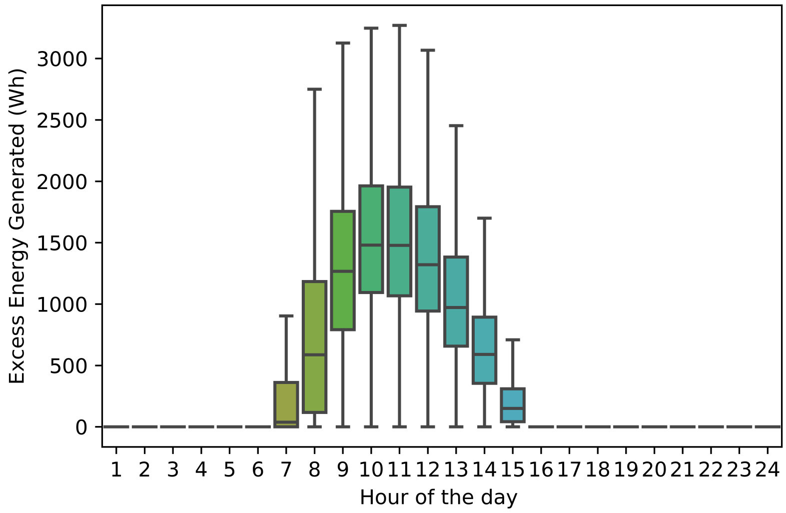

Figure 7.22: Range of hourly excess energy generated by an interconnected network of 6 large commercial and 6 large domestic SHSs over 10 years

Table 7.17: Value of Unused Excess energy for a network of 6 commercial and 6 domestic SHSs

System Type	**Total Excess (kWh)**	**Excess Per SHS (kWh)**	**Value of Energy Per SHS at \$0.1/kWh**	**Value of Energy Per SHS at \$0.2/kWh**
Small SHSs	4255.90	354.66	\$35.47	\$70.93
Large SHSs	31864.50	2655.38	\$265.54	\$531.08

The value of the energy normalised to a per system dollar value is shown in table 7.17. Over 10 years, this energy would be worth \$30-70 for each small SHS and between \$265-531 for the large systems.

We can then calculate the 10 year system cost and new LCOE for the SHS customers, assuming 80% of this energy is sold to a suitable flexible load.

7.7 Final LCOE Comparison

We have now established estimates for two reductions in LCOE that can be attributed to the interconnection of SHSs, both due to extended battery lifetime and utilisation of excess energy within the network.

Table 7.18 and 7.19 show a comparison of 10 year LCOE for each individual system and the average LCOE achieved through interconnection and the sale of 80% of excess energy to flexible loads.

Table 7.18: LCOE comparison for 6 small domestic and 6 small commercial SHSs without and with interconnection over 10 years, including sale of 80% excess energy at $0.2/kWh

Average LCOE for 6 SD SHSs and 6 SD SHSs Without Interconnection ($/kWh)	Average LCOE for 6 SD SHSs and 6 SD SHSs With Interconnection ($/kWh)	Percentage Reduction in LCOE	Average Total Per System Cost for 10 years ($)
1.57	0.703	55.23%	249.09

Table 7.19: LCOE comparison for 6 large domestic and 6 large commercial SHSs without and with interconnection over 10 years, including sale of 80% excess energy at $0.2/kWh

Average LCOE for 6 LD SHSs and 6 LD SHSs Without Interconnection ($/kWh)	Average LCOE for 6 LD SHSs and 6 LD SHSs With Interconnection ($/kWh)	Percentage Reduction in LCOE	Average Total Per System Cost for 10 years ($)
1.219	0.632	48.12%	891.70

This cost does not account for the cost of building the network infrastructure, but places an upper bounds on the 10 year cost per system for the maintenance, operation and capital costs of undertaking interconnection for the explored system types.

In practice, all of this value may not be passed on to the consumer. Potential business and operation models and the consequences for the consumers are explored in more detail in chapter 8.

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7.8 Summary

In this chapter it was demonstrated that interconnection of SHSs can have significant positive impact to reduce LCOE through the reduction of battery replacement under a range of conditions.

The effects of diversity of system type connected are also demonstrated. Introducing diverse demand profiles can further increase the benefits of interconnection. This should be considered when deciding which systems to interconnect and further exploration of how to translate these findings into a system design tool is of significant interest.

In chapter 8, the implications of these findings for the practical implementation of these systems are explored, from the perspective of business models and system planning.

Chapter 8

Business Models for Interconnected SHS Microgirds

8.1 Introduction

Interconnection presents opportunities for innovative business models that effectively fit the requirements of end users. The exploration of interconnected systems in chapters 4 and 5 gives a framework for quantitative analysis of these systems and demonstrates a number of case studies where this approach can be considered a viable path to upgrade offgrid systems from a techno-economic standpoint. It does not address the practical questions of who pays for these upgrades and how the benefits are spread between stakeholders.

This chapter will investigate the policy, planning and business implications of bottom-up interconnection and the possibility of new operation and business models for off grid energy systems.

A short investigation of relevant theory will be applied to the problem, then three potential operation and ownership models for interconnected SHS networks will be presented: a system operator model, an aggregator model and peer-to-peer market model. Each presents distinct advantages and challenges which will be contrasted.

8.2 Investigating Network Effects in Markets

When investigating the value of peer to peer markets, there are a number of relevant theoretical underpinnings to consider that can inform the formulation and exploration of ownership and operational models.

8.2.1 Network Theory

Metcalfe's Law states that for any communications network where a two way transfer of information can occur, like the internet, the "value" of that network is proportional to the square of the number of connections between agents [171]. This idea was a motivating factor behind the growth of the Internet. The law states that the marginal value of new connections grew exponentially, but the marginal cost of connecting a new user was roughly linear.

The law is generally considered to be overoptimistic, including by its namesake [172], as it assumes each new connection offers equivalent marginal value to the network. A number of alternative laws, such as Briscoe's law have been proposed, where the utility scales with log(n) [173], where n is the number of systems in the network.

This concept has been applied to economic networks where users buy and sell goods. The more users are present in a market, the greater the chance of beneficial exchange between them. This is of interest to us as an interconnected peer to peer power system falls under this paradigm [174].

As observed in figure Chapter 7, the utility of interconnected SHSs follows this law of exponentially diminishing returns as more users connect to the network. The marginal utility of each new user is less than the previous user. This is best observed in the graphs displaying battery replacement rates - figures 7.1 to 7.4.

These network effects could impact user uptake in an interesting manner. As the utility of a network increases with the number of users, agents are more likely to participate in larger networks. Therefore, early adopters may have to be incentivised to participate in order to drive the long term viability of a network but also it is also vital to manage expectations of the increasing utility of the system as it grows to reflect the diminishing marginal utility of new users.

8.2.2 Consumer Cooperation

In the empirical investigation so far in this thesis, the action of individual agents has been to act towards the good of the system within a set of confines. The setting of a threshold at which systems will willingly share energy from their batteries, explored in chapter 7, showed this, but assumed that each agent would co-operate and act according to the set rules. In a real peer to peer network, users could choose to 'defect' and act in another manner if it offered them increased utility over cooperation [175]. This is of particular interest in the case where each user owns their own storage and generating assets, such as the solution proposed in this work and would benefit from extending the lifetime of their own SHS.

Each household is given the choice to cooperate fully (agree to share energy in a manner that results in the best outcome across all systems), to defect fully (act in the manner that optimises the result for their individual system with no regard for the overall performance of other SHSs) or act at any degree in between these two points. The case where every agent co-operates fully would result in the greatest overall utility for the system. Full control of the actions of every agent would allow the theoretical optimal dispatch to be achieved [176].

If an agent wanted to raise their own reliability further, they could refuse to share their energy or raise the threshold at which they share. This agent would see an improvement in their reliability over time. Their battery would, on average, be more charged and experience a higher average depth of discharge, shown in chapter 6 to extend the life of the system. This choice comes at the cost of utility from the rest of the community, as their battery no longer contributes to help others. This would result in a fall in net utility, but a gain for the defecting house.

Choosing to defect if you think all other houses will cooperate is the highest utility choice, as you gain all the benefit from the support of other users' batteries, while not discharging your own. However, if all houses choose to defect, everyone is effectively operating their SHS in its original islanded configuration and the utility for each agent is lower than in the case of mutual cooperation. This is a classical formulation of "The Prisoner's Dilemma" [177] where agents are rewarded for not cooperating only if they think that the other agents in the system will cooperate.

Similar challenges are faced in global action on climate change as outlined in [178] and have been shown in grid connected minigrids in [179].

Any incentives to sell energy into such a system, damaging your battery, must therefore consider this dynamic, ensuring that the cost of energy sold is enough to push the balance in the favour of cooperation.

8.3 Business and Ownership Models for Interconnected SHSs

It is clear from chapters 6 and 7 that there is significant possible value that can theoretically be derived from interconnection. This section investigates possible operation and ownership that could facilitate practical operation of interconnected SHSs. These solutions focus on the social impact and economic viability of each approach and how the value streams are divided between stakeholders, taking into account the network effects, game theoretical principles outlined above in this chapter. In addition to these factors, the complexity of actions expected from each agent must be taken into account. [180] explores the challenges of engaging consumers in domestic flexibility markets and establishes that reduction of complexity and perceived control on the part of the user are the primary drivers for user engagement. As with any international development project, communication and informed collaboration with the communities in question is vital and different solutions may be appropriate in different economic and cultural contexts.

Four possible implementation models with differing benefits and challenges are proposed. These can act as a starting point for understanding and investigating this new modality for provided electricity access. Each has implications for how a practical system would be planned, funded, owned and operated, which will be outlined and discussed.

8.3.1 Anchor Load

As shown in chapters 6 and 7, the majority of the excess energy is present in the middle of the day and could be utilised by a load with daytime demand, such as a school or healthcare centre or a suitably flexible demand such as an irrigation pump. This approach is commonly used in minigrids to provide a reliable source of income to subsidise the provision of domestic energy and mitigate the risk and uncertainty of investment [181]. [182] identifies anchor loads combined with domestic lighting as a common and effective business model for rural electrification.

The simplest model for economic operation of such systems would be simple agreement between households and such a load to sell their excess energy in order to support the load. The costs of the network's construction and maintenance would be covered by the owner of the anchor load and users could retain full ownership and control of their SHSs. Users would receive compensation for their energy exported and the anchor load would receive the excess energy from the SHSs at a rate competitive with running their own standalone system.

This approach would make economic sense in cases where the construction of the network infrastructure to facilitate interconnection is less than the required investment from the anchor load to install its own minigrid or standalone system, but could also be subsidised by those wishing to develop network infrastructure for future aims.

Under this model, users would retain full ownership and operation of their SHS and should experience no change in quality of service, either positive or negative, from interconnection. Users would only export unused energy directly generated by the PV array of each SHS, not utilising energy stored in batteries and therefore not impacting the ageing or replacement rate of the batteries.

This approach minimises the possibility of net negative effects for consumers from interconnection - consumers can not be worse off after interconnection - but only makes use of one of the possible value streams from interconnection outlined in chapter 6, the excess energy generated. This downside is balanced by the relative simplicity, both of implementation and user engagement. Consumers would only export excess energy from their solar panels when not being used domestically, requiring no active choice from the user. This simplistic implementation could be used as a springboard or proof of concept for interconnected SHSs.

Another key advantage of this approach is the familiarity of the minigird community with the model of business based anchor loads and connected households. In [183] 5/29 surveyed minigrids follow a models of utilising an anchor load, businesses and domestic consumers as customers.

8.3.2 System Operator

Under a system operator model, the network including the generation and storage assets in each SHS are owned and operated by a centralised entity with the intention of optimising for specific outcomes. The concept of a Distribution System Operator (DSO) has gained traction in recent years in the context of distribution networks on larger grids with distributed energy and storage assets [184] and a similar concept could be applied in this context.

This would involve a single entity directly managing each storage and generation asset, both those in the existing connected SHSs and any additional assets installed. It is most likely that this system operator would be a private company or government organisation, rather than community group, due to the required technical competencies, but programs of technical capacity building could lead to community system operators becoming a viable model [183].

This approach most resembles the operation of most traditional minigrids, which tend to utilise centralised control [185].

From the perspective of the end user, they could experience a lower cost of energy due to more optimal control of storage assets reducing the battery replacement rate, if the system operator chose to pass on the savings. Alternatively, consumers could see an improved reliability of service with the SO taking the savings. Otherwise their system would operate identically to an islanded SHS from the perspective of the system user, with no additional direct engagement required.

The system operator would pay for the capital and operational costs by selling more energy to consumers, and can be targeted to communities where bottom-up engagement and remote monitoring data identify the potential for this excess energy to be utilised, making the endeavour financially viable. This model could be combined with anchor loads described above.

This approach also facilitates the setting of flexible tariffs to achieve social aims, as the system operator is in direct control of the offered tariffs [186]. For example, low income households could be offered a reduced rate or free energy and large bulk buyers, like shops and light industry, using energy in the middle of the day could be offered a discounted rate to use the excess solar peak energy. This could engage new customers who would otherwise be unwilling or financially unable to utilise an islanded SHS, expanding the pool of potential customers.

From a technical standpoint, the advantages of this centralised approach are that the dispatch of generation and storage can be optimised over the entire system [187]. Smart approaches to managing the distributed energy storage, such as those discussed in chapter 4 could be implemented most easily in this approach by an operator with full visibility and control over the storage and generation within the system.

Investment decisions can also be made by a single entity, with full visibility of the system, but could be motivated by the aims of the SO, to maximise profit, rather than to maximise the positive social contribution of the grid.

Communities are not required to have a high level of energy literacy in order to participate in a system run by a system operator, compared to the more market driven dynamics of the other options. This can be seen as an advantage, reducing the barrier to participation, but it also removes much of the opportunity for more direct engagement of consumers in their consumption and the potential educational and well-being benefits that this could bring.

Centralised control brings its own disadvantages. Firstly, it is open to manipulation by the system operator, who has a natural monopoly on electricity supply and direct control on tariff setting [188]. Although many countries are making moves to legislate ‘fair’ or cost reflective tariffs, the legislation dealing with offgrid energy providers is less well developed globally [189] [190].

Privacy and data protection are also issues in this paradigm. In order to optimally operate the system and derive the maximum benefit from centralised control, the SO would require full knowledge of energy generation, consumption and storage levels within each household. The energy use data collected by the operator, combined with the other personal data that would be collected on consumers could potentially represent a significant breach of privacy and could be used in an unethical manner [191] [192].

For example an unscrupulous SO could observe when a household is reducing their energy consumption towards the end of the month, surmise that they are struggling to meet bill payments and make ends meet and sell their data to a high interest payday loan company who could market to them in a targeted manner [193].

8.3.3 Aggregator

Under this model, a system operator would still exist, but would not have full control and visibility of each user's SHS. Instead, they would act as an intermediary, facilitating the trading of energy by creating a managed energy market in which SHS owners could engage.

Users connected to the network could sell excess energy directly to the aggregator, either at a fixed price or at a spot price which depends on demand at the time. This functions similarly to a feed in tariff [194]. A similar approach has been implemented in a minigrid in Tanzania [195], but the level of the tariff was set lower than the cost of generation - making it unappealing. In the case where SHSs have latent excess energy and zero marginal costs, as shown in the proposed network of interconnected SHSs, this approach would be more appealing. Likewise, users could also buy energy from the aggregator when available, again either at a fixed price or spot price determined by supply and demand.

This would enable users to have more financial flexibility. A user could reduce demand and sell excess energy during a difficult financial period or simply derive a profit from their excess energy, acting as engaged energy prosumers. This approach has been shown to be effective in [196], where a number of prosumers act as agents in an energy market run by minigrid operator for a grid connected minigrid.

In order to engage in this form of energy market, end users are required to have a more sophisticated understanding of energy than an SO model. This presents a challenge for education and capacity building, but can also be seen as an opportunity to more directly engage users in their energy use in a manner that could be more tangible, accessible and relatable [197].

As with any energy market, this model would be open to manipulation and would require careful regulation on the part of the aggregator. This could include limitation on third party connections to the system, similar to the connections process undertaken by DNOs in main power grids [198], where connections are subject to consents and cost reflective charging.

The aggregator could operate some form of centralised battery storage in order to aggregate demand over longer periods of time and provide balancing services to the system [199] [200] and could also operate anchor loads such as water pumping alongside this energy storage as outlined in chapter 7.

8.3.4 Peer to Peer

In a peer to peer system, each agent would operate independently, choosing when to buy and sell energy directly to and from other agents with no intermediary. This could take the form of an instantaneous spot price or unilateral virtual private wire arrangements between individual users

The option requires the most direct customer engagement and education, as each consumer must dynamically adapt their priorities and understand the relative costs and benefits of buying and selling their energy [201].

An additional challenge of this approach is the unproven nature of peer to peer markets for energy. Although some work in this area was outlined in 4.8.5, these focused on private wire or virtual private wire arrangements between consumers who also have the backup of a national grid connection. Different approaches will be required for offgrid consumers, with different expectations of services quality [202].

This approach is potentially open to abuse or manipulation. One agent with a larger amount of generation or storage could in theory manipulate the market pricing to their own advantage, creating artificial scarcity to drive up prices [203]. Some form of check or balance could be implemented to prevent or mitigate this, such as energy trading caps, increased transaction fees for higher volume prosumers. In many cases community level peer to peer markets have proven to be self regulating - with defecting actors being heavily penalised by other participants [204].

In a peer to peer system, there is still a requirement to pay for both the capital and operational and maintenance costs of the system. This differs from many peer to peer systems, such as cryptocurrency or ride share apps, which utilise existing infrastructure to facilitate trades [205]. Any viable model must account for these costs. Consumers could pay a connection cost to cover the initial capital expenditure associated with the hardware required to build the network and facilitate trade and pay a small fee towards a community operated system. Alternatively, the system could be funded via a transaction fee, either a flat rate fee or fixed fee for each energy trade [206]. The fee could be paid either by the seller, purchaser or shared between the two and could be a flat rate or the magnitude of this fee could depend on how much energy is traded as a percentage.

8.4 Summary

Chapters 6 and 7 demonstrate potential value to be derived from interconnection of SHSs, both in terms of optimal dispatch of assets and use of excess energy. How this value pie is split between the stakeholders of system operators, commercial and domestic users and other organisations such as government is a vital question to determine long term ethical and economic viability.

When considering electricity access, the driving motivation must be to provide the best value to the end uses, while remaining financially viable and practical. This chapter proposed 4 operational models for an interconnected SHS minigrid, that of a productive anchor load, a System Operators with full visibility and control, a traditional market based solution and a decentralised peer to peer market.

There are significant challenges for each model of implementation. It is not possible to undertake quantitative analysis of each model without analytical data from real world trials, but some qualitative comparisons between the three approaches can be made.

The SO model allows the best possible utilisation and optimisation of available assets, potentially offering the greatest reduction in LCOE at the cost of increased control complexity and reduced engagement and choice from consumers. There is also the greatest potential for "predatory" business operation, tying consumers into environments that do not offer good value.

In contrast, the peer to peer model offers the greatest consumer choice and engagement, but could more easily lead to sub-optimal utilisation of available energy, ultimately offering worse value for consumers.

The aggregator model offers a middle ground, still allowing consumer choice while high level operation of the system can be managed centrally.

In all cases, it is important to consider the ethics of operating for profit businesses to provide lifeline energy to consumers with little disposable income. Any of these operation models would be equally suited to a social enterprise or donor lead intervention.

Further practical field work and modelling is required to fully understand the social and economic impacts of this approach, but the business models outlined above offer an overview of potential approaches. More detailed agent based modelling of user behaviour and deeper economic modelling would offer greater insight into each of the proposed operational models, facilitating a quantitative assessment of the impact of each and the ability to assess the changes in cost of energy driven by differing user behaviours and business practices.

Chapter 9

Conclusion

9.1 Key Contributions

The key contributions of this work are:

- Literature based exploration of the limitations of SHSs in delivering modern energy services and SHS interconnection as a route to address these issues.
- Development of a novel, time sequential Monte Carlo simulation methodology to investigate questions of demand and generation diversity of SHSs and the impacts of SHS interconnection in a stochastic manner.
- Application of this methodology to a range of differnt case-study SHSs - demonstrating the presence of demand diversity, excess energy generation and the lifetime limitations of the systems due to battery degradation.
- Modelling of interconnected SHSs under a range of system dispatch regimes, demonstrating significant potential to extend battery lifetime and reduce LCOE
- Investigation of operational business models for interconnected SHSs, informed by both simulation results and literature.

9.2 Thesis Summary

9.2.1 "Traditional" Aproaches Electricity Access and Planning

This thesis begin with a quote from the 8th United Nations secretary general Ban Ki-moon, stating that energy is:

> “The golden thread that connects economic growth, social equity, and environmental sustainability.”

The huge humanitarian benefits to electrify access are clear, transforming millions of lives each year, and leading the charge towards the UNSDG goal of universal access by 2030 is the innovative technology of the SHS.

But this revolution is not without disadvantages. In aiming to reach universal electricity access as soon as possible, quick and easy to deploy SHSs are being prioritised. While these systems, comprising a battery, solar panel and small loads have proven life changing for millions of people already, as they are currently deployed they do not represent cost effective, reliable and sustainable modern energy systems, but instead an interim measure in the absence of more scalable and sustainable systems and methods of electrification that can evolve at a pace with communities' energy needs.

The limitations of a binary measure of electricity access - the fraying of the golden thread - that is driving this uptake is the the main context for this work. In the rush to electrify all, there is risk that rapid deployment of SHSs will result in two classes of electrified people - those mostly in developed countries and urban centres of developing countries with grid connections providing high power, cheap electricity and those trapped in remote locations with expensive and low power SHSs. In solving one problem there is a risk of creating another.

Accepting that SHSs alone do not offer a sustainable, scalable or long term means of achieving widespread electrification, there are two options that may offer more scope and potential for long term, affordable, reliable and sustainable rural electrification. The first is to stop using SHS and hold out for high quality minigrid or national grid connections for the communities in question. This solution is similarly problematic. While the LCOE may ultimately be less for these systems than that of widespread distribution of stand-alone SHSs, the up-front capital costs associated with minigrid installations, and in particular main grid extensions, is prohibitive and can result in extensive delays. Therefore, these three options of SHSs, minigrids and gird extension are often considered separately and exclusively by planning approaches that focus on geographic zoning based on topography, demography and dispersion of the population as the parameters for selecting one of the three options that are SHSs, minigrids or gird extension as the most appropriate method of electrification. The priority of these planning methodologies is to provide some form of electricity access and does not necessarily consider long term demand growth. This can result in large populations receiving high cost and low quality electricity connections from SHSs, which do not scale with demand growth.

The second option is the one explored in this thesis - designing energy systems to use SHSs not as a final destination - but the first step on the ladder of electrification for these communities - taking advantage of their simple, modular nature to grow and evolve alongside and at a pace with energy demands of communities in an incremental and flexible manner.

Interconnection of SHSs to form small minigrids has been proposed in literature as one solution to this scaling problem - combining many small systems already operating in the field to create an interconnected system greater than the sum of its part, but little analytical work has been done to understand the long term benefits of such systems. The core question of this thesis was:

> Can interconnection of SHSs weave together the fraying ends of this golden thread, acting as an evolutionary transition towards bottom up electrification and universal access to affordable, sustainable and reliable energy?

Interconnection of SHSs could offer a solution to some of these problems, by providing a way to both lower the cost of SHSs over an extended lifetime and a path to upgrade systems in a flexible manner if and when demand growth occurs and avoid the issue of stranding the existing SHS assets. Instead these existing SHSs can become nodes on a larger system providing more reliable and affordable energy. This approach could also unlock potential for new models of operation - facilitating peer to peer trade of excess energy to provide income streams for SHS users.

Despite this potential, there is little analytical modelling work investigating this in the literature explored in chapter 4, especially at realistic multi year operational timescales or taking account of the random and stochastic behaviour of users and the impact this has on the system.

9.2.2 Modelling Interconnected SHSs

In order to explore this, chapter 5 presented a stochastic, time sequential Monte Carlo model. Each part of the system - the batteries, generation, demand and dispatch - have a separate model detailed in chapter 5. These where then combined into a single model to allow different scenarios to be explored, investigating a range of types of SHS with differing batteries, generation and loads, both in islanded and interconnected modes. This approach was chosen to allow random stochastic behaviour of users to be captured. A load probability was established from literature for each appliance for each hour of the day and determined at random for each time-step - resulting in a varying load profile reflecting the possible actions of each user.

A Monte Carlo simulation then runs a large number of simulations with some factors - the demand from each appliance in this case - selected at random based on some statistical rules. This process is repeated hundreds or thousands of times to create a large number of simulations - each reflective of a different possible worlds. These results can then form a probability distribution of likely outcomes - rather than a single answer - to capture low probability, high impact events that traditional deterministic simulation may miss - such as a large number of users connecting high power devices for a short time.

9.2.3 Evidence for the Viability of SHS Interconnection

Using the model - chapter 6 presents analytical evidence for a number of the motivating factors outlined in chapter 4 - specifically that SHSs have excess energy and exhibit demand diversity when operating in islanded, not interconnected mode. It is often argued in literature that each SHS produces surplus energy - often in excess of 50% of total demand [78] [112]. The model was used to validate this claim and to investigate when in the day this excess energy is available. The diversity of this excess energy between a number of systems was also modelled over multi year operational timescales.

Four case study systems were investigated - a small domestic SHS, a large domestic SHS, a small commercial SHS and a large commercial SHS. The loads, demand profiles and asset sizing of these systems was based on real case study SHSs. Excess generated energy was shown to have a range of between and average of 100 Wh/day for the smaller system types and 1000 Wh/day for the larger systems, in excess of 50% of total generated energy.

In addition to demonstrating the presence of excess energy and demand diversity - battery lifetime was shown to be a limiting factor for SHSs. Using a battery degradation model and simulated high resolution demand and generation profiles, battery capacity degradation was modelled for each system type. The average time to replacement varied from 2.73 for the small domestic system to 3.14 years for the small commercial system. Under annual demand growth of 8% the outlooks are even worse, with the large systems having an average time to replacement of 1.82 years and the smaller systems an average time to replacement of 1.25 years.

Demand diversity was also simulated and observed to exponentially drop as the number of combined systems increased, with small clusters of 20 houses with identical appliances exhibiting an average peak of less than 70% of the combined worst case peak for those houses.

Therefore, without any SHS interconnection, the simulations showed the generation of significant amounts of surplus energy, levels of demand diversity and routine battery replacement.

If we examine the key research question outlined in chapter one, the findings of this chapter strongly demonstrate all the required elements for interconnection of SHSs to offer benefits over standalone systems are present in the modelled systems, meriting further examination, that was undertaken in chapter 7.

9.2.4 Results from Interconnected SHS simulations

To simulate interconnection of SHSs a number of dispatch methodologies were established to model the behaviour of users on the system. These dispatch methods utilised energy from all batteries on the system in a more optimal manner to reduce the depth and regularity of charge/discharge cycles and extend system lifetime, resulting in a lower LCOE. Under all dispatch approaches, battery life was extended and LCOE lowered, with the "non-greedy" and "Low SoC Prioritisation" methods both offering comparable results, with a reduction of 0.36$/kWh observed for a network of 10 small domestic SHSs compared with stand alone operation.

The greatest benefit was observed when diverse system types where interconnected - with average 44.9% reduction in LCOE seen for a network of 6 small domestic and 6 small commercial systems interconnected - from $.57/kWh to $0.86/kWh.

A further reduction in LCOE for domestic customers was achieved by exporting a proportion of any leftover energy after actions to optimise batteries (mostly mid day solar energy) to a flexible load such as a water pump at a reduced tariff of $0.2/kWh to reflect the unpredictable nature of the energy.

This resulted in a final LCOE of $.63/kWh for a network of 12 large SHSs - a reduction of 48.12% compared to islanded operation and an LCOE $.703/kWh for a network of 12 small SHSs - a reduction of 55.23% compared to islanded operation.

This reduction in LCOE is significant, clearly providing evidence in favour of the key research question of the thesis - showing that interconnection of SHS can provide value when contrasted with islanded systems.

9.2.5 Business Models for Interconnected SHSs

The analytical modelling work presented in chapters 6 and 7 shows the potential of this approach. Multiple potential value streams are identified - extended battery lifetime, ability to grow energy demand and the utilisation of otherwise wasted excess solar energy, while also facilitating phased capital investment and reduced LCOE. In practice, technical viability must be supported by business models that are sustainable and offer value to all stakeholders. The three proposed models are:

- Energy System Operator - an agent with full visibility and control of each users system - which could allow optimal dispatch, but limits individual user's engagement and agency. The operator makes money by lowering LCOE and can pass savings onto the energy customers with affordable tariffs.
- An Aggregator - The system operator facilitates trades by buying and selling energy at a fixed spot price. Users can choose when to buy and sell, but only to the energy aggregator. The operator makes money through arbitrage - buying low and selling high. Users can sell excess energy to generate additional income.
- Peer to Peer - Users can freely trade bilaterally with any other user. This offers the greatest freedom to users, but would likely introduce too much complexity for customers to engage. The system owner could charge a transition fee to pay for the operation of the required infrastructure

As well as expressing the numerical value of the systems, these models present a new framework to consider the operational realities of this novel approach and consider who stands to benefit from the value created.

9.3 Further Work

The evidence presented in this thesis shows there is clear potential for SHS interconnection to level up electricity access for millions and provide a practical, bottom up pathway to high tier electricity access - moving from tier one or two access to tier three access. In order to fully realise the potential of interconnection between SHSs, a range of further work is required.

9.3.1 Other Combinations of System Types

Further investigation into other system type combinations would further inform planning implications. This would include investigating combinations of large and small SHSs and including other widely used models of SHS not investigated in the analysis, such as even larger domestic systems, systems designed specifically for productive agricultural use and load profiles informed by data from other locations around the globe.

This methodology is modular and flexible enough that it could easily be adapted to other combinations of system types.

9.3.2 Dispatch Regimens

As well as the dispatch methods explored in this chapter a range of other approaches could be taken. The most obvious additional dispatch method would be one focusing on minimising the number of charge and discharge cycles experienced by each battery. This would be in contrast to the state of charge of minimising approach and could potentially result in extended battery lifetime under certain circumstances.

Other dispatch methodologies could also be explored utilising machine learning and optimisation techniques to establish the optimal modes of operation of the battery. It would be possible to initialise an optimisation with average battery lifetime the objective function and apply a range of different machine learning techniques to determine optimal operation.

9.3.3 Ancillary Loads

Measured load profiles for ancillary loads like those explored in the section above could be utilised to better understand the suitability of these systems to power these loads. In addition other loads such as health care centres, schools and workshops, mainly using energy during the day, could be modelled to understand the potential contributions of these systems to infrastructure within a community.

9.3.4 Centralised Storage and Generation Assets

Additional loads and sources of generation and storage could be introduced onto a network of interconnected SHSs. New generation could take the form of a centralised diesel generator or additional solar generation shared between systems connected to the network. SHSs with only battery storage capacity could be introduced.

9.3.5 Infrastructure Costs

In order to fully evaluate this approach compared to others the costs of the infrastructure for interconnection between systems must be more carefully understood this cost will be highly dependent on the geography and density of SHSs, the distance between systems and topology of the network constructed.

9.3.6 Optimal Power Flow and Network Topology

A more in-depth investigation of the cost associated with network losses and the relative costs and gains from different network topologies utilising optimal power-flow techniques could further inform system level planning for interconnected SHSs.

9.3.7 Operations and Maintenance Model

As it is not a key focus of this work, a simple operations and maintenance model was utilised for assessing the system costs. A more sophisticated model, taking into account locational features such as travel time from maintenance hubs, locational cost of labour and fuel could further inform system type choice for a given location

9.3.8 Integration with Planning Tools

It has been established that this approach can offer potential value and a route to scale existing solar home system infrastructure. Further investigation is required to understand how this methodology could be integrated into existing planning tools. How could wide area tools take a tiered approach to electricity access? Could international goals and targets be adjusted to have scaling targets, considering the quality of electricity access? Planning methodology could be envisaged that specifies not just a fixed demand but a number of targets at different times and uses a range of optimisation techniques to compare pure SHS solutions, solutions removing SHSs and replacing them with minigrids or grid connection at a given stage and solutions like the one proposed in this thesis, interconnecting SHSs as demand and resources allow.

9.3.9 Case Study Integration

The aim of this thesis was to establish the motivation for further investigation of interconnection. Applying the methodology to real world case studies using measured data for generation and demand profiles is an important next step. This could also allow further tuning and validation of the stochastic demand model using measured demand data.

9.3.10 Battery Technology

Building models for other battery technologies beyond the valve regulated lead acid battery would facilitate a detailed comparison of the relative impacts and merits of interconnection on differing storage mediums.

The key battery technology to investigate would be lithium ion batteries, widely used in electric vehicles, due to their high energy density and lifetime. These batteries have a greater capital cost than lead acid batteries, but they can experience a greater number of charge/discharge cycles before reaching their end of life.

Bibliography

[1] "United Nations Sustainable Development Goals." United Nations, https://sdgs.un.org/goals. , Date Accessed: 22/7/19.

[2] M. Bhatia and N. Angelou, "Beyond Connections," 2015. `https://openknowledge.worldbank.org/handle/10986/24368`, Date accessed: 26/6/19.

[3] P. Alstone, D. Gershenson, and D. M. Kammen, "Decentralized energy systems for clean electricity access," vol. 5, pp. 305–314, mar 2015.

[4] B. Pillot, M. Muselli, P. Poggi, and J. Dias, "Historical trends in global energy policy and renewable power system issues in sub-saharan africa: The case of solar pv," *Energy Policy*, vol. 127, pp. 113–124, 04 2019.

[5] World Bank, "Access to electricity (% of population) Data." `https://data.worldbank.org/indicator/eg.elc.accs.zs`, Date Accessed: 2019-08-12.

[6] H. Ritchie and M. Roser, "Access to energy," *Our World in Data*, 2019. https://ourworldindata.org/energy-access, Date Accessed 23/11/2019.

[7] "RENEWABLES 2019 GLOBAL STATUS REPORT." Renewable Energy Network, `http://www.ren21.net/gsr-2019/` Date Accessed: 7/1/2019.

[8] M. Nique and H. Smertnik, "The Synergies Between Mobile Phone Access and Off Grid Energy Solutions," pp. 185–193, 2015.

[9] G. Bensch, J. Peters, and M. Sievert, "The lighting transition in rural Africa — From kerosene to battery-powered LED and the emerging disposal problem," *Energy for Sustainable Development*, vol. 39, pp. 13–20, aug 2017.

[10] T. A. P. P. Association, "What is electricity?," May 2021. https://www.publicpower.org/public-power/electricity-basics, Date Accessed = 2/5/2021.

[11] M. Gul, Y. Kotak, and T. Muneer, "Review on recent trend of solar photovoltaic technology," *Energy Exploration and Exploitation*, vol. 34, pp. 485–526, jul 2016.

[12] "2018 Global Off-Grid Solar Market Trends Report – Lighting Global," tech. rep., World Bank, 2018.

[13] Energypedia, "Grid extension vs off grid, island / isolated system," 2021. https://energypedia.info/wiki/Grid_Extension_vs_Off_grid,_Island_/_Isolated_System, Date Accessed = 6/4/2021.

[14] A. Alsop, A. Eales, S. Strachan, J. Leary, J. Persson, and I. R. Almeyda, "A global market assessment methodology for small wind in the developing world," in *2017 IEEE Global Humanitarian Technology Conference (GHTC)*, pp. 1–6, 2017.

[15] M. Wild, A. Ohmura, C. Schär, G. Müller, D. Folini, M. Schwarz, and M. Z. Hakuba, "The global energy balance archive (geba) version 2017: a database for worldwide measured surface energy fluxes," *Earth System Science Data*, vol. 9, no. 2, pp. 601–613, 2017.

[16] N. Narayan, T. Papakosta, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Estimating battery lifetimes in solar home system design using a practical modelling methodology," *Applied energy*, vol. 228, pp. 1629–1639, 2018.

[17] S. Barrett and C. Fudge, *Policy and action: essays on the implementation of public policy*, vol. 756. Routledge, 1981.

[18] B. Ki-Moon, "Secretary-general to global development center: 'energy is the golden thread' connecting economic growth, social equity, environmental sustainability," 4 2014.

[19] IEA; IRENA; UNSD; WB; WHO, "Tracking SDG 7: The Energy Progress Report 2019," 2019.

[20] H. Ahlborg and L. Hammar, "Drivers and barriers to rural electrification in tanzania and mozambique–grid-extension, off-grid, and renewable energy technologies," *Renewable Energy*, vol. 61, pp. 117–124, 2014.

[21] K. Aidoo and R. C. Briggs, "Underpowered: Rolling blackouts in africa disproportionately hurt the poor," *African Studies Review*, pp. 1–20, 2018.

[22] F. F. Nerini, O. Broad, D. Mentis, M. Welsch, M. Bazilian, and M. Howells, "A cost comparison of technology approaches for improving access to electricity services," *Energy*, vol. 95, pp. 255–265, 2016.

[23] A. Ehsan and Q. Yang, "Optimal integration and planning of renewable distributed generation in the power distribution networks: A review of analytical techniques," *Applied Energy*, vol. 210, pp. 44–59, 2018.

[24] E. Adkins, S. Eapen, F. Kaluwile, G. Nair, and V. Modi, "Off-grid energy services for the poor: Introducing led lighting in the millennium villages project in malawi," *Energy Policy*, vol. 38, no. 2, pp. 1087–1097, 2010.

[25] I. Bisaga and P. Parikh, "To climb or not to climb? investigating energy use behaviour among solar home system adopters through energy ladder and social practice lens," *Energy research & social science*, vol. 44, pp. 293–303, 2018.

[26] N. Narayan, A. Chamseddine, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Exploring the boundaries of Solar Home Systems (SHS) for off-grid electrification: Optimal SHS sizing for the multi-tier framework for household electricity access," *Applied Energy*, pp. 907–917, apr 2019.

[27] B. Tenenbaum, C. Greacen, T. Siyambalapitiya, and J. Knuckles, *From the bottom up: how small power producers and mini-grids can deliver electrification and renewable energy in Africa.* The World Bank, 2014.

[28] J. Peters, M. Sievert, and M. A. Toman, “Rural electrification through mini-grids: Challenges ahead,” *Energy Policy*, vol. 132, pp. 27–31, 2019.

[29] M. Franz, N. Peterschmidt, M. Rohrer, and B. Kondev, “Mini-grid Policy Toolkit: Policy and Business Frameworks for Successful Mini-grid Roll-outs,” tech. rep., European Union Energy Initiative Partnership Dialogue Facility, 2014.

[30] B. Soltowski, J. Bowes, S. Strachan, and O. Anaya-Lara, “A Simulation-Based Evaluation of the Benefits and Barriers to Interconnected Solar Home Systems in East Africa,” in *2018 IEEE PES/IAS PowerAfrica, PowerAfrica 2018*, 2018.

[31] F. Fuso Nerini, J. Tomei, L. S. To, I. Bisaga, P. Parikh, M. Black, A. Borrion, C. Spataru, V. Castán Broto, G. Anandarajah, B. Milligan, and Y. Mulugetta, “Mapping synergies and trade-offs between energy and the Sustainable Development Goals,” *Nature Energy*, vol. 3, no. 1, pp. 10–15, 2018.

[32] S. Anand and A. Sen, “Human Development Index: Methodology and Measurement.,” 1994. `https://ora.ox.ac.uk/objects/uuid:98d15918-dca9-4df1-8653-60df6d0289dd/download{_}file?file{_}format=application/pdf{&}safe{_}filename=HDI{_}methodology.pdf{&}type{_}of{_}work=Report`, Date Accessed: 6/1/2019.

[33] R. Ferguson, W. Wilkinson, and R. Hill, “Electricity use and economic development,” *Energy policy*, vol. 28, no. 13, pp. 923–934, 2000.

[34] J. Cornillie and S. Fankhauser, “The energy intensity of transition countries,” *Energy Economics*, vol. 26, pp. 283–295, may 2004.

[35] M. Verbič, S. Filipović, and M. Radovanović, “Electricity prices and energy intensity in Europe,” *Utilities Policy*, vol. 47, pp. 58–68, aug 2017.

[36] N. S. Ouedraogo, “Energy consumption and human development: Evidence from a panel cointegration and error correction model,” *Energy*, vol. 63, pp. 28–41, 2013.

[37] S. Niu, Y. Jia, W. Wang, R. He, L. Hu, and Y. Liu, "Electricity consumption and human development level: A comparative analysis based on panel data for 50 countries," *International Journal of Electrical Power and Energy Systems*, vol. 53, no. 1, pp. 338–347, 2013.

[38] S. Niu, Y. Jia, W. Wang, R. He, L. Hu, and Y. Liu, "Electricity consumption and human development level: A comparative analysis based on panel data for 50 countries," *International Journal of Electrical Power & Energy Systems*, vol. 53, pp. 338–347, 2013.

[39] "Electrifying africa: Grid extension models in sub-saharan africa." https://energypedia.info/wiki/Electrifying_Africa:_Grid_Extension_Models_in_Sub-Saharan_Africa#cite_note-Msofe.2C_2009.3B_Uisso.2C_2009-7 Date Accessed: 22/9/2018.

[40] D. Farquharson, P. Jaramillo, and C. Samaras, "Sustainability implications of electricity outages in sub-saharan africa," *Nature Sustainability*, vol. 1, no. 10, pp. 589–597, 2018.

[41] L. Lenz, A. Munyehirwe, J. Peters, and M. Sievert, "Does Large-Scale Infrastructure Investment Alleviate Poverty? Impacts of Rwanda's Electricity Access Roll-Out Program," *World Development*, vol. 89, pp. 88–110, jan 2017.

[42] D. T. Ton and M. A. Smith, "The U.S. Department of Energy's Microgrid Initiative," *Electricity Journal*, vol. 25, pp. 84–94, oct 2012.

[43] M. Nasir, Z. Jin, H. A. Khan, N. A. Zaffar, J. C. Vasquez, and J. M. Guerrero, "A decentralized control architecture applied to dc nanogrid clusters for rural electrification in developing regions," *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1773–1785, 2018.

[44] N. Wamukonya, "Solar home system electrification as a viable technology option for africa's development," *Energy Policy*, vol. 35, no. 1, pp. 6–14, 2007.

[45] J. Keane, *Pico-solar electric systems: The Earthscan expert guide to the technology and emerging market*. Routledge, 2014.

[46] G. Bensch, J. Peters, and M. Sievert, "The lighting transition in africa–from kerosene to led and the emerging dry-cell battery problem," *Available at SSRN 2706526*, 2015.

[47] J. Tracy and A. Jacobson, "The True Cost of Kerosene in Rural Africa," tech. rep., Lighting Africa, 2012.

[48] D. Muyanja, J. Allen, J. Vallarino, L. Valeri, B. Kakuhikire, D. Bangsberg, D. Christiani, A. Tsai, and P. Lai, "Kerosene lighting contributes to household air pollution in rural uganda," *Indoor air*, vol. 27, no. 5, pp. 1022–1029, 2017.

[49] S. Schare and K. R. Smith, "Particulate emission rates of simple kerosene lamps," *Energy for Sustainable Development*, vol. 2, no. 2, pp. 32–35, 1995.

[50] J. E. Shepherd and F. A. Perez, "Kerosene lamps and cookstoves—the hazards of gasoline contamination," *Fire safety journal*, vol. 43, no. 3, pp. 171–179, 2008.

[51] M. Grimm and J. Peters, "Solar off-grid markets in Africa. Recent dynamics and the role of branded products," *The journal of field actions*, pp. 160–163, oct 2016.

[52] S. Batchelor, E. Brown, N. Scott, and J. Leary, "Two birds, one stone—reframing cooking energy policies in africa and asia," *Energies*, vol. 12, no. 9, p. 1591, 2019.

[53] S. Batchelor, E. Brown, J. Leary, N. Scott, A. Alsop, and M. Leach, "Solar electric cooking in africa: Where will the transition happen first?," *Energy research & social science*, vol. 40, pp. 257–272, 2018.

[54] IEA, "Global energy & co2 status report 2018," 2019. Date Accessed: 17/4/2019.

[55] K. W. Hedman, M. C. Ferris, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Co-optimization of generation unit commitment and transmission switching with N-1 reliability," *IEEE Transactions on Power Systems*, vol. 25, pp. 1052–1063, may 2010.

[56] G. A. Orfanos, P. S. Georgilakis, and N. D. Hatziargyriou, "A more fair power flow based transmission cost allocation scheme considering maximum line loading for n-1 security," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3344–3352, 2013.

[57] M. Vagliasindi, *Implementing energy subsidy reforms: Evidence from developing countries.* The World Bank, 2012.

[58] I. Dube, "Impact of energy subsidies on energy consumption and supply in zimbabwe. do the urban poor really benefit?," *Energy Policy*, vol. 31, no. 15, pp. 1635–1645, 2003.

[59] International Energy Agency (IEA) and the World Bank, *Sustainable Energy for All 2015—Progress Toward Sustainable Energy.* World Bank, Washington, DC, 2015.

[60] F. Farzan, S. Lahiri, M. Kleinberg, K. Gharieh, F. Farzan, and M. Jafari, "Microgrids for fun and profit: The economics of installation investments and operations," *IEEE power and energy magazine*, vol. 11, no. 4, pp. 52–58, 2013.

[61] World Bank, Sustainable Energy for All (SE4ALL) database from the SE4ALL Global Tracking Framework led jointly by the World Bank, International Energy Agency and the Energy Sector Management Assistance Program., "Access to electricity, rural (% of rural population)," tech. rep., 2019.

[62] World Bank, Sustainable Energy for All (SE4ALL) database from the SE4ALL Global Tracking Framework led jointly by the World Bank, International Energy Agency and the Energy Sector Management Assistance Program., "Access to electricity, urban (% of urban population)," tech. rep., 2019.

[63] G. Boden, T., Andres, B. & Maryland, "Global Greenhouse Gas Emissions Data. Global, Regional, and National Fossil-Fuel CO2 Emissions," *Oak Ridge National Laboratory, U.S. Department of Energy, (2017) U.S. Department of Energy, Oak Ridge, Tennessee*, 2017.

[64] IRENA, "Solar PV in Africa: Costs and Markets," 2016. ISBN 978-92-95111-47-9.

[65] A. Ulbig, T. S. Borsche, and G. Andersson, "Impact of low rotational inertia on power system stability and operation," *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 7290–7297, 2014.

[66] United Nations Treaty Collection, "Paris Agreement," 2015. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en Date accessed: 24/09/19.

[67] D. U. Case, "Analysis of the cyber attack on the ukrainian power grid," *Electricity Information Sharing and Analysis Center (E-ISAC)*, 2016.

[68] E. H. Allen, R. B. Stuart, and T. E. Wiedman, "No light in august: power system restoration following the 2003 north american blackout," *IEEE Power and Energy Magazine*, vol. 12, no. 1, pp. 24–33, 2013.

[69] M. E. Beatty, S. Phelps, C. Rohner, and I. Weisfuse, "Blackout of 2003: public health effects and emergency response," *Public Health Reports*, vol. 121, no. 1, pp. 36–44, 2006.

[70] N. Newman, "Off-the-grid thinking to end nigeria's blackouts," *Engineering & Technology*, vol. 14, no. 2, pp. 68–71, 2019.

[71] H. Farhangi, "The path of the smart grid," *IEEE power and energy magazine*, vol. 8, no. 1, pp. 18–28, 2009.

[72] D. Apostolopoulou, S. Bahramirad, and A. Khodaei, "The interface of power: Moving toward distribution system operators," *IEEE Power and Energy Magazine*, vol. 14, no. 3, pp. 46–51, 2016.

[73] M. Naumann, R. C. Karl, C. N. Truong, A. Jossen, and H. C. Hesse, "Lithium-ion battery cost analysis in pv-household application," *Energy Procedia*, vol. 73, pp. 37–47, 2015.

[74] Z. Chmiel and S. C. Bhattacharyya, "Analysis of off-grid electricity system at isle of eigg (scotland): Lessons for developing countries," *Renewable Energy*, vol. 81, pp. 578–588, 2015.

[75] N. Narayan, A. Chamseddine, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Exploring the boundaries of Solar Home Systems (SHS) for off-grid electrification: Optimal SHS sizing for the multi-tier framework for household electricity access," *Applied Energy*, pp. 907–917, apr 2019.

[76] P. Halder, "Potential and economic feasibility of solar home systems implementation in bangladesh," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 568–576, 2016.

[77] T. Linsley, *Basic electrical installation work.* Routledge, 2018.

[78] H. Kirchhoff, "Identifying Hidden Resources in Solar Home Systems as the Basis for Bottom-Up Grids," pp. 23–32, 2015.

[79] GOGLA, "Global Off-Grid Solar Market Report Semi-Annual Sales and Impact Data July-December 2018, Public Report," tech. rep., 2018.

[80] C. Blodgett, P. Dauenhauer, H. Louie, and L. Kickham, "Accuracy of energy-use surveys in predicting rural mini-grid user consumption," *Energy for Sustainable Development*, vol. 41, pp. 88–105, dec 2017.

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

[82] S. Groh, D. Philipp, B. E. Lasch, and H. Kirchhoff, "Swarm Electrification: Investigating a Paradigm Shift Through the Building of Microgrids Bottom-up," pp. 3–22, Springer, Cham, 2015.

[83] "Mini-grid policy toolkit," European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF).

[84] A. Wildavsky, "The policy cycle," *Beverly Hills (LA)*, vol. 332, p. 34, 1978.

[85] P. A. Sabatier, "Top-down and Bottom-up Approaches to Implementation Research: A Critical Analysis and Suggested Synthesis," *Journal of Public Policy*, vol. 6, no. 1, pp. 21–48, 1986.

[86] B. Hjern and D. O. Porter, "Implementation structures: A new unit of administrative analysis," in *Realizing social science knowledge*, pp. 265–277, Springer, 1983.

[87] B. Tenenbaum, C. Greacen, T. Siyambalapitiya, and J. Knuckles, *From the Bottom Up: How Small Power Producers and Mini-Grids Can Deliver Electrification and Renewable Energy in Africa.* The World Bank, jan 2014.

[88] A. Belward, B. Bisselink, K. Bódis, A. Brink, J. Dallemand, A. De Roo, T. Huld, F. Kayitakire, P. Mayaux, M. Moner-Girona, *et al.*, "Renewable energies in africa," *F. Monforti (Ed.)*, pp. 1–62, 2011.

[89] D. Mentis, S. Hermann, M. Howells, M. Welsch, and S. H. Siyal, "Assessing the technical wind energy potential in africa a gis-based approach," *Renewable Energy*, vol. 83, pp. 110–125, 2015.

[90] D. D. A. Ellman, *The reference electrification model: a computer model for planning rural electricity access.* PhD thesis, Massachusetts Institute of Technology, 2015.

[91] R. Amatya, M. Barbar, Y. Borofsky, M. Brusnahan, P. Ciller, T. Cotterman, F. de Cuadra, C. Drouin, P. Duenas, D. Ellman, A. García, S. Lee, V. Li, C. Mateo, O. Oladeji, R. Palacios, I. Pérez-Arriaga, R. Stoner, and C. Vergara, "Computer-aided electrification planning in developing countries: The Reference Electrification Model (REM)," pp. 1–111, 2019.

[92] C. Drouin, *Geospatial cost drivers in computer-aided electrification planning: the case of Rwanda.* PhD thesis, Massachusetts Institute of Technology, 2018.

[93] D. Mentis, M. Howells, H. Rogner, A. Korkovelos, C. Arderne, E. Zepeda, S. Siyal, C. Taliotis, M. Bazilian, A. de Roo, *et al.*, "Lighting the world: the first application of an open source, spatial electrification tool (onsset) on sub-saharan africa," *Environmental Research Letters*, vol. 12, no. 8, p. 085003, 2017.

[94] L. Parshall, D. Pillai, S. Mohan, A. Sanoh, and V. Modi, "National electricity planning in settings with low pre-existing grid coverage: development of a spatial model and case study of kenya," *Energy Policy*, vol. 37, no. 6, pp. 2395–2410, 2009.

[95] K. Lee, E. Miguel, and C. Wolfram, "Experimental evidence on the demand for and costs of rural electrification," Working Paper 22292, National Bureau of Economic Research, May 2016.

[96] B. Soltowski, J. Bowes, S. Strachan, and O. limpo Anaya-Lara, "A simulation-based evaluation of the benefits and barriers to interconnected solar home systems in east africa," in *2018 IEEE PES/IAS PowerAfrica*, pp. 491–496, IEEE, 2018.

[97] S. Sinha and S. Chandel, "Review of software tools for hybrid renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 192–205, 2014.

[98] J. Manwell, A. Rogers, G. Hayman, C. Avelar, J. McGowan, U. Abdulwahid, and K. Wu, "Hybrid2–a hybrid system simulation model–theory manual," *Renewable Energy Research Laboratory, University of Massachusetts*, 2006.

[99] S. Sinha and S. Chandel, "Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems," *Renewable and Sustainable Energy Reviews*, vol. 50, pp. 755–769, 2015.

[100] S. Chen, H. B. Gooi, and M. Wang, "Sizing of energy storage for microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 142–151, 2011.

[101] J. P. Fossati, A. Galarza, A. Martín-Villate, and L. Fontan, "A method for optimal sizing energy storage systems for microgrids," *Renewable Energy*, vol. 77, pp. 539–549, 2015.

[102] M. B. Shadmand and R. S. Balog, "Multi-objective optimization and design of photovoltaic-wind hybrid system for community smart dc microgrid," *IEEE Transactions on Smart Grid*, vol. 5, no. 5, pp. 2635–2643, 2014.

[103] H. Yang, W. Zhou, L. Lu, and Z. Fang, "Optimal sizing method for stand-alone hybrid solar–wind system with lpsp technology by using genetic algorithm," *Solar energy*, vol. 82, no. 4, pp. 354–367, 2008.

[104] J. R. Koza, "Genetic programming," *Citeseer*, 1997.

[105] D. DESILVER, "Despite global concerns about democracy, more than half of countries are democratic," May 2019. https://www.pewresearch.org/fact-tank/2019/05/14/more-than-half-of-countries-are-democratic/, Date Accessed: 20/12/19.

[106] "Mobisol to secure a sustainable position through restructuring process." https://plugintheworld.com/uncategorized/mobisol-gmbh-to-secure-a-sustainable-position-through-restructuring-process/, 2019. Date Accessed: 20/12/19.

[107] J. J. Lewis and S. K. Pattanayak, "Who adopts improved fuels and cookstoves? a systematic review," *Environmental health perspectives*, vol. 120, no. 5, pp. 637–645, 2012.

[108] J. Townsend and A. Townsend, "Accountability, motivation and practice: Ngos north and south," *Social & Cultural Geography*, vol. 5, no. 2, pp. 271–284, 2004.

[109] M. Kurata, N. Matsui, Y. Ikemoto, and H. Tsuboi, "Do determinants of adopting solar home systems differ between households and micro-enterprises? evidence from rural bangladesh," *Renewable energy*, vol. 129, pp. 309–316, 2018.

[110] C. Barteczko-Hibbert, "After diversity maximum demand (admd) report," *Report for the 'Customer-Led Network Revolution'project: Durham University*, 2015.

[111] F. Monforti, T. Huld, K. Bódis, L. Vitali, M. D'Isidoro, and R. Lacal-Arántegui, "Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach," *Renewable Energy*, vol. 63, pp. 576–586, 2014.

[112] B. Soltowski, J. Bowes, S. Strachan, and O. Anaya-Lara, "A simulation-based evaluation of the benefits and barriers to interconnected solar home systems in east africa," 11 2018. IEEE PES Power Africa Conference 2018 ; Conference date: 26-06-2018 Through 29-06-2018.

[113] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, pp. 83–88, Aug 2011.

[114] W. Quattrociocchi, G. Caldarelli, and A. Scala, "Self-healing networks: Redundancy and structure," *PLOS ONE*, vol. 9, pp. 1–7, 02 2014.

[115] M. Amin, "Challenges in reliability, security, efficiency, and resilience of energy infrastructure: Toward smart self-healing electric power grid," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, pp. 1–5, July 2008.

[116] L. Tsoukalas and R. Gao, "From smart grids to an energy internet: Assumptions, architectures and requirements," in *2008 Third International Conference on Electric Utility Deregulation and Restructuring and Power Technologies*, pp. 94–98, IEEE, 2008.

[117] I. J. Balaguer, Q. Lei, S. Yang, U. Supatti, and F. Z. Peng, "Control for grid-connected and intentional islanding operations of distributed power generation," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 147–157, Jan 2011.

[118] N. Narayan, T. Papakosta, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Estimating battery lifetimes in solar home system design using a practical modelling methodology," *Applied energy*, vol. 228, pp. 1629–1639, 2018.

[119] J. Barrie and H. J. Cruickshank, “Shedding light on the last mile: A study on the diffusion of pay as you go solar home systems in central east africa,” *Energy Policy*, vol. 107, pp. 425–436, 2017.

[120] P. Yadav, A. P. Heynen, and D. Palit, “Pay-as-you-go financing: A model for viable and widespread deployment of solar home systems in rural india,” *Energy for sustainable development*, vol. 48, pp. 139–153, 2019.

[121] G. Adwek, S. Boxiong, P. O. Ndolo, Z. O. Siagi, C. Chepsaigutt, C. M. Kemunto, M. Arowo, J. Shimmon, P. Simiyu, and A. C. Yabo, “The solar energy access in kenya: a review focusing on pay-as-you-go solar home system,” *Environment, Development and Sustainability*, pp. 1–42, 2020.

[122] R. Berahab, “How are innovative financing approaches contributing to wider electricity access in kenya?,” 2020. Policy Centre for the New South, Report, https://www.policycenter.ma/publications/how-are-innovative-financing-approaches-contributing-wider-electricity-access-kenya Date Accessed: 7/1/2020.

[123] C. H. Cooper, D. L. Fone, and A. J. Chiaradia, “Measuring the impact of spatial network layout on community social cohesion: a cross-sectional study,” *International journal of health geographics*, vol. 13, no. 1, p. 11, 2014.

[124] J. Hamari, M. Sjöklint, and A. Ukkonen, “The sharing economy: Why people participate in collaborative consumption,” *Journal of the association for information science and technology*, vol. 67, no. 9, pp. 2047–2059, 2016.

[125] J. Chikaire, A. Ani, F. Nnadi, C. Godson-Ibeji, *et al.*, “Energy extension and energy literacy for sustainable energy development in rural nigeria,” *Agricultural Advances*, vol. 4, no. 8, pp. 84–92, 2015.

[126] Z. Ding and W.-J. Lee, “A stochastic microgrid operation scheme to balance between system reliability and greenhouse gas emission,” in *2015 IEEE/IAS 51st Industrial & Commercial Power Systems Technical Conference (I&CPS)*, pp. 1–9, IEEE, 2015.

[127] J. Decuir and P. Michael, "Draft ieee standard for dc microgrids for rural and remote electricity access applications," in *2017 IEEE Conference on Technologies for Sustainability (SusTech)*, pp. 1–5, Nov 2017.

[128] F. Xue, R. Yu, and A. Q. Huang, "A 98.3% efficient gan isolated bidirectional dc–dc converter for dc microgrid energy storage system applications," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 9094–9103, 2017.

[129] T. R. de Oliveira, A. S. Bolzon, and P. F. Donoso-Garcia, "Grounding and safety considerations for residential dc microgrids," in *IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society*, pp. 5526–5532, IEEE, 2014.

[130] J. Leary, M. Czyrnek-Deletre, A. Alsop, A. Eales, L. Marandin, M. Org, M. Craig, W. Ortiz, C. Casillas, J. Persson, *et al.*, "Finding the niche: A review of market assessment methodologies for rural electrification with small scale wind power," *Renewable and Sustainable Energy Reviews*, vol. 133, p. 110240, 2020.

[131] M. Roser and E. Ortiz-Ospina, "Literacy," *Our World in Data*, 2016.

[132] K. Unger, *Organically Grown Microgrids: the Development and Simulation of a Solar Home System-based Microgrid.* Master of applied science, University of Waterloo, 2012.

[133] H. Kirchhoff, "Identifying hidden resources in solar home systems as the basis for bottom-up grids," in *Decentralized Solutions for Developing Economies* (S. Groh, J. van der Straeten, B. Edlefsen Lasch, D. Gershenson, W. Leal Filho, and D. M. Kammen, eds.), (Cham), pp. 23–32, Springer International Publishing, 2015.

[134] S. Groh, D. Philipp, B. E. Lasch, and H. Kirchhoff, "Swarm electrification - Suggesting a paradigm change through building microgrids bottom-up," in *2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)*, pp. 1–2, IEEE, may 2014.

[135] S. Groh, D. Philipp, B. Edlefsen Lasch, and H. Kirchhoff, *Swarm Electrification: Investigating a Paradigm Shift Through the Building of Microgrids Bottom-up*, pp. 3–22. 03 2015.

[136] M. Koepke and S. Groh, "Against the odds: The potential of swarm electrification for small island development states," *Energy Procedia*, vol. 103, pp. 363–368, 2016.

[137] H. Kirchhoff, N. Kebir, K. Neumann, P. W. Heller, and K. Strunz, "Developing mutual success factors and their application to swarm electrification: Microgrids with 100% renewable energies in the global south and germany," *Journal of cleaner production*, vol. 128, pp. 190–200, 2016.

[138] N. Narayan, A. Chamseddine, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, and M. Zeman, "Quantifying the Benefits of a Solar Home System-Based DC Microgrid for Rural Electrification," *Energies*, vol. 12, p. 938, mar 2019.

[139] P. Hollberg, "Swarm grids-innovation in rural electrification," 2015. Masters Thesis, KTH School of Industrial Engineering and Management.

[140] M. M. Hoffmann and D. Ansari, "Simulating the potential of swarm grids for pre-electrified communities–a case study from yemen," *Renewable and Sustainable Energy Reviews*, vol. 108, pp. 289–302, 2019.

[141] B. Koirala, A. Schies, B. Ortiz, T. Limbu, and B. Shakya, "Interconnected mini-grids for rural energy transition in nepal," in *Micro Perspective of Decentralized Energy Supply*, 02 2013.

[142] B. Shakya, A. Bruce, and I. MacGill, "Micro hydro interconnected mini grids in nepal: Potential and pitfalls," *Asis Pacific Solar Research Confernece, Brisbane Queensland*, 2015.

[143] P. Kumar, T. Yamashita, A. Karki, S. Rajshekar, A. Shrestha, and A. Yadav, "Nepal - scaling up electricity access through mini and micro hydropower applications : a strategic stock-taking and developing a future roadmap," 2015.

[144] N. J. Gil and J. A. P. Lopes, "Hierarchical frequency control scheme for islanded multi-microgrids operation," in *2007 IEEE Lausanne Power Tech*, pp. 473–478, July 2007.

[145] N. Nikmehr and S. N. Ravadanegh, "Optimal power dispatch of multi-microgrids at future smart distribution grids," *IEEE Transactions on Smart Grid*, vol. 6, no. 4, pp. 1648–1657, 2015.

[146] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Enhancing power system resilience through hierarchical outage management in multi-microgrids," *IEEE Transactions on Smart Grid*, vol. 7, no. 6, pp. 2869–2879, 2016.

[147] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing," in *2011 4th International Symposium on Resilient Control Systems*, pp. 83–88, Aug 2011.

[148] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The brooklyn microgrid," *Applied Energy*, vol. 210, pp. 870–880, 2018.

[149] N. Menon, "From Concept to Reality – Engineering Innovation." `https://www.okrasolar.com/blog/engineering-our-innovation/`, 2018. Date Accessed: 20/09/19.

[150] Wee Lab, "Solshare, the startup for sharing solar energy in bangladesh." https://medium.com/le-lab/solshare-the-startup-for-sharing-solar-energy-in-bangladesh-en-377002b21716, 2017. Date Accessed: 19/09/19.

[151] R. Billinton, Y. Cui, *et al.*, "Reliability evaluation of small stand-alone wind energy conversion systems using a time series simulation model," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 150, no. 1, pp. 96–100, 2003.

[152] A. Sankarakrishnan and R. Billinton, "Sequential monte carlo simulation for composite power system reliability analysis with time varying loads," *IEEE Transactions on power Systems*, vol. 10, no. 3, pp. 1540–1545, 1995.

[153] S. Pfenninger and I. Staffell, "Long-term patterns of european pv output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, 2016.

[154] R. Perez, R. Seals, and A. Zelenka, "Comparing satellite remote sensing and ground network measurements for the production of site/time specific irradiance data," *Solar Energy*, vol. 60, no. 2, pp. 89–96, 1997.

[155] R. Gelaro, W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, *et al.*, "The modern-era retrospective analysis for research and applications, version 2 (merra-2)," *Journal of Climate*, vol. 30, no. 14, pp. 5419–5454, 2017.

[156] A. L. Read, "Linear interpolation of histograms," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 425, no. 1-2, pp. 357–360, 1999.

[157] H. Patel and V. Agarwal, "Matlab-based modeling to study the effects of partial shading on pv array characteristics," *IEEE transactions on energy conversion*, vol. 23, no. 1, pp. 302–310, 2008.

[158] C. J. Willmott, "On the climatic optimization of the tilt and azimuth of flat-plate solar collectors," *Solar Energy*, vol. 28, no. 3, pp. 205–216, 1982.

[159] P. Ericksen, J. de Leeuw, P. Thornton, M. Said, M. Herrero, and A. Notenbaert, "Climate change in sub-saharan africa," *Pastoralism and development in Africa: Dynamic change at the margins*, vol. 71, 2013.

[160] B. Arbetter, R. Erickson, and D. Maksimovic, "Dc-dc converter design for battery-operated systems," in *Proceedings of PESC'95-Power Electronics Specialist Conference*, vol. 1, pp. 103–109, IEEE, 1995.

[161] S. Matteson and E. Williams, "Residual learning rates in lead-acid batteries: Effects on emerging technologies," *Energy Policy*, vol. 85, pp. 71–79, 2015.

[162] S. Matteson and E. Williams, "Learning dependent subsidies for lithium-ion electric vehicle batteries," *Technological Forecasting and Social Change*, vol. 92, pp. 322–331, 2015.

[163] ESMAP, "Benchmarking study of solar pv mini grids investment costs," 12 2017.

[164] L. Economics, "The value of lost load (voll) for electricity in great britain," *Final report for OFGEM and DECC*, 2013.

[165] S. Mandelli, C. Brivio, E. Colombo, and M. Merlo, "A sizing methodology based on levelized cost of supplied and lost energy for off-grid rural electrification systems," *Renewable Energy*, vol. 89, pp. 475–488, 2016.

[166] C. F. Institute, "What is the levelized cost of energy (lcoe)?," 9 2021.

[167] "bPower50, BBOXX." https://www.bboxx.co.uk/bPower50/. Date Accessed: 2019-10-28.

[168] "Lighting Global Standardized Specifications Book Product Image," tech. rep., 2021.

[169] D. Frame, P. Dauenhauer, A. Eales, and S. Galloway, "Experiences from deploying solar pv energy businesses in rural malawi," *Energising the Sustainable Development Goals Through Appropriate Technology and Governance*, 2019.

[170] K. Smith, A. Eales, D. Frame, and S. Galloway, "Techno-economic analysis of payg productive uses of energy in malawi," in *IEEE Global Humanitarian Technology Conference 2019*, 2019.

[171] B. Briscoe, A. Odlyzko, and B. Tilly, "Metcalfe's law is wrong-communications networks increase in value as they add members-but by how much?," *IEEE Spectrum*, vol. 43, no. 7, pp. 34–39, 2006.

[172] B. Metcalfe, "Metcalfe's law after 40 years of ethernet," *Computer*, vol. 46, no. 12, pp. 26–31, 2013.

[173] A. Madureira, F. den Hartog, H. Bouwman, and N. Baken, "Empirical validation of metcalfe's law: How internet usage patterns have changed over time," *Information Economics and Policy*, vol. 25, no. 4, pp. 246–256, 2013.

[174] T. Peterson, "Metcalfe's law as a model for bitcoin's value," *Alternative Investment Analyst Review Q*, vol. 2, 2018.

[175] T. Ma and Y. Nakamori, "Modeling technological change in energy systems–from optimization to agent-based modeling," *Energy*, vol. 34, no. 7, pp. 873–879, 2009.

[176] M. Steinheimer, U. Trick, and P. Ruhrig, "Energy communities in smart markets for optimisation of peer-to-peer interconnected smart homes," in *2012 8th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, pp. 1–6, IEEE, 2012.

[177] R. Axelrod, "Effective choice in the prisoner's dilemma," *Journal of conflict resolution*, vol. 24, no. 1, pp. 3–25, 1980.

[178] M. S. Soroos, "Global change, environmental security, and the prisoner's dilemma," *Journal of Peace Research*, vol. 31, no. 3, pp. 317–332, 1994.

[179] K. Anoh, S. Maharjan, A. Ikpehai, Y. Zhang, and B. Adebisi, "Energy peer-to-peer trading in virtual microgrids in smart grids: A game-theoretic approach," *IEEE Transactions on Smart Grid*, vol. 11, no. 2, pp. 1264–1275, 2019.

[180] B. Parrish, P. Heptonstall, R. Gross, and B. K. Sovacool, "A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response," *Energy Policy*, vol. 138, p. 111221, 2020.

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

[182] S. C. Bhattacharyya, "Business issues for mini-grid-based electrification in developing countries," in *Mini-Grids for Rural Electrification of Developing Countries*, pp. 145–164, Springer, 2014.

[183] J. Knuckles, "Business models for mini-grid electricity in base of the pyramid markets," *Energy for Sustainable Development*, vol. 31, pp. 67–82, 2016.

[184] P. Olivella-Rosell, E. Bullich-Massagué, M. Aragüés-Peñalba, A. Sumper, S. Ø. Ottesen, J.-A. Vidal-Clos, and R. Villafáfila-Robles, "Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources," *Applied energy*, vol. 210, pp. 881–895, 2018.

[185] E. Nyeche and E. Diemuodeke, "Modelling and optimisation of a hybrid pv-wind turbine-pumped hydro storage energy system for mini-grid application in coastline communities," *Journal of cleaner production*, vol. 250, p. 119578, 2020.

[186] T. J. Reber, S. S. Booth, D. S. Cutler, X. Li, and J. A. Salasovich, "Tariff considerations for micro-grids in sub-saharan africa," tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018.

[187] Z. Wang, R. Yang, and L. Wang, "Multi-agent control system with intelligent optimization for smart and energy-efficient buildings," in *IECON 2010-36th annual conference on IEEE industrial electronics society*, pp. 1144–1149, IEEE, 2010.

[188] S. Corneli and S. Kihm, "Will distributed energy end the utility natural monopoly," *Electricity Daily*, vol. 2, p. 9, 2016.

[189] C. Monyei, A. Adewumi, and K. Jenkins, "Energy (in) justice in off-grid rural electrification policy: South africa in focus," *Energy research & social science*, vol. 44, pp. 152–171, 2018.

[190] A. P. Heynen, P. A. Lant, S. Smart, S. Sridharan, and C. Greig, "Off-grid opportunities and threats in the wake of india's electrification push," *Energy, Sustainability and Society*, vol. 9, no. 1, pp. 1–10, 2019.

[191] E. McKenna, I. Richardson, and M. Thomson, "Smart meter data: Balancing consumer privacy concerns with legitimate applications," *Energy Policy*, vol. 41, pp. 807–814, 2012.

[192] P. McDaniel and S. McLaughlin, "Security and privacy challenges in the smart grid," *IEEE Security & Privacy*, vol. 7, no. 3, pp. 75–77, 2009.

[193] N. Martin, "1,000% interest-good while supplies last: A study of payday loan practices and solutions," *Ariz. L. Rev.*, vol. 52, p. 563, 2010.

[194] A. Klein, A. Held, M. Ragwitz, G. Resch, and T. Faber, "Evaluation of different feed-in tariff design options: Best practice paper for the international feed-in cooperation," *Energy Economics Group & Fraunhofer Institute Systems and Innovation Research, Germany*, 2008.

[195] M. Moner-Girona, R. Ghanadan, M. Solano-Peralta, I. Kougias, K. Bódis, T. Huld, and S. Szabó, "Adaptation of feed-in tariff for remote mini-grids: Tanzania as an illustrative case," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 306–318, 2016.

[196] N. Liu, X. Yu, C. Wang, and J. Wang, "Energy sharing management for microgrids with pv prosumers: A stackelberg game approach," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1088–1098, 2017.

[197] C.-K. Park, H.-J. Kim, and Y.-S. Kim, "A study of factors enhancing smart grid consumer engagement," *Energy Policy*, vol. 72, pp. 211–218, 2014.

[198] SSEN, "Statement of methodology and charges for connection to scottish hydro electric power distribution plc's electricity distribution system version 1.32 – 15th december 2020," tech. rep., 2020.

[199] M. Kazemi, H. Zareipour, N. Amjady, W. D. Rosehart, and M. Ehsan, "Operation scheduling of battery storage systems in joint energy and ancillary services markets," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 4, pp. 1726–1735, 2017.

[200] A. Kumar, N. K. Meena, A. R. Singh, Y. Deng, X. He, R. Bansal, and P. Kumar, "Strategic integration of battery energy storage systems with the provision of distributed ancillary services in active distribution systems," *Applied Energy*, vol. 253, p. 113503, 2019.

[201] F. Hawlitschek, T. Teubner, and H. Gimpel, "Consumer motives for peer-to-peer sharing," *Journal of Cleaner Production*, vol. 204, pp. 144–157, 2018.

[202] C. L. Azimoh, P. Klintenberg, F. Wallin, and B. Karlsson, "Illuminated but not electrified: An assessment of the impact of solar home system on rural households in south africa," *Applied energy*, vol. 155, pp. 354–364, 2015.

[203] D. J. Wilkins, R. Chitchyan, and M. Levine, "Peer-to-peer energy markets: Understanding the values of collective and community trading," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2020.

[204] M. Cohen and A. Sundararajan, "Self-regulation and innovation in the peer-to-peer sharing economy," *U. Chi. L. Rev. Dialogue*, vol. 82, p. 116, 2015.

[205] K. Mannaro, A. Pinna, and M. Marchesi, "Crypto-trading: Blockchain-oriented energy market," in *2017 AEIT International Annual Conference*, pp. 1–5, IEEE, 2017.

[206] N. Houy, "The economics of bitcoin transaction fees," *GATE WP*, vol. 1407, 2014.