Innovative technology to Enable Bottom-Up Electrification in Rural Regions of Sub-Saharan Africa

PhD Thesis

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Abstract

Over the past decade, off-grid systems, in the form of stand-alone solar home systems (SHSs), have proved the most popular and immediate solution for increasing energy access in rural areas across the Global South. Although deployed in significant numbers, issues remain with the cost, reliability, utilization, sustainability, and scalability of these off-grid systems to provide higher-tiered energy access. Interconnection of existing stand-alone solar home systems (SHSs) can form a microgrid of interconnected prosumers (i.e., households owning SHS capable of producing and consuming power) and consumers (i.e., households without an SHS, and only capable of consuming power).

This thesis investigates and develops a Smart Power Management platform to enable the interconnection of off-grid systems making this bottom-up electrification scalable with prospects of providing a new range of opportunities to existing off-grid assets. It also reveals how interconnection can improve the overall sustainability, efficiency, and flexibility of off-grid technology to satisfy growing electrical demand. Other aspects presented explain design of the product equipped with appropriate functionality using low-cost electronics providing smart interconnections between households with SHSs.

An interconnected SHS microgrid has the potential to unlock latent generation and storage capacity, and so effectively promote connected customers to higher tiers of energy access. This approach can therefore extend the range of products currently used by people located in the remote areas of developing countries to include higher-power devices such as refrigerators, TVs and more. The results illustrate the potential for a technology providing bottom-up electrification as well as difficulties that need to be faced while proposing this new electrification architecture.

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I want to thank my parents for helping me to choose academic research as a career path. To my wife, I want to thank you for supporting me in the last three years and unloading me with housework during periods when I had to run lab experiments all day long.

Abbreviations

AC	Alternating Current
CPU	Central Processing Unit
DC	Direct Current
DSM	Demand Side Management
ESMAP	Energy Sector Management Assistance Program
GOGLA	Global Off-Grid Lighting Association
GPRS	General Packet Radio Service
HDI	Human Development Index
ICT	Information and Communication Technology
IMEI	International Mobile Equipment Identity
LVDC	Low Voltage Direct Current
MPPT	Maximum Power Point Tracking
PAYGO	Pay-As-You-Go
PCB	Printed Circuit Board
PLC	Power Line Communication
PV	Photovoltaic
PWM	Pulse Width Modulation
RCT	Randomized Control Trial
RM	Remote Monitoring
RTOS	Real Time Operating System
SMD	Surface Mounted
SoC	State of Charge
SPM	Smart Power Management
µC	Microcontroller
µG	Microgrid

1. Introduction to Bottom-Up Electrification

Approximately 1.2 billion people are living without access to electricity in the world [1]. Former UN Secretary General Ban Ki-moon referred to energy as “the golden thread that connects economic growth, social equity and environmental sustainability” , offering an opportunity for improved living standards for some of the world’s poorest people residing in remote rural locations across the Global South [2]. The UN’s Sustainable Development Goal No.7 represents a call to action on the part of the international community to “ensure access to affordable, reliable, sustainable and modern energy for all” by 2030 which has been the key motivation while conducting research presented in this thesis [3], [4].

Evidence suggests that introduction of reliable access to electricity has been a fundamental aspect driving socio-economic development for billions of people. Despite the enormous benefits that electricity brings, many of those residing across the Global South still rely on traditional sources of energy, without any prospects to gain a connection to the national network in the next decade or more. Most of these people reside across Sub-Saharan Africa and Developing Asia, as indicated in Figure 1-1.

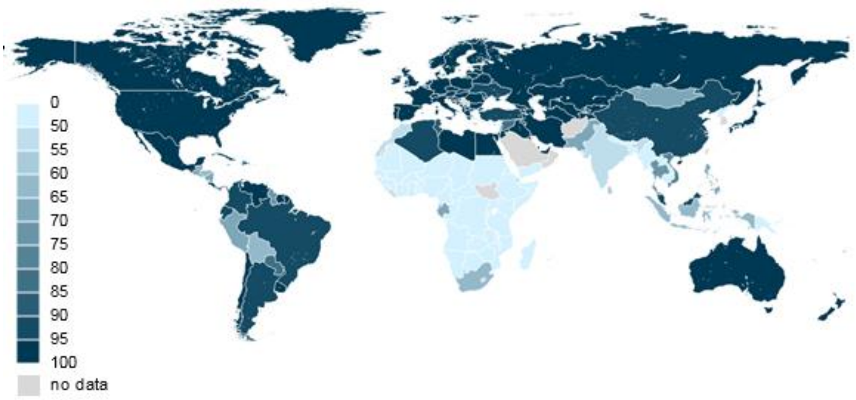

Figure 1-1. Access to Electricity per Country around the World [Source: U.S. Energy Information Administration, based on the World Bank Population and Access to Electricity datasets, Accessed: 11-Feb-2022]

The primary reason why millions of people residing across the Global South lack grid connection is the high upfront cost required to extend national systems. This, together with low financial capabilities to pay for energy indicated by millions of those across the Developing World makes rapid grid expansion to reach UN targets difficult to achieve [5], [6].

Lack of electricity access limits the range of income generation opportunities for millions of people who are typically required to shut down their commerce activities as soon as the sun goes down [7]. Moreover, living off-grid means high dependency on traditional sources for energy, mainly biomass for cooking and kerosene for lighting which exposes people to highly toxic indoor air pollution causing over 4.3 million premature deaths each year around the world [8], [9], [10]. Relying on kerosene lamps can also be dangerous, especially amongst families with kids who often suffer burns due to contact with hot lamps [11], [12]. Lack of electricity also affects the education sector. Most children residing off-grid have limited time to revise school material and prepare for classes due to inadequate light quality produced by kerosene lamps. Other important issues to which approximately 1 billion people around the world are exposed is the lack of minimal adequate health service capabilities in rural settlements, often due to lack of refrigeration systems in the village where vaccines and medicines could be stored in low temperatures [13], [14].

All difficulties associated with lack of electricity access cause significant limitations for millions of people who have no prospects of improving their life quality. It is also evident that due to inadequate access to electricity, the Human Development Index (HDI) for countries with low electrification rates is significantly below HDI for countries where access to energy is prevalent. Such relationship for various countries around the world is presented in Figure 1-2 [15], [16].

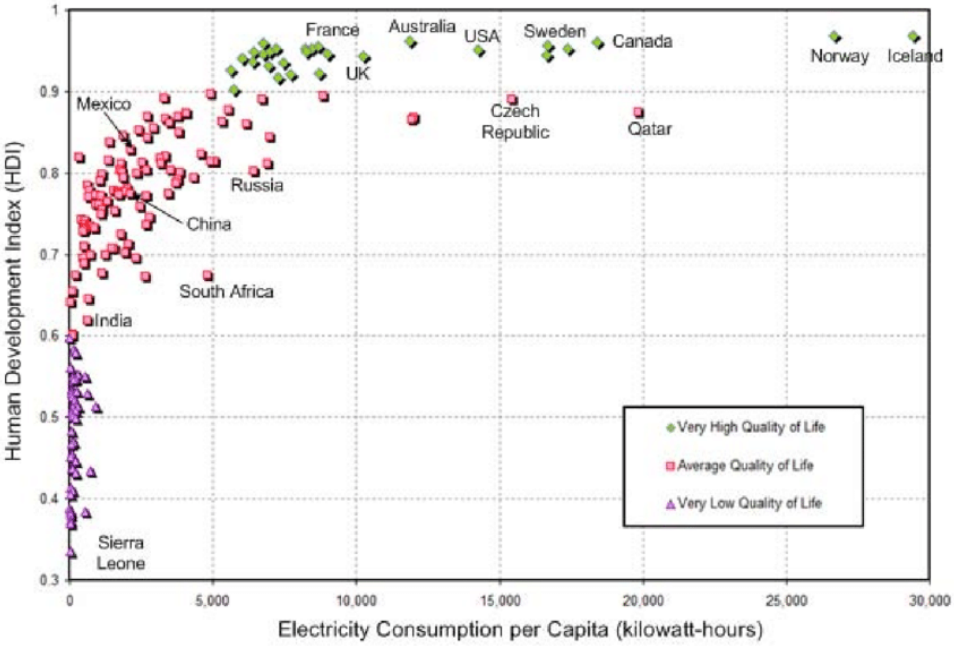

Figure 1-2. Human Development Index (HDI) vs. Electricity Consumption per Capita

Considering the scale of the energy access problem (see Figure 1-1) as well as challenging targets of reaching universal access to electricity for all by 2030, it can be concluded that national grid expansion under current pace cannot meet the UN Sustainable Goals number 7. As a result, new technological solutions supported by novel business models are required to be introduced to accelerate this transition. Such solutions may include adoption of off-grid systems which can support basic electric demand in rural regions out of the national grid range.

Over the past 15-20 years, such off-grid systems have successfully provided access to electricity to over 400 millions people around the Globe [17]. Capability to operate as a standalone system made them a viable alternative to the traditional top-down approach known from the Western World (based on a model with the centralised generation, transmission and distribution providing household connection). Although off-grid systems often impose significant limitations in terms of the range of appliances to be supported, the overall connection cost per household is substantially lower for a family with limited financial capacity than payment for the connection to the national grid. Off-grid solutions can often be installed on a rural household level, frequently without a highly trained technician. As a result, rapid expansion of such system configurations is possible.

To date, different forms of off-grid systems providing basic access to electricity have been introduced. Such systems typically produce power with the support of hydro or wind turbines, photovoltaic (PV) modules with energy storage or diesel generators. Appropriate selection of the generation unit depends on the natural resources on-site as well as trends in fuel costs. Evidence suggests that for most off-grid rural villages across the Developing World Solar Home Systems (SHSs) comprised of solar PV module and battery at the household level are the most viable solution to provide universal access to electricity in the coming years. Analysis of such technology, its abilities to meet electric demand in rural regions as well as the potential for future expansion by introducing a concept of Bottom-Up Electrification is the key areas of focus for this thesis [18].

1.1. Literature Review on Off-Grid Electrification across the Global South

Providing access to electricity in rural regions of the Developing World can be achieved in multiple ways. Optimal solutions may vary depending on a country, locations, mobile money penetrations, village topographies, abilities to pay performed by electricity consumers, regulation, fuel costs and many more [19], [20]. It is vital to match users' demand expectations with appropriate technical infrastructure. Furthermore, it is crucial to maintain costs of off-grid systems at a similar (or lower) level as corresponding monthly expenditures on traditional sources of energy, such as kerosene for lighting. As a result, chances of encouraging people into new, clean and renewable energy sources can be maximized [21]. The fundamental technologies providing off-grid energy access are Solar Home Systems (SHS), microgrids and solar kiosks presented in sections 1.2, 1.3 and 1.4 respectively.

1.2. Solar Home Systems

To reach millions of those residing far from the population centers (i.e., farmers in rural locations) who are located beyond national grid coverage, it is required to offer solutions with on-site power generation capabilities which can operate as standalone solutions (independently from the grid), providing electricity often for a single household. Such benefits could be obtained by the introduction of Solar Home Systems (SHS) comprised typically of one solar panel, battery, control unit integrated with a communication module as well as basic appliances. One of the main advantages of SHSs is their ad-hoc nature which does not require to comply with any national electrification plans. As such, SHS is a fast and effective solution primarily supporting lighting and phone charging within off-grid communities [22], [23].

Basic structure of the SHS is illustrated in Figure 1-3.

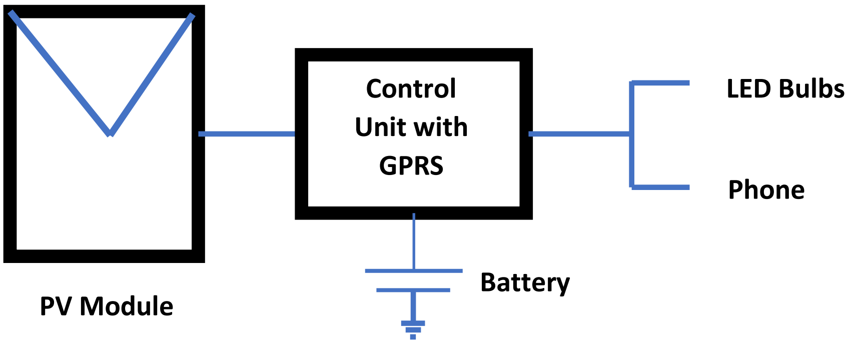

Figure 1-3. Configuration of a Typical Solar Home System (SHS)

SHSs have shown tremendous growth across the Global South in the last years. Only in Bangladesh, 5.5 million of SHSs have been installed since 2010, mainly due to affordable micro-payments scheme for SHSs, incentivizing people to purchase these solutions for basic lighting and phone charging [24], [25]. In recent years, SHSs have been becoming widely popular in Sub-Saharan African (SSA) countries, mainly in Eastern Africa region where mobile money penetration is particularly high and SHSs users are allowed to pay for their systems remotely [26], [27], [28]. Widely available General Radio Packet Services (GPRS) network can also support SHS providers by offering capabilities to control SHS and disconnect loads once the end customer does not pay for the installation. As a result, such a solution can be provided to all houses within the GPRS network range and financial capacity to pay for such a system.

Pay-as-you-go (PAYGO) business model allowing users to split SHSs costs over time is another key off-grid electrification "enabler" [29]. Typical SHS user is required to regulate payments over a certain period (varies from one SHSs provider to another) which significantly reduces upfront cost barrier for many low-income families. PAYGO fees are therefore completed with the support of mobile money systems, such as M-Pesa in Kenya and Tanzania, MTN Mobile Money in Rwanda and Uganda or many more [30], [31], [32]. Figure 1-4 presents growing popularity of the PAYGO business model for solar products in different parts of the world with significant off-grid electrification potential [33].

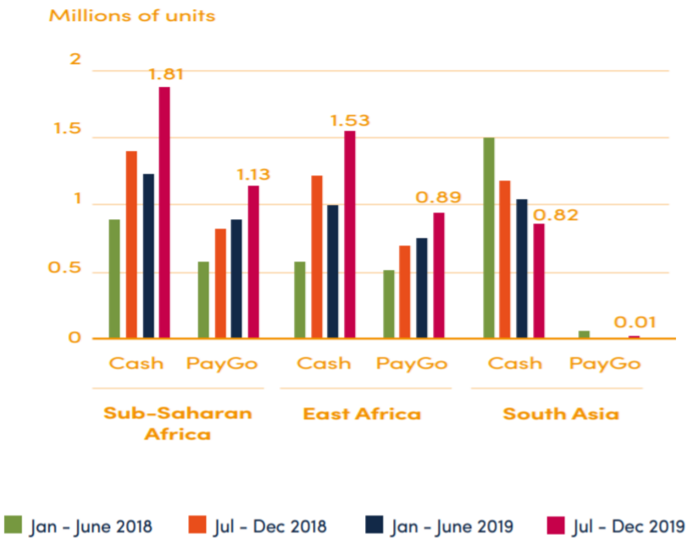

Figure 1-4. Semi-Annual Evaluation of Volume of Products Sold Regionally with Split Cash and PAYGO

SHSs solutions generally succeed in providing households with the basic appliance of the lowest energy requirements. Although electricity generation of such devices is typically very low, SHSs often have a significant effect on a wide range of aspects including the health and wellbeing of those living off-grid. This is primarily due to solar energy not requiring fossil fuels producing air pollution. Clean and reliable lighting introduces also benefits for education (lighting classrooms for evening study), commerce through productive uses of energy (e.g., local grocery shops) and many more aspects of daily life within rural communities. However, technical limitations associated with maximum power ratings allowed as well as typical storage capacity for stand-alone SHSs restrict their use to servicing typically lighting systems and phone chargers and so, the range of offers for scaling-up the demand after completing the initial pay-as-you-go contract is very limited.

1.3. Hub-and-Spoke Microgrids

For communities with high population densities, microgrids are often a more viable solution than SHSs, due to the capabilities of providing electricity from a single source of power to a wide range of customers at once. These hub-and-spoke networks are comprised of generation and often energy storage modules in the central part of the village supporting low voltage distribution network terminated by a smart meter at each household level. Additional remote monitoring capabilities give chance to scale up the generation and storage of the system in compliance with growing electric demand within the community. Similarly to SHSs, smart meters installed within rural microgrid also can disconnect households whenever bills for electricity are not paid [34], [35].

Microgrids do not require medium or high voltage infrastructure as well as costly transformers to support basic energy access in rural villages. This gives an opportunity to provide access to a network for significantly lower costs in comparison to the national grid connection. The drawbacks of consuming electricity from the microgrid systems are associated with relatively high costs of electricity offered by the system provider due to low number of households connected (in comparison to the national network). As such, off-grid microgrids show low feasibility in supplying electrical appliances of particularly high power and energy demand including electric cooking, mills, etc.

Evidence suggests that microgrids can provide different distribution system specifications. Some convert DC electricity (typical for solar-battery systems prevalent in SSA) into AC to support standard appliances currently available on the market [36]. Those which are designed mainly to provide electricity for lighting and phone charging may connect users directly to battery busbar through the distribution system, maintaining Direct Current (DC) characteristics of the network (such as MeshPower[1] solutions in Rwanda) [37], [38],

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[1] www.meshpower.co.rw

[39]. These networks are controlled by maximizing electricity production by the PV modules to charge local energy storage modules at the same voltage as the microgrid distribution network. As a result, such a system does not rely on power inverter and overall capital as well as operating costs are minimized.

A typical configuration of hub-and-spoke DC microgrid with a centralized PV generation and energy storage devices connected to four households is illustrated in Figure 1-5.

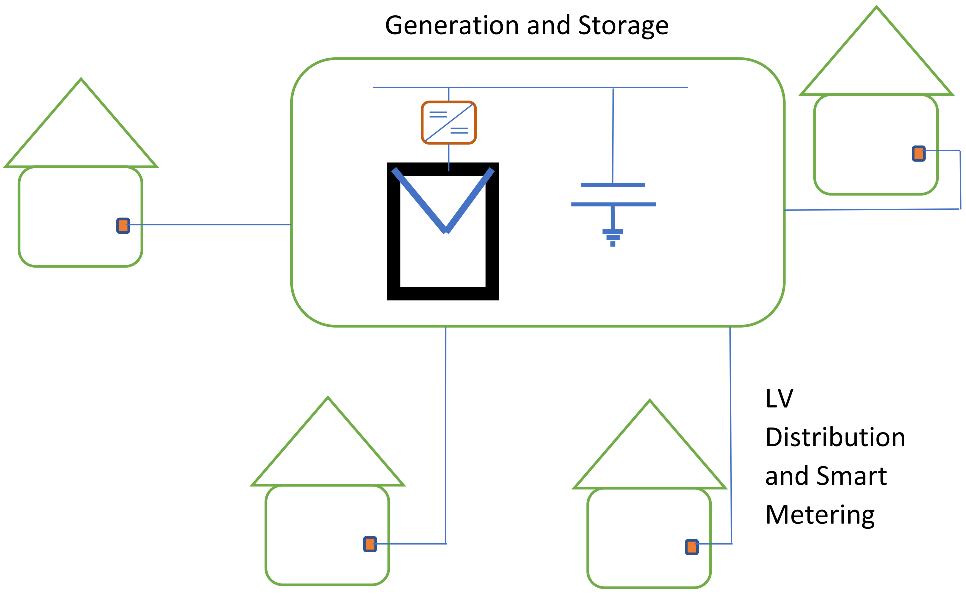

Figure 1-5. DC Hub-and-Spoke Microgrid Configuration

In comparison to SHSs, microgrids expenditure costs are higher, primarily due to the installation of the distribution system required for each household. According to MeshPower, supplying households with basic lighting and phone charging appliances, the distribution network can reach around 60% of the total system expenditure cost [40]. This proportion might change while scaling-up demand for electricity. As a result, the distribution network can remain in place whereas power generation and storage capabilities are required to be upgraded.

Sources for electricity generation within microgrids highly depend on resources available in the location. In most Sub-Saharan Africa countries, solar generation based microgrids are becoming dominant mainly due to favorable solar resources. Hydro and wind generation is preferable in Developing Asia mainly within AC microgrids, primarily in Nepal, Bhutan whereas systems producing electricity using fossil fuels are predominant in countries where price for diesel is particularly low, such as Myanmar or Nigeria [41], [42], [43].

According to various microgrid providers in SSA, the successful deployment of microgrids needs to be supported by appropriate policy and regulations. This prevents microgrid operators from competing against grid electricity and other off-grid providers. Lack of regulations and relatively long payback period from the microgrid system (in comparison to SHSs) limits investors attractiveness in this sector of off-grid sector leaving millions of people without opportunities to consume electricity capable of being supported by microgrids [44], [45].

1.4. Solar Kiosks

Solar kiosks are comprised of PV modules and often energy storage devices. Such configuration is primarily designed to support local entrepreneurs. Electricity produced by solar kiosks is normally used to charge mobile phones on-site, charge mini solar lanterns or even sell cold drinks. As a result, the installed capacity of the solar kiosks can vary from one to another [46], [47].

Figure 1-6. Solar Kiosk offering Mobile Phone Top Up as well as Wi-Fi Hotspot [Source: The African Exponent, Accessed: 11-Feb-2022]

1.5. Growing Market for Off-Grid Solution

It is estimated that for over 60% of people currently without access to electricity, off-grid systems are optimal solutions to match basic demand requirements [48]. This primarily involves microgrids (34%) as well as SHSs (29%). Evidence suggests that demand for stand-alone SHSs has been rapidly growing over the past 10 years, as indicated in Figure 1-7 distinguishing pico-solar (up to 20W generation capacity) and plug-and-play SHS progress in sales (in thousands of units sold). It also proves trends where the contribution of SHSs to other solutions on the market is steadily increasing. This could be primarily resulting from falling costs of bigger solar modules which make bigger and more reliable systems more affordable for many residents across Sub-Saharan Africa and Developing Asia. As a result, future demand for electricity within the off-grid environment is expected to grow opening new opportunities for this electrification sector across the Global South.

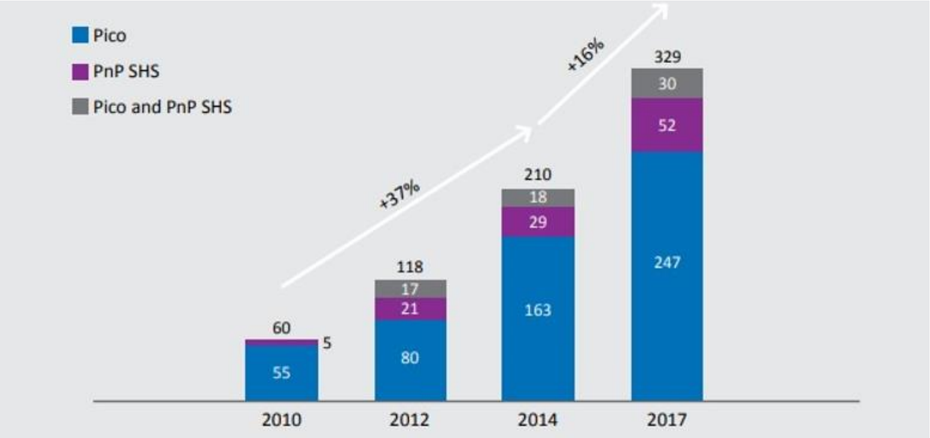

Figure 1-7. Market Share between SHSs and Pico-PV (in thousands)

1.6. Benefits of Off-Grid Solutions and its Future Opportunities

Figure 1-2 presenting the relationship between energy consumption and HDI indicates that introduction of low electricity rates (illustrated as purple dots as countries with Very Low

Quality of Life) can significantly improve overall wellbeing within communities/households with no previous access to electrical energy. It is evident that a very modest amount of electricity can be effectively provided by low-cost standalone small scale solar installations including SHSs and microgrids supplying electricity mainly for lighting and phone charging. Some of the main reasons why off-grid solar based solutions are becoming prevalent across the Global South are associated with the declining trend in costs of solar modules, as presented in Figure 1-8 [49]. These rates have reached an affordable level for many of those living below the global poverty level of 1.90$/day. Furthermore, prices of lithium-ion batteries (with 80% of usable capacity) are rapidly declining too. Based on forecasts available, costs of such technologies is estimated to drop from approximately 300US$/kWh in 2018 to 62US$/kWh by 2030 which will further introduce positive impact on off-grid electrification sector currently mostly relying on lead-acid systems (with usable capacity of 50%) for electricity storage [50], [51].

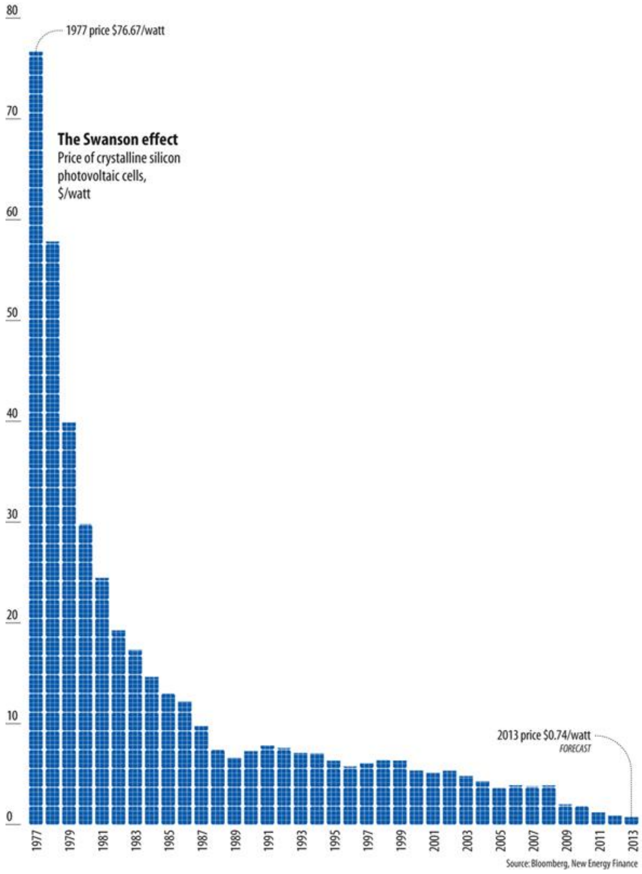

Figure 1-8. Falling Costs of PV modules across 1977-2013. Data in US$/Watt.

Off-grid renewable systems despite being very efficient in improving the life quality of millions of people around the globe have also presented high resiliency in supporting access to electricity in regions frequently affected by natural disasters (hurricanes, floods, etc.). This is a result of simplicity in the SHS/microgrid design which does not require medium or high voltage transmission infrastructure and where the power supply can be disconnected instantaneously, as requested by the operator. Such systems providing electricity for the whole village can be shut down few hours before the hurricane (just like it applies for Sigora in Haiti) to reduce a risk of facilities destruction (i.e. solar PV modules). The system can be restored soon after conditions improve, even a few hours later [52]. This flexibility in operation and resulting in higher reliability of power supply than national grid make off-grid systems repeatedly preferable over the main grid in various location across the Global South – according to Frank Bergh from Sigora [53].

The range of services provided by off-grid installations can vary and is typically limited by the financial capacity to purchase new appliances for each family powered by SHS or a microgrid. Some providers (like BBOXX[2]) do not permit customers to use other appliances than provided by the operator since they can overstress the system reducing its overall life cycle. After the connection of other appliances than provided by BBOXX, SHS can disconnect users from the electricity supply.

The basic appliances provided within the standard 50W SHS set include lighting and phone charging and are offered by BBOXX for approximately $5-$5.50/month for 36 months – according to Christopher Baker-Brian, CEO of BBOXX. Other SHS of different specification (than basic systems) and generation capacities of 250W can support enough energy to drive fridges, fans or TVs. Such systems are occasionally installed by BBOXX in

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[2] www.bboxx.com

eastern regions of Democratic Republic of Congo (DRC) within families capable to cover the cost of $100/month for such product.

To categorise the quality of energy access, ESMAP (Energy Network Management Assistance Program) has developed a multi-tiered which defines ascending tiers of energy access (0–7) based on capacity, duration reliability, quality, affordability and more. Such classification is presented in Table 1-1. Tier 0 represents customers with no electricity access, while higher-level tiers represent the levels of energy access generally associated with a reliable grid connection [54].

Table 1-1. Multi-tier Framework for Energy Access

TIER NUMBER	APPLIANCES	ENERGY PER DAY (WH)
0	No Electricity	0
1	Lighting + Phone Charging	12
2	Radio, TV, Fans	200
3	Refrigeration	1000
4	Access to Clean Water	3400
5	Productive Use of Electricity	8200

Most off-grid electricity providers currently focus on introducing Tier 1 or Tier 2 levels of energy access. This is primarily a result of low power requirements for appliances within these tiers which can be met by a small standalone SHSs installation of 20W-50W. Total investment cost in such system is expected to be significantly lower for technology capable to supply Tier 3 appliances which normally requires a generation module of approximately 200W, as seen in Figure 1-9 giving an understanding of the biggest off-grid market providers in Sub-Saharan Africa, appliances offered, and sizes of solar installations provided by each of them [55].

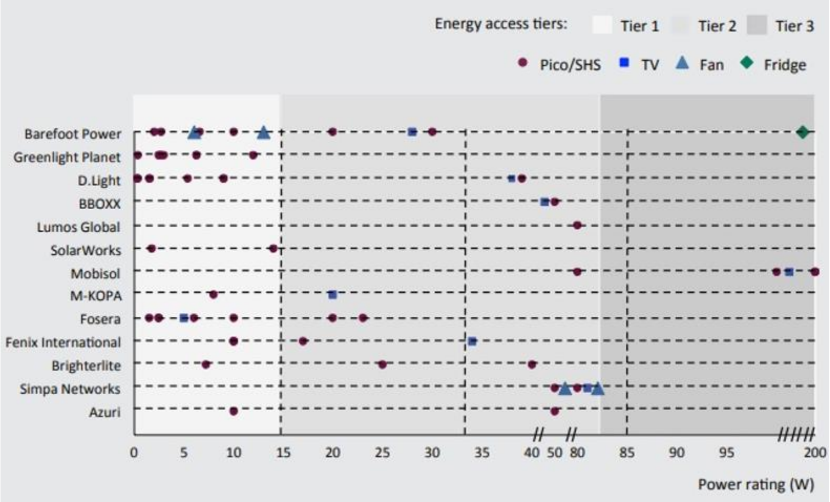

Figure 1-9. Companies Providing Off-grid Solutions on a Household level in Sub-Saharan Africa

1.7. Proposed Bottom-Up Electrification Concept

While off-grid solutions have proven to be an effective and agile means of delivering basic energy access, it can be challenging to reinforce, and upgrade generation and storage capacities associated with these systems, to accommodate the future growth in demand. Connecting a new range of appliances such as fridges or TVs could drain battery charge quickly, leaving users with the highly unreliable system, not capable to provide enough energy even lighting and phone charging anymore. Consequently, communities can become effectively “locked into” these lower tiers of basic energy access with no prospects to scale it up.

Innovation that addresses these issues is presented in this thesis. The new electrification concept considers the role of standalone off-grid systems in delivering cost efficient and scalable energy access solutions. Interconnection of households with solar installations to form a microgrid of connected prosumers and consumers is a solution that, by employing Smart Power Management (SPM) of the power distribution amongst connected households enabling microtransactions for energy exchange and business models, has the potential to balance supply and demand within the newly established microgrid, offering consumers more affordable energy, and energy providers a greater return on their investment.

The concept of bottom-up electrification could provide a smooth multitier energy access transition allowing people with basic access to electricity to scale up their demand without covering the significant upfront cost. Instead of that, the energy produced by other prosumers (power producers and consumers) in the village could be utilized by appliances currently not available within stand-alone installations.

Most households connected to the proposed microgrid are equipped with a PV module, a battery, and a charge controller. Battery storage capacity in such configuration is required to ensure an electrical supply is available in the evenings when zero solar resources exist for generation, and to offer days of autonomy during prolonged periods of the low solar resource. However, an interconnected SHS microgrid arrangement gives users the flexibility to import and export energy and maximize the available pooled storage (and generation) capacity. The proposed concept of bottom-up electrification in the Developing World is illustrated in Figure 1-10.

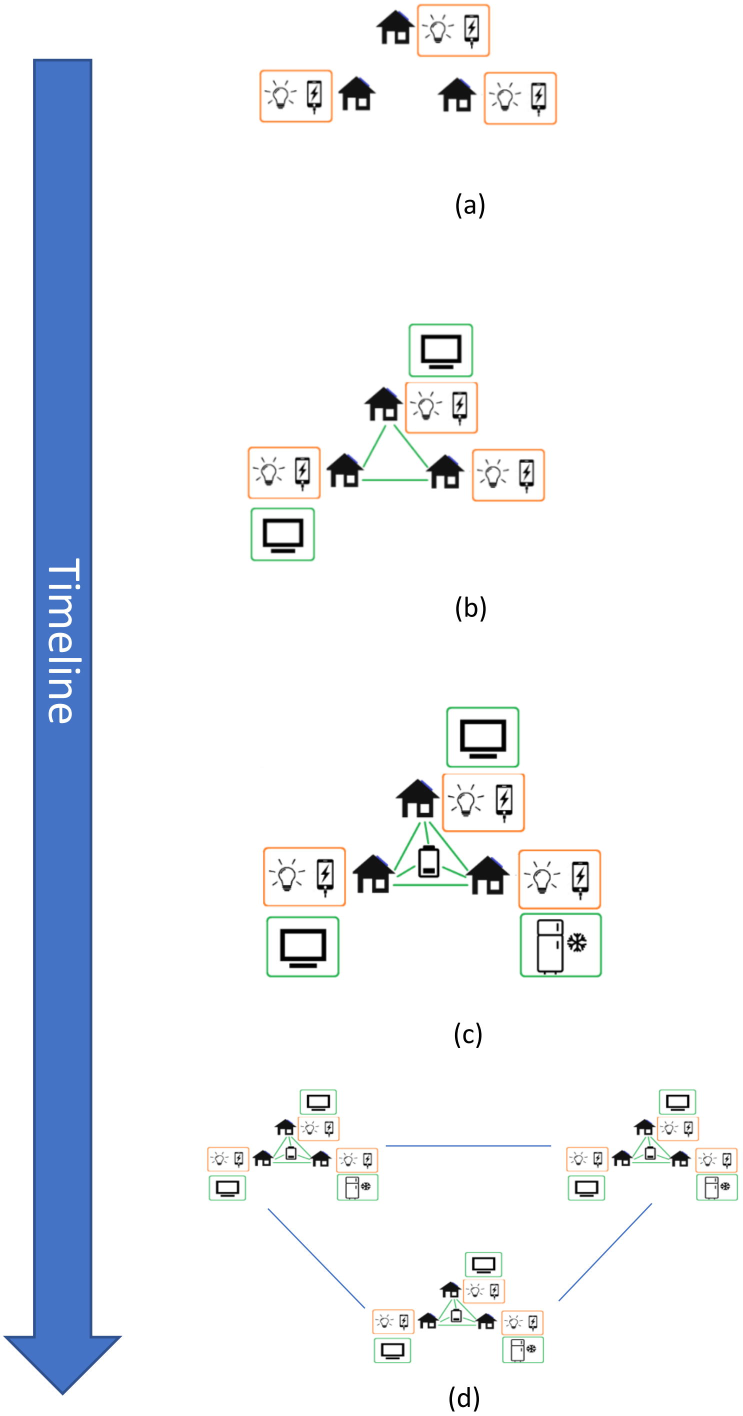

Figure 1-10. (a): Basic access to electricity provided by standalone SHSs. (b): Microgrid arrangement provided by interconnecting SHSs. (c): Improved access to electricity provided by adding centralized storage within a microgrid of interconnected SHSs. (d): Improved access to currently available appliances by interconnecting microgrids.

Figure 1-10 (b) shows how it is possible to interconnect existing households with electricity generation and storage capabilities to bring all the benefits of a local energy network (and more) to a community, without the need for additional installed PV modules or batteries. Therefore, at the cost of interconnecting cables and the SPM platform introduced in this thesis and with enough off-grid installations in the region, customers can ascend the energy access ladder using the same SHS assets already installed on-the-ground. Figure 1-10 (c) shows how the addition of some centralized storage and generation could then be incorporated to deliver energy access for loads of higher demand, while Figure 1-10 (d) shows improved levels of the off-grid infrastructure potentially being achieved through the interconnection of microgrids.

According to a Global Off-grid Lighting Associating (GOGLA) report from 2018, the rural poor may initially gain energy access through the introduction of pico-PV products (e.g., solar lanterns, mobile phone chargers). Over time, as people become familiar with these basic appliances, they may invest in an SHS, which will enable a better, though still basic, level of energy access (lighting and phone charging). Achieving energy access levels beyond basic lighting and phone charging, capable of powering higher-power appliances such as TVs or refrigerators, will require people to often switch to systems with higher capacity, replacing old solar installations for new once.

To date, these kinds of transitions are capital intensive, as they require substantial costs to be covered for new generation and storage, as well as the purchase of new higher power appliances. Interconnecting these existing SHS assets represents a new approach to accommodating higher power appliances and increasing energy access levels without the need for the addition of expensive generation and storage capacity. Instead, this approach utilizes electrical energy that is currently wasted by distributed stand-alone SHSs across a village to connect users with a willingness to add new electrical devices. This energy (quantified in Chapter 3 of this thesis) effectively substitutes new capacity that would need to be added within the off-grid village, which contributes to the highest portion of the system overall. Such a concept could reduce investment costs in upgrading existing off-grid assets and could provide a smooth and affordable transition to meet growing electric demand.

Through simulation and analysis, this thesis evidences the step-change in energy access introduced to communities (with pre-existing SHSs), through the bottom-up transition from the configuration shown in Figure 1-10 (a) to that of Figure1-10 (b). The proposal also uses this evidence to define the principal requirements for the operation of a Smart Power Management (SPM) platform required to facilitate and enable this transition. Providing such a platform introduces a component to the interconnection off-grid systems that are required for scalable, bottom-up electrification which can sustainably, efficiently, and flexibly meet the growth in customer demand that inevitably evolves in these rural communities.

1.8. Interconnected SHSs Microgrids - Review

The concept of interconnected SHSs has initially been introduced in Bangladesh by Solshare, where SHSs have been interconnected to form local energy networks relying on 12V DC distribution systems [56], [57] . By January 2020 the company had already 20 microgrids deployed in the field. The main reasons for selecting Bangladesh as a place to initiate the installation of interconnected SHSs by Solshare primarily results from successful off-grid electrification programs launched in 2010. As such, over 5.5 million individual SHSs have been installed to date [58]. This, together with a high population density makes Bangladesh a great location for bottom-up electrification hub.

The proposed technical solution developed by Solshare, although being already in the field in multiple villages, presents significant technical limitations and difficulties with adoption to the African context where most PAYGO solar companies operate and where rapid deployment of SHSs has been observed in recent years. Moreover, studies performed in Bangladesh do not indicate socio-economic opportunities and benefits which bottom-up transition can provide amongst rural communities. Detailed analysis presented in this thesis addresses these gaps and focuses on technical development of a controller providing bottom-up transition in SSA. Research validates essential functions of the novel Smart Power Management system providing capabilities to establish microgrids with functionality to integrate various SHSs models currently available on the African market.

1.8.1. Capabilities and Potential for Interconnected SHSs deployed in Sub-Saharan Africa

As it stands, SHSs' specification (generation capabilities and electric appliances connected), as well as business models supporting their deployment are fundamentally different in Bangladesh where Solshare operates and in SSA. Furthermore, typical village topographies in each of these regions are distinct which may have a strong impact on the successful deployment of interconnected SHSs microgrids and can influence design of technology used to develop interconnections. Feasibility studies for interconnected SHSs installations available to date and revealed by Solshare are primarily based on high level demand assessment in Bangladesh and do not cover details on how the proposed bottom-up electrification concept can transform access to communities across the SSA [59]. Although existing studies indicate that the overall reliability of power supply in the microgrid of interconnected SHSs could improve, further research with significantly more comprehensive analysis based on telemetry records for a wide group of prosumers has been presented in this thesis. Such assessment (performed in Chapter 3) gives a greater understanding of the future potential for a bottom-up transition and capabilities of such a concept to support new range of electric appliances to provide a scalable path within the multitier framework.

1.8.2. Selection of Appropriate Power Converters providing Bottom-Up Electrification

Most SHSs currently deployed in Sub-Saharan Africa and Developing Asia are based on 12V battery systems [60]. Providing interconnections between households at this voltage can be effectively achieved only within communities where population densities are particularly high and distances between households are low [61]. Simultaneously, maximum power transfers over such networks are strictly limited and providing electricity supply for new high-power appliances (like fridges or TVs) can be difficult and might introduce significant losses associated with power distribution in the microgrid [62]. As a result, introduction of appropriate power converters between SHSs and microgrid is required. Consequently, development of appropriate power converters arrangement is required to be proposed on each household level, together with suitable control architecture to match power supply and existing demand.

1.8.3. Smart Power Management (SPM) Design

Existing technologies providing interconnections between SHSs are not equipped with appropriate smart power management optimising performance of the batteries within existing microgrids. As a result, by introducing direct interconnections between 12V batteries at each household level, some SHSs within proximity to high-power devices can experience blackouts sooner than other SHSs which maintain electricity surplus. Designing appropriate SPM which keeps equilibrium between the state of charge (SoC) of each energy storage within the network can significantly extend their overall life-duration and maximise microgrid system reliability [63]. As a result, a new architecture for an SPM is required to be introduced which gives capabilities to adapt a new range of high-power appliances without exceeding the technical constraints of existing SHSs. Such technical solutions need to have the potential to be developed using low-cost electronics to support people living below the worlds' poverty levels with the very low financial capacity to scale up their demand.

1.8.4. Adoption to Existing SHSs in Sub-Saharan Africa

Establishing interconnected SHSs networks introduced by Solshare requires removal of the existing charge controller to adapt Solbox – device providing electricity exchange between neighboring SHSs. As a result, deployment of a new microgrid requires appropriate technical knowledge of SHSs technology to rewire the system. Such a solution, although being successfully adapted in Bangladesh, does not give capabilities to interconnect SHSs in most regions of SSA. This is primarily due to fundamental differences between SHSs deployed in Africa and those in Bangladesh. As it stands, solar installations supported by Solbox consists of a photovoltaic panel, batteries and charge controllers purchased separately by the user on the local market [64]. As such, it is possible to modify configuration of the existing infrastructure and rewire it to adapt Solbox. Such a transition from standalone SHSs to a network of interconnected SHSs is not possible in SSA. All SHSs PAYGO providers on the African market distribute fully integrated technologies without capabilities of being reconfigurable. Replacement of existing charge controller to adapt Solbox is not feasible since each attempt to open SHSs enclosure containing battery, charge controller and remote monitoring (RM) unit leads to SHS being deactivated from use [65]. As a result, the existing approach (developed by Solshare) to interconnect SHSs in the African context would not succeed and new technical solutions to bypass existing SHS control architecture are required.

1.8.5. Adoption of Interconnected SHSs Networks in SSA

Once appropriate technology to interconnect SHSs is revealed, it is important to present its capabilities while working in field and quantify impact on local communities introduced by new range of high-power appliances adapted in rural SSA. These non-technical research outcomes can be fundamental while developing appropriate policy to stimulate growth of interconnected SHSs microgrids in the future [66]. Results presented in this thesis give major outcomes of based on interviews with users relying on interconnected SHSs for two weeks. The principal opportunities as well as barriers faced by such bottom-up transition are indicated in this thesis. These ultimately present a new scope for further deployment of interconnected SHSs microgrids.

1.9. Summary of the Chapter

Introduction of clean and reliable access to electrical energy by introducing small scale (primarily) solar-based solutions has a life-changing effect on millions of people residing across SSA and Developing Asia. Although such technologies are effective in providing basic access to electricity (primarily lighting and phone charging) issues remain with their long-term sustainability and lack of capabilities to scale-up demand step-by-step. To face some of these challenges, appropriate solution has been proposed by Solshare in Bangladesh. Such systems which have successfully interconnected some SHSs in Asia, present low capabilities for adoption to the SSA market where SHSs specification is fundamentally different from one introduced in Bangladesh. As a result, alternative methods of introducing a bottom-up electrification transition are required. To develop them, appropriate methodology assessing feasibility for the first stage of bottom-up electrification has been proposed and is introduced in Chapter 2. Execution of the methodology to obtain optimal architecture of interconnected SHSs microgrids in SSA is revealed in the following chapters in this thesis.

2. Methodology for Assessing the Initial Stages of a Bottom-Up Electrification Transition

Bottom-Up electrification has the potential to become an innovative electrification paradigm supporting increased rates of electricity access and a new range of electrical loads within off-grid villages. Challenges associated with the introduction of such a concept are multidimensional and require interaction between engineers and policymakers as well as local stakeholders understanding the socio-economic implications associated with deploying new off-grid solutions within rural communities.

This thesis presents a methodology to assess the feasibility for the first stage of bottom-up electrification (transition from “standalone SHSs” Figure 1-10 (a) to “interconnected SHSs” Figure 1-10 (b)), focusing on the off-grid sector in SSA. The key stages of this methodology are summarized in Figure 2-1.

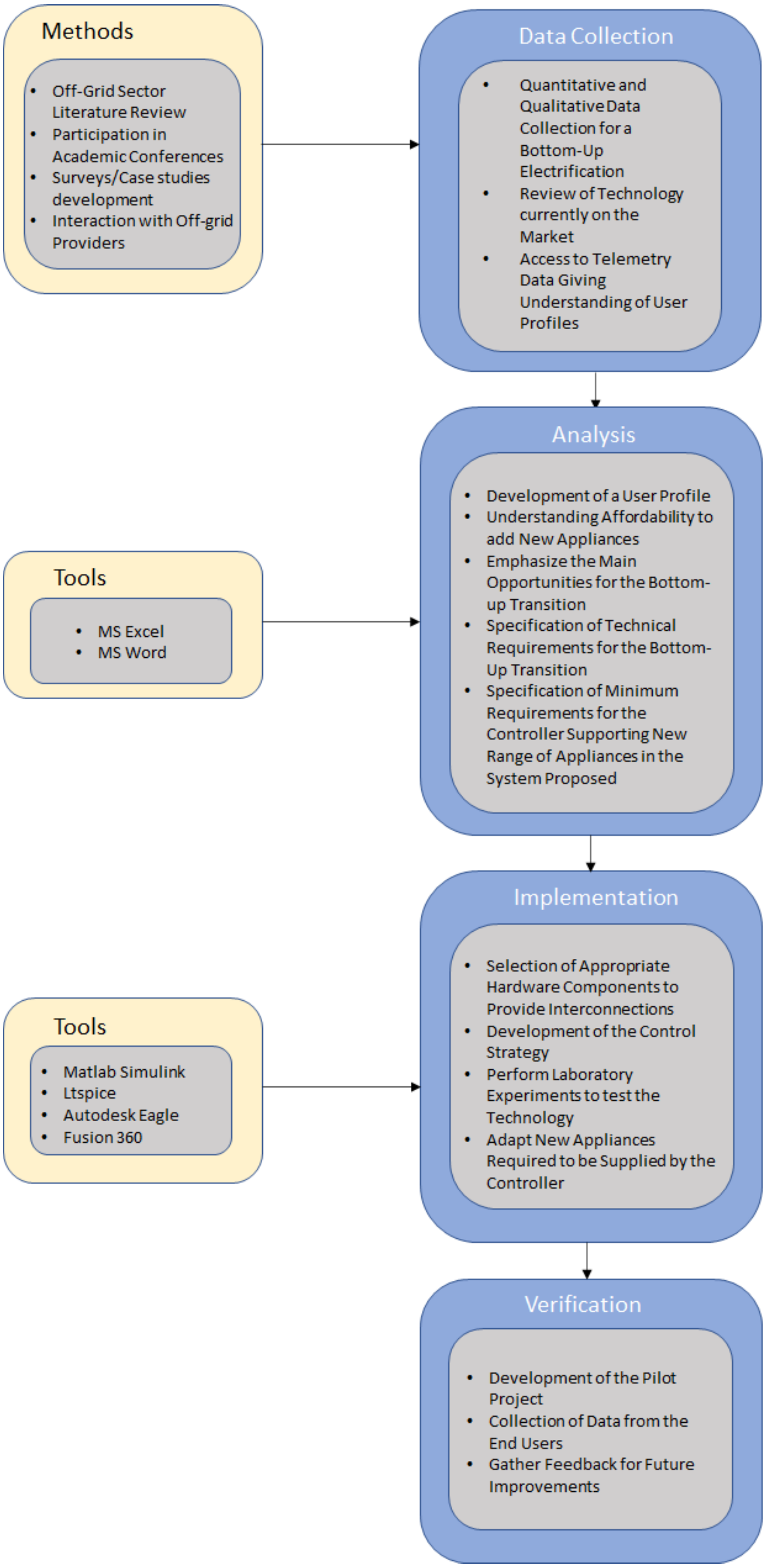

Figure 2-1. Methodology Applied for introduction of the First Stage of the Bottom-Up Transition

Figure 2-1, shows the methodology divided into four stages: Data Collection, Analysis, Implementation and Verification. Each stage involves the use of certain tools and methods, which are shown as inputs.

2.1. Data Collection to Indicate Viability of the Bottom-Up Transition

The first step required to assess the feasibility of a bottom-up electrification paradigm considers a detailed understanding of the off-grid market within a specific region. Stand-alone energy systems have the potential to become low-cost solutions supplying basic lighting and phone charging in the vast majority of African and Asian countries. Differences in their technical specification can vary from one site to another [67]. Design features typically depend on the ability to pay for electricity amongst users, their understanding of benefits resulting from energy access, types of activities conducted in the village, etc. As such, it is crucial to perform a detailed analysis of the user profile, their willingness and ability to accept and adapt to using new electrical devices as well as an assessment of appliances available on the market before initiating technical modelling of the controller providing interconnections. As a result, the recommended steps used to gather adequate information on the off-grid energy sector involved an extensive academic review of this specific area of energy access. Following such background studies, it is necessary to also interact with the local stakeholders involved in the deployment of off-grid energy systems. This can further support the gathering of fundamental qualitative and quantitative data to indicate the potential for scaling-up demand amongst prosumers after providing interconnections.

2.1.1. Engaging with off-grid sector and practitioner community

The off-grid research and practitioner community has focused much of its attention on the challenges of increasing energy access in rural regions across the Global South [68], [69]. This effort has resulted in increasing availability of qualitative and quantitative data being gathered from case studies conducted in various regions of Sub-Saharan Africa and Developing Asia where the potential for off-grid systems is particularly high. Continued collaboration and interaction between experts in this field, builds understanding of the opportunities, challenges and barriers facing the bottom-up electrification paradigm across the Global South. Building these networks and engaging in discussions with researchers and practitioners has been vital in conducting the studies and fieldwork presented in this thesis.

2.1.2. Partnering with local stakeholders

To introduce microgrids by interconnecting off-grid SHSs it is recommended to cooperate with in-country stakeholders who have successfully provided basic access to electricity in a region by distributing stand-alone systems (Figure 1-10 (a)). Such interaction maximizes the chances of understanding the main opportunities and barriers faced by the off-grid sector as well as appropriate business models. Furthermore, this engagement is key to identifying where the potential for bottom-up electrification is high in relative terms, which also requires collection of data from stakeholder interviews and surveys with potential end-users.

2.1.3. Collection of qualitative data gathered within off-grid households

Deep interaction with off-grid communities is crucial to understand the range of appliances that may be required or desired, but which cannot be supported by systems currently in the field. As such, a set of surveys were developed to gain an understanding of their willingness to accept and use new devices and the level of demand for these. This market assessment for new electrical devices, is a key part in assessing the feasibility of the first transition stage of bottom-up electrification. This also ultimately results in optimizing the specification of the controller which provides interconnections between SHSs supporting a new range of appliances at a minimum cost to maintain ensure these systems remain affordable for families residing in rural regions of the developing world.

2.1.4. Collection of quantitative data on off-grid electrification

This set of data was accessed after obtaining permission from the local off-grid providers which maintain remote monitoring of assets deployed in the field. Technical data gives information on typical electricity consumption patterns within households currently relying on stand-alone installations, supplying electricity for lighting and phone charging (i.e. baseload). Access to quantitative data gives further understanding of the potential to introduce new, high-power devices within off-grid communities by utilizing the energy surplus from PV generation that would otherwise go to waste. Further analysis provides an understanding of the relationship between the quantity of new appliances introduced within the community and the reliability of power supply within a network of strictly limited generation and storage capacities as a form of SHSs.

2.2. Analysis of Data Gathered

Once adequate qualitative and quantitative data is gathered, appropriate numerical analysis presenting feasibility for the interconnections can be conducted. This can be provided with the support of MS Excel. Based on available data, various benefits resulting from the introduction of bottom-up electrification could be identified and highlighted to supports further development of the bottom-up electrification concept. The outcomes of the analysis emphasize a wide range of social and technical prospects resulting from the interconnection of SHSs, which can ultimately provide life-changing opportunities for millions of people currently relying on SHSs. Compiled data can also be used to conduct a market assessment for new higher-powered appliances that can be supported by interconnecting SHSs. Furthermore, deep analysis of market for electrical appliances can inform the rating of a Smart Power Management (SPM) controller required as a technology enabler for the first transition stage of bottom-up electrification [70]. Such a system is required to operate by utilizing existing infrastructure without exceeding its design limitations. In addition, a full list of all technical constraints, which had to be met and respected were defined to ensure safe operation of the system and SPM enabling electricity exchange.

2.3. Implementation of the System Enabling the First Transition Stage of the Bottom-Up Electrification

Once the appropriate technical specification of the system providing interconnections between prosumers and consumers is obtained by analyzing existing off-grid users, technical modelling of the controller was conducted. This stage requires a deep understanding of the power converter's functionality as well as the control system designed to drive them. To model the SPM performance, Matlab Simulink[3] software was used. It indicates stability performance within a network after providing the appropriate control algorithms. Following tests of the control system, minimum hardware requirements can be specified and tested in LTspice[4] to

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[3] www.uk.mathworks.com

[4] www.analog.com/en/index.html

verify whether each component within the power converters can operate safely, without exceeding maximum technical limitations.

Further work included the design of the prototype system enabling this bottom-up transition. As such, several iterations of the hardware design were required to optimize each hardware element of the SPM including gate drive and power converter itself. Modelling of the system required various types of software to design printed circuit boards (PCBs). Autodesk Eagle[5] was used which is presents a well-developed interface with the Fusion 360 used to design the enclosure of the final product used for fieldwork. That stage of the research was used to verify the approach of providing a bottom-up transition in a selected rural community.

2.4. Verification of the Results

After successful production of the prototypes, it was required to test the system amongst several prosumers to understand the potential for the proposed bottom-up transition. It was therefore necessary to monitor such a community for a certain period to understand how a new range of appliances would be utilized within the network and what kind of productive use of electricity activities could be stimulated. In addition to informing the technical specification of the system, this understanding provided further indications of the potential for the bottom-up transition in these rural regions to improve quality of life and act as some socio-economic stimulus for these communities.

After running field tests with the prototype of the controller it was necessary to interact directly with the target community. As such, it was possible to gain appropriate feedback which could be used for further optimization of the system. Results gathered from the

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[5] https://www.autodesk.co.uk/

fieldwork also indicate new income generating activities within the community which could become fundamental in future tariff development in rural communities making use of the proposed bottom-up transition.

2.5. Methodology Applied for Bottom-Up Transition in Rwanda

Due to the novelty of the bottom-up electrification concept and therefore relatively limited information available about such a transition in SSA, outcomes presented in this thesis are supplemented by results gathered from numerous case studies focusing on off-grid rural villages considered to have a significant potential for this bottom-up approach to electrification, mainly due to already exhibiting a relatively high penetration of off-grid standalone SHS installations. Feasibility studies on villages were conducted to identify such case studies. These feasibility studies were fundamental in enabling modelling of the SPM technology providing the first transition stage of bottom-up electrification. Furthermore, a wide range of case studies performed during fieldwork resulted in a deeper understanding of the off-grid energy sector in the regions investigated, which ultimately led to the successful development of the first pilot project introducing this approach to interconnecting SHSs to the continent.

Field studies were primarily focused on the energy market in Rwanda – a country with a relatively well developed off-grid sector where several University of Strathclyde project partners have deployed high quantities of off-grid installations over the past five years.

The analysis presented in this thesis began with the introduction of a typical user profile currently relying on stand-alone off-grid installations. The assessment provides fundamental information indicating overall aspirations to scale-up future demand among those with basic access to electricity. This investigation was conducted with the support of companies operating in Rwanda within the scope of off-grid electrification - BBOXX, MeshPower and Rwanda Energy Group (REG)[6]. The principal outcomes aimed to maximize understanding of the potential for bottom-up electrification, highlight challenges with the introduction of this paradigm as well as providing an indication of acceptance levels associated with this transition amongst prospective low energy access and low-income household consumers.

Feasibility studies conducted in Rwanda were also supported by a wide range of analysis based on telemetry data (accessed with support of BBOXX) representing power consumption profiles of users currently supplied by off-grid systems. Such analysis evidences opportunities for the provision of new, additional electrical load, involving a range of new appliances and new income generation activities within rural communities. This can be achieved by utilizing surplus generated electricity which normally would go to waste, and so minimizing the need for additional installed generation or storage capacity in the system to meet this new higher level of demand.

Field surveys were conducted with off-grid practitioners and communities to gain an understanding of SHS users, their consumption patterns, willingness to share electricity within the local community network and broad knowledge of appliance specifications. This was a fundamental requirement for the development of an appropriately rated SPM technology, capable of accommodating new higher-power devices within these off-grid communities, including new TV sets within a household; or refrigeration devices (identified as the most desired appliances), such as those designed by Embraco[7] - a leader in refrigeration technologies supporting research.

The functionality of the SPM algorithm was primarily verified with the support of technical models primarily developed in Matlab Simulink which emulated all functions to ensure stable

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[6] www.reg.rw

[7] www.embraco.com

operation of a newly formed network utilizing these new controllers enabling bi-directional power-flow and exchange. Once the SPM functionality had been emulated in Simulink, a final control algorithm to maintain optimal power flows was deployed onto a microcontroller to perform lab tests using the University of Strathclyde facilities. This stage of project implementation was supported by numerous Code Generation tools available in Simulink enabling rapid prototyping of the final product, which became known as the “Energy Box”. This plug-and-play technology is the key tangible outcome of the research presented in this thesis. It has been designed with an interface capable of enabling the exchange of electricity between households equipped with electricity generation and storage to form a distributed and meshed low voltage (LV) microgrid network of interconnected SHSs. A key aspect of this electricity exchange is the ability of the controller to control power flows bi-directionally from the existing off-grid household (prosumers on export mode) to support new high-power appliances (prosumers or consumers on import mode).

After completing lab tests and assembling eight controllers with SPM functionality, the first demo project introducing bottom-up transition was established in Murambi Village, Northern Province of Rwanda. The system was deployed mainly to validate the technical capabilities of this novel controller and to verify the feasibility for increased demand through adoption of new higher-powered loads, without reducing the reliability of SHSs which were already in the field. Results from the field tests then offered final practical validation of the functionality implemented within the Energy Box technology. This stage of the research also indicated significant non-technical challenges while deploying Energy Boxes such as promoting and raising awareness amongst the communities of the new electric devices and the opportunities they presented, to stimulate demand. This has been accomplished based on a wide range of surveys conducted with the microgrid users. It primarily focuses on presenting customers interactions with the new technology as well as opportunities arising from the introduction of such microgrids.

2.7. Structure of the Research

This thesis has been divided into seven chapters. The first two introduce the concept of rural, off-grid electrification; current trends and solutions providing basic access to electricity, their limitations as well as methodology to provide the first stage of a bottom-up electrification.

Chapter 3 gives a fundamental understanding of SHSs users' power consumption profiles. This part is primarily based on the research conducted during the first visit to Rwanda. It introduces outcomes gathered from locations where project partners are the most prevalent off-grid providers. Studies also indicate overall aspirations to scale up the electrical demand by those who are currently supplied by off-grid systems. The results gathered and presented in Chapter 3 were produced with the support of Dr. Scott Strachan (University of Strathclyde) as well as the BBOXX team in Rwanda – primarily Iwona Bisaga and Amaury Fastenakels.

Chapter 4 gives an understanding of technical aspects of the off-grid systems currently deployed in rural regions of Sub-Saharan Africa and Developing Asia. It emphasizes technical opportunities to introduce the concept of bottom-up electrification as well as presents a broad understanding of how the control system for a new microgrid with interconnected prosumers can be established.

Chapter 5 of the thesis describes SPM modelling. The analysis is supported by graphs that illustrates the technical functionality of the system providing interconnections between off-grid assets. All functions explained in the chapter were therefore deployed into the Energy Box. The work presented in Chapter 5 was strongly supported by the technical expertise of Dr. David Campos-Gaona who provided guidance while developing automatic code generation techniques to support future development of the first Energy Box prototype.

Chapter 6 of the thesis involves a description of the further case studies performed in Rwanda, including the installation of the first Energy Box pilot project. At this stage, deep involvement of Fraser Stewart (University of Strathclyde) was essential. The outcomes present successful operation of the controller providing interaction between prosumers. Surveys conducted at the ultimate stage of fieldwork indicate great interest in Energy Box technology from the local community where interconnected SHSs were initially deployed.

The final chapter of the thesis (Chapter 7) includes a summary of the research and future work to be conducted to further exploit the potential of the bottom-up electrification concept, beyond the scope included in this thesis.

2.8. Publications

Bottom-up electrification studies presented in this thesis resulted in producing the following publications:

Journals Publications:

- Soltowski B., Campos-Gaona D., Strachan S., Anaya-Lara O., „Bottom-up electrification introducing new smart grids architecture: concept based on feasibility studies in Rwanda", June 2019, in Energies, 12, 2439.
- Soltowski B., Stewart F., Strachan S., Campos-Gaona D., Anaya-Lara O., Galloway S., "A Field Trial of Smart Off-grid SHS Interconnection in Rwanda's Northern Province", Paper Under Review.

Conference Publications:

- Soltowski, B., Strachan, S., Anaya-Lara, O., Frame, D. & Dolan, M., "Using power management control to maximise energy utilisation and reliability within a microgrid of interconnected solar home systems" 19th October 2017, IEEE Global Humanitarian Technological Conference

- Soltowski, B., Bowes, J., Strachan, S. & Anaya-Lara, O., “A simulation-based evaluation of the benefits and barriers to interconnect solar home systems in East Africa” 5th Nov 2018, IEEE PowerAfrica Conference

2.9. Research Timeframe

Due to rapid development of the off-grid sector across the Global South as well as dynamic expansion of SHSs and business models supporting its development together with growing awareness of solar installations amongst millions of Africans, it is essential to present a timeframe within which bottom-up electrification studies presented in this thesis were undertaken.

This research has been conducted between October 2016 and January 2020. The first part of studies primarily focuses on identifying the feasibility for a bottom-up electrification. It was supported by data available within the remote monitoring system interfacing with all SHSs deployed in Rwanda. Results presented are based on several groups of customers located in villages with high SHSs densities who were monitored between June and September 2017.

The following part of the research included fieldwork performed in Rwanda. Such assessment presenting typical users’ profiles, typical energy consumption within SHSs together with a potential to scale up their demand was supported by three visits to Rwanda – in March 2018, May 2019 and August 2019.

Technical modeling of the system started in October 2017 and has been performed until August 2019. It involves the development of the SPM algorithms for interconnected SHSs as well as technical analysis of the power control strategies which lead to assembly of the Energy Box in a laboratory environment. The first eight samples of the controller were deployed in the rural off-grid villages of Africa where eight households were making use of the system. This was carried out in August 2019.

2.10. Achievements to date

Controller for the bottom-up Electrification has been awarded on numerous occasions. The team consisting of the author of this thesis (Bartosz Soltowski), Fraser Stewart, Jonathan Bowes, Kyle Lawson and Jack Haynes working around the implementation of the Energy Box has also performed great effectiveness in gaining funding for hardware development and regular fieldwork conducted in Rwanda. This section of the chapter presents the most important achievements as well as competitions in which the University of Strathclyde team developing the Energy Box participated. All events and competitions were taking place between 2016 and 2020 when studies were undertaken.

IEEE Empower a Billion Lives

A global competition, initiated by the Institute of Electronic and Electrical Engineering (IEEE) and Georgia Tech [71]. The competition aimed to find new solutions improving access to electricity across the Global South. The competition was divided into 3 stages. First (online) required description of the technology and business model “to sell” it as well as an explanation of the social impact that this solution can introduce. Second (regional round) required a presentation of the project and demonstration of the solution. Third (final round) stage involved field testing at the selected site as well as presentation at the Global IEEE Empower a Billion Lives final in Baltimore in September 2019. The team of University of Strathclyde students (Connex Solar) reached the final stage of the competition during which field tests had to be carried out.

Kickstart Converge Challenge

Business competition aiming to identify and support start-ups in the engineering sector in Scotland [72]. This entrepreneurial challenge was divided into three stages. Connex Solar team was announced as the runners-up in the challenge out of over 150 applications in Scotland.

Iberdrola Scottish Power (ISP) Innovation Challenge

Running in 2017 at the University of Strathclyde, ISP challenge aimed to identify new technologies or business models which can have a positive impact on businesses of Iberdrola interests [73]. Project introducing interconnected SHSs networks by Connex Solar won the competition which was the key to allow further prototyping of the Energy Box system. The competition included the application phase as well as three presentation stages.

Proptech Challenge

Initiated in 2017 by Shaf Rasul, Proptech Challenge aimed to identify projects of a start-up potential emerging from the University of Strathclyde research [74]. New project ideas were required to be associated with the property industry. Connex Solar team was awarded first place in the competition. Funding was primarily used to conduct fieldwork in Rwanda as well as to sponsor summer internships for undergraduate students at the University of Strathclyde who developed the Energy Box Remote Monitoring System.

University of Strathclyde Rising Stars Programme

The start-up accelerator at the University of Strathclyde aims to support the development of projects with a potential to scale-up [75]. The Rising Stars Programme involves numerous presentations from experts in different fields guiding through the process of commercialisation.

Participation in numerous innovation competition was fundamental to fund studies in rural regions of SSA. Such fieldwork was crucial to gain a solid understanding of power prosumers currently relying on off-grid installations. The principal outcomes identified while performing research in Rwanda supplemented by the literature review on bottom-up electrification. The basic profiles of users currently relying on SHSs are presented in Chapter 3 of this thesis.

3. Challenges and Opportunities for the Off-Grid Energy Market in Rwanda

Providing reliable access to electricity for all might be a challenging task requiring understanding of techno-economic difficulties associated with deployment of energy infrastructure. Chapter 3 starts with an introduction to the most fundamental difficulties faced by the power sector in one of the countries where access to electricity is among the lowest in the world – Rwanda [76]. Analysis reveals reasons why top-down approach (installation of centralized generation, high voltage transmission and distribution) to connect millions of Rwandans is not the most efficient way of providing access to electricity and never reached majority of Rwanda residents. Studies also reveal features of alternative off-grid solutions in rural regions of the country, primarily deployed by private sector. The assessment is supported by data for various off-grid installations as well as surveys conducted with people relying on SHSs. Studies presented are also supported by numerous interviews with experts from the energy sector in Rwanda, where high growth of off-grid solar installations has been noticed in recent years [77], [78]. Although Rwanda being just one of many countries on the African continent where access to reliable grid is very limited, content presented in Chapter 3 refers to challenges experienced in majority of African countries which undergo similar difficulties.

The key challenges associated with expansion of power network infrastructure into rural Rwanda are strictly associated with significant costs needed to be covered for grid extension – estimated to around \$700-\$800 per household [77]. Consequently, for many of those who gained grid connection, costs were fully subsidized by the government. Such incentives often turn out to be the only way to introduce electricity in rural Rwanda.

To find other cost-effective ways of bringing electricity to remote areas of the country, different strategies have been implemented in the past 3-5 years. These consider introduction of off-grid systems. Such solutions have already reached over 500 thousand users in the country of 12 million citizens [79]. High reputation of off-grid systems amongst users together with a relatively small size of a country can enable Rwanda to benefit from bottom-up electrification approach. As such, interconnection of off-grid systems to improve overall system reliability could also provide smooth multi-tier transition for energy access [80].

Work presented in Chapter 3 is supported by analytical data, indicating typical power and energy consumption patterns by the end users, currently relying on stand-alone SHSs installations. Based on the assessment provided, it is presented how introducing interconnections between prosumers can benefit them in delivering more reliable access to electricity by offering new range of appliances.

Analysis also represents results of case studies conducted in off-grid regions of Rwanda by the University of Strathclyde students. Assessments are based on surveys outcomes gathered after interviewing 28 families currently making use of BBOXX SHSs. Research gave introduction to a bottom-up electrification concept within several communities as well as basic understanding of potential benefits resulting from introduction of interconnections in Rwanda.

Interviewed families could show their future ambitions to add new electrical appliances as well as preliminary feedback on the proposed solution. Field tests were undertaken between March and April 2018 in locations specifically recommended by the project partner – BBOXX, whose installation team could identify places where SHSs are particularly prevalent, and densities of SHSs are high. BBOXX has been also supporting development of the bottom-up electrification concept by offering full access to telemetry data for over 100,000 SHSs deployed in Eastern Africa. Figures were accessed by a Smart Solar Remote Monitoring system which collects data for all BBOXX SHSs deployed in field [81].

Based on the telemetry data accessed, analysis was performed indicating theoretical improvement in reliability of power supply within interconnected SHSs microgrids. Sharing demand in such network between prosumers can also introduce a positive impact on overall lifecycle of batteries– the most vulnerable elements of SHSs [82]. As a result of optimizing power flows within the interconnected SHSs networks, minimum SoC of batteries can be increased to extended duration of battery operation which ultimately reduces maintenance costs of the system.

All these studies are primarily based on BBOXX SHSs analysis. Such devices are comprised of 50W PV generation module - standard size of SHS offered by the company. The specification of 50W BBOXX SHS is presented in the Table 3-1 [83].

Table 3-1. BBOXX System Specification

PV Capacity (W)	50
Charging Method	MPPT
Battery Technology	Sealed Lead-Acid, Maintenance free
Battery Capacity (Ah)	17
Battery Voltage (V)	12
Number of 12V DC Output Ports	5
Number of 5V DC Output Ports	2
Total Maximum Current Outflow (Amp)	5
Maximum Current Outflow per 12V Terminal (Amps)	3.5

Preliminary interviews with BBOXX technicians revealed that SHSs offered by the company are significantly oversized for most of the customers and significant portion of electricity generated goes to waste. Such technical design has been selected for several reasons. Firstly, it is more convenient to produce a single size for SHSs which could be adapted to bigger group of users, including those with very basic demand as well as energy consumers with extra demand aspirations. Secondly, oversizing battery is associated with extending lifecycle of the lead-acid battery. As a result of keeping overall SoC high at 70% or more, systems can maintain sufficient capacity for longer than while discharged them down to 50% (minimum recommenced SoC for lead acid batteries) [84].

Based on data available and estimation of generation profiles for 50W solar panel at the optimal inclination angle it was assumed that a single BBOXX SHS installed in Rwanda has a capability to produce between 150 – 250 Wh/day, with an average of 202 Wh/day in locations where BBOXX SHSs are prevalent [85]. Such capacity can primarily support Tier 1 and Tier 2 electrical appliances. These are connected to one of five 12V or two 5V terminals. The full list of BBOXX appliances for a 50W SHS and their specification is presented in the Table 3-2.

Table 3-2. Appliances offered by BBOXX

Appliances Type	Power Rating (W)
LED	1.1
Phone Charger	~2
Radio	1
TV	8
Hair Clipper	2

Despite limited range of appliances offered by BBOXX, demand diversity between prosumers can become significant. Field studies reveal that some families use SHSs purely to support lighting at night, other use it for generating income by charging mobile phones or running local grocery shops. Occasionally, small TV sets are introduced within local pubs which are considered as the main meeting points within given community.

Field studies in off-grid Rwanda reveal that the basic and most prevalent version of BBOXX SHS set in Rwanda contains two LEDs as well as a phone charger. Customers have option to decide whether they are willing to buy more light bulbs or upgrade their installations by other appliances. This typically depends on their financial capabilities as well as number of people occupying given household.

3.1. Off-Grid Market in Rwanda

High costs associated with main grid expansion and its reinforcements have urged government in Rwanda to consider off-grid electrification as a viable solution providing basic access to electricity in rural regions of the country. Off-grid systems are now providing energy to hundreds of thousands of people which in overall significantly helps to achieve country’s electrification goals to provide energy access for all by 2024 [86]. Due to attractive tax incentives for “solar products” (full VAT and duties exception for PV modules, batteries and charge controllers), Rwanda became an attractive market to introduce off-grid electrification deployment [87]. As a result, since 2014, the solar installations in rural regions of the country are experiencing significant growth [88], [89].

Solar microgrids and SHSs are predominant in providing off-grid energy access in the country for multiple other reasons, including aspects related to broad access to mobile network allowing off-grid providers to communicate with assets located in rural regions without need to have any representative within the community. Information exchanged between solar installations and data centre gives understanding of consumption patterns to help off-grid systems providers in scaling-up the demand. It also improves understating of end customers to find optimal solutions for off-grid system providers such as BBOXX – the most popular SHSs distributor in Rwanda. Communication platform provided between each asset deployed in field and cloud-based software storing data allow operators to understand nature of technical problems occurring within the system. This helps to diagnose performance of the installation and identify element which do not operate appropriately and require service. According to Christopher Baker-Brian, CEO of BBOXX, SHSs can often be repaired before user notices problems with the solar panel, battery system or any other element of their installation. Such process also reduces overall maintenance costs of the system and preserves a good customer service for many of those currently relying on SHSs. All these aspects make wide communication infrastructure crucial for successful deployment of off-grid electrification projects across SSA.

Communication with off-grid assets can also support mobile money payment scheme enabling people living in rural regions to complete micro-payments with a support of systems such as MTN MoMo which is easy to use and can be supported by most mobile phones available in the country. As a result of a simple payment platform millions of Rwandans can now pay for electricity on a monthly, weekly, or even daily basis without need to travel to another village (or a city) to complete the transaction [90].

Field work also revealed that majority of people with access to electricity through off-grid systems in rural Rwanda rely on standalone SHSs rather than hub-and-spoke microgrids. The biggest microgrid operator – MeshPower, provided approximately 1500 household connections in the country. Simultaneously, the biggest SHS provider in the country – BBOXX, had installed over 40 000 SHSs between 2014 and 2018 (when first field visit was undertaken by the University of Strathclyde team). The total SHS deployment cost is lower than microgrid connection typically due to lower expenditure required for cabling. Furthermore, ad-hoc nature of SHSs makes these installations being deployed on significantly larger scale than it is in case of microgrid solutions. MeshPower networks are typically deployed in highly populated villages of around 30–40 households within 150 m from the centralised generation unit. Typical generation capacity ranges from 2 to 4 kW and is normally distributed over 48V low voltage DC (LVDC) system to provide basic lighting and phone charging. Based on analysis of BBOXX and MeshPower tariffs for lighting and phone charging it was also concluded that monthly costs of electricity access are around 30% lower for microgrid providers than while relying on microgrid system. This might be a result of two different business models introduced. Typical PAYGO contract for SHSs requires regular fees for a period of 36 months to gain full ownership of such system. Simultaneously, microgrid operators offer “electricity as a service” charging for energy consumption for as long as system operates in field.

Conversations with Iwona Bisaga, researcher conducting studies within the field of energy access at the University College London (UCL), reveal that in some rural areas of the country SHSs remain preferable solution than grid electricity. This is primarily due to higher reliability of SHSs which can serve electricity independently from the main national grid. Field work in Rwanda also indicated that off-grid solutions have been commissioned just several kilometres from the capital city of Rwanda, Kigali, where national grid connection is widely available which indicates that even in urban areas for some households reliability of supply is more important than cheap energy access (as a form of grid electricity).

Although off-grid system reliability remains significantly higher than while services provided by the national grid infrastructure, there are some electricity consumers who prefer grid energy over small scale off-grid solar installations. According to Jean Pascal Niyigena from Rwanda Energy Group (REG), there is a higher status perception associated with a household grid connection in communities that can lead to them being considered as the preferred energy access option over off-grid systems.

Field work in rural Rwanda also indicated that in some unelectrified regions basic electrical infrastructure including poles and wires within the proximity to the village was deployed. It was also observed that wires did not connect households. According to residents, lines have been installed for a few years but have never been energised. This can be a result of high costs of secondary transformers to reach the village. Further discussions with REG and literature review prove that distribution network operators tend to focus on providing adequate infrastructure primarily in highly populated areas where people also have higher capacity to pay for electricity. That way the revenues from electricity provision could be maximised, leaving many Rwandans without access to grid [91], [92].

Further in-country research was primarily conducted within locations where SHSs are prevalent and where BBOXX initiated their operations. These places were used as main reference to conduct analysis of potential to interconnect SHSs to form local community microgrid.

3.2. Typical Consumption Patterns of BBOXX Customers and their Demand Diversity affecting performance of Networks of Interconnected SHSs

As indicated in the previous chapters, introduction of interconnected SHS microgrids could create wide range of social benefits associated with improved levels of energy access which is also defined by improved levels of system reliability, that requires a more technically robust electrical distribution system. Interconnecting existing SHSs also introduces several technical benefits that serve to form a more robust energy infrastructure, and hence an improved quality and service of electric supply to connected customers. In order to fully understand and quantify potential for interconnected SHSs it is required to present statistical data, based on telemetry records gathered from systems currently in field. Such analysis can provide fundament to understand opportunities as well as barriers in providing smooth multi-tier energy transition by interconnecting SHSs. Such analysis was established by selecting numerous SHSs deployed within the same geographical region. Results of such analysis are presented in Section 3.2 and provide fundamental understanding to develop suitable SPM, as indicated in Chapters 4 and 5 of this thesis.

Based on data analysis from the BBOXX RM (Remote Monitoring) it can be concluded that generation profiles of SHSs tend to be similar across the village. The estimated rate of electricity produced per SHS per day is 202Wh. The differences may purely arise from differences of the inclination angles of the PV installations, rate of dust accumulated on the PV module as well as potential shading occurring limiting generation capabilities.

Although generation profiles remain similar for SHSs located in the same geographical region, demand can significantly vary from one user to another in the same village. These variations depend on the type of activities conducted within the household and differ based on the users' professions, number of household occupants, whether electricity is used for supporting local business etc.

Figure 3-1 presents the demand across one week for a village with seven SHSs located in a single village of Rwanda. The results were gathered from the BBOXX RM and present consumption patterns with 1-hour sample resolution.

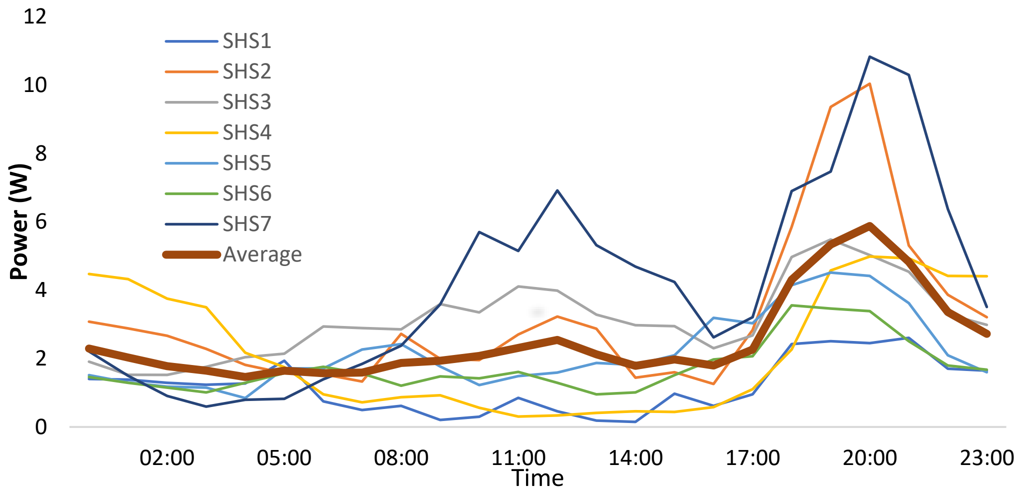

Figure 3-1. Demand Variation of seven BBOXX SHSs deployed in the Muzega Village

Figure 3-1 reveals that demand profiles indicated by dark blue and orange are significantly higher than all other in the village. This proves that by interconnecting existing SHSs and equally sharing load demand it is possible to significantly reduce maximum peak power consumption per SHS. Equal demand sharing can reduce it from 11W (dark blue) down to 6W (brown) as presented in Figure 3-1. Load sharing can also extend battery operational duration and minimize its replacements which can positively improve acceptance of SHSs within off-grid regions of SSA. Such smart battery management functionality reducing frequency of battery replacements offers clear financial benefits to SHSs distributors who typically provide warranties on their products for as long as user pays regular fees for the system.

Further studies have been conducted to estimate typical rate of energy that goes to waste within the BBOXX SHSs. This unutilized electricity could therefore be a base to provide new range of high-power appliances within the network of interconnected SHSs. According to

BBOXX recommendations, Kageyo Village (64 BBOXX SHSs deployed by January 2018) was selected as site for such case studies. The village is located in the Eastern Province of Rwanda. During the period when studies were undertaken, Kageyo village was comprised of higher number of SHSs installed than any other site in Rwanda – according to BBOXX, making it appropriate location for a bottom-up electrification research.

Data analysis of SHSs in Kageyo village primarily focuses on each SHSs’ daily demand profile which was recorded for a period of three months. Results obtained and presented in Figure 3-2 give solid understanding of typical demand variations between households. Results illustrated also give fundamental understanding of high rate of energy which currently is not utilized within BBOXX SHSs’ (out of approximately 202 Wh/day generated).

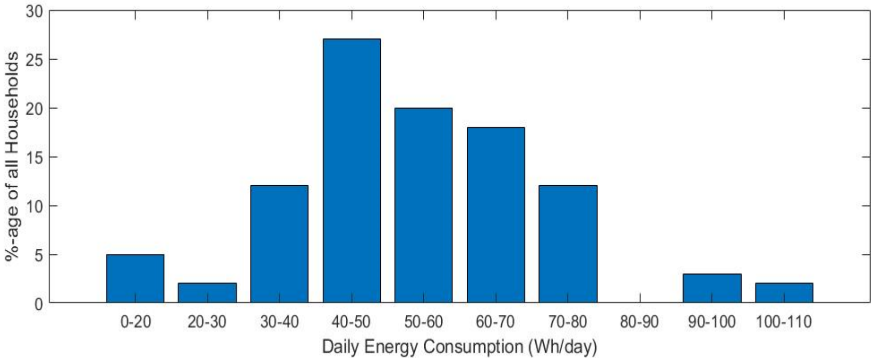

Figure 3-2. Typical Demand for Kageyo Village, Eastern Province of Rwanda

According to Figure 3-2, the majority of BBOXX customers in the Kageyo village consume between 40 and 80 Wh/day. Further analysis of demand profiles in the village indicates that around 65% of electricity is consumed directly from the energy storage, when PV generation drops (evening and night). This is primarily due to lighting systems being switched on which contributes to most significant portion of the electrical demand amongst BBOXX customers. Furthermore, some users utilize approximately 90-110 Wh/day. This is mainly a result of TV set installed within the household in addition to basic lighting and phone charging devices. Such TV unit is currently the biggest single load offered within a standard

BBOXX set (see Table 3-2). Despite its high-power consumption, total rate of energy is still below typical generated by the BBOXX SHS.

Further analysis of demand profiles for Kageyo Village was conducted to indicate potential improvements of batteries operational duration after enabling load sharing within a network of interconnected SHSs. Typical depths of discharge for SHSs users are indicated in Figure 3-3 where size of the bubble represents number of users within the group.

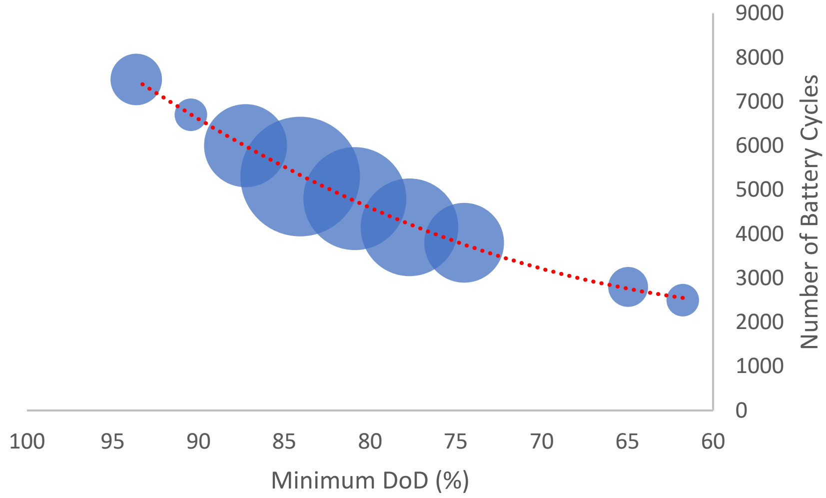

Figure 3-3. Typical Depths of Discharge (DoD) of BBOXX Customers in Kageyo Village based on 68 installations.

Figure 3-3 illustrates typical depth of discharge vs. number of operational lifecycles of the lead-acid battery (indicated by the red curve). Although realistic assessment of energy storage life-cycle duration requires detailed understanding of parameters to which such system is exposed to (i.e. temperature or humidity) data presented in Figure 3-3 and used in further analysis are purely based on the relationship between DoD and number of life-cycles, ignoring other parameters which may affect overall operational duration of the batteries [93], [94].

The lowest depths of discharge are experienced by SHSs which supply electricity for 8W 12V DC TVs - appliances with the highest power consumption within BBOXX setup. As a result, batteries within such SHSs often discharge down to 60-65% of full capacity and their overall operational lifecycle is significantly lower than it is for batteries supporting only lighting and phone charging with minimum SoC of 80-85% - evident in Kageyo Village.

Based on data indicating relationship between lead-acid battery duration and depth-of-discharge in Figure 3-3, further simulations were performed in other to estimate overall improvement of battery lifecycle within interconnected SHSs over standalone systems. Studies consider a scenario under which full demand in the village is equally shared between each SHSs. In order to present benefits of sharing load equally between all prosumers in the system, it was assumed that all systems maintain equalized SoC of the batteries and losses due to power distribution within the local network are ignored. Furthermore, to find the approximated number of operational cycles for the batteries within the interconnected SHS microgrid, total daily demand in the given community was calculated and equally divided between all SHSs. Estimated number of the battery cycles was therefore projected after extrapolating data from the curve in Figure 3-3 which gives average SoC of each SHS under the analyzed scenario. Results obtained for Kageyo Village indicate that equalizing state of charge of all SHSs could improve average number of operational cycles for each battery by approximately 200 cycles (nearly 5% in comparison to non-interconnected scenario).

Although battery life-cycle duration extension is not significant, mainly due to oversized capacity, the results can be considerably different while investigating future demand growth due to interconnections provided and electricity sharing when average minimum state-of-charge of the batteries per day drops from 80% (as it stands for a typical household in Kageyo Village) to approximately 60% of full battery capacity. Such analysis indicating benefits of interconnection while introducing new range of appliances requires estimation of future demand growth as well as understanding of usage patterns for fridges, TVs and other high-power appliances. As a result of such high number of unknowns, such analysis a subject for future investigation, not included in this research.

3.3. Introduction to Villages identified for a Bottom-Up Electrification Studies

Field studies presenting potential for a bottom-up transition in Rwanda were performed in two locations in the Northern Province and were selected by BBOXX technicians, according to wide use of SHSs. One of these villages was Ruli in Rulindo District, where around 80 households were located out of which 60 were supplied by SHSs (April 2018). Typical distances between households range from 10 to 80 m, with the majority within 30 to 50 m. It was also revealed that these distances are significantly higher than those where microgrid providers such as MeshPower deploy their systems (between 30 and 40 households within 150 m from the central point in the village).

Musega village is another location where studies were conducted. The community is divided into two population centers with five houses in the first group of households and 15 in the other. The distance between these two populations centers was around 100 m. It was observed that population densities of SHSs were much higher than it was in Ruli village. Estimated distances between households were often very short, ranging from 2 to 10 m between two neighboring homes with BBOXX installations.

Both villages (Ruli and Musega) were in the same region of the country, separated by around 5 km. The map of Rwanda representing number of SHSs over total number of residents per sector is illustrated in Figure 3-4 where red square indicates locations of Ruli and Musega villages.

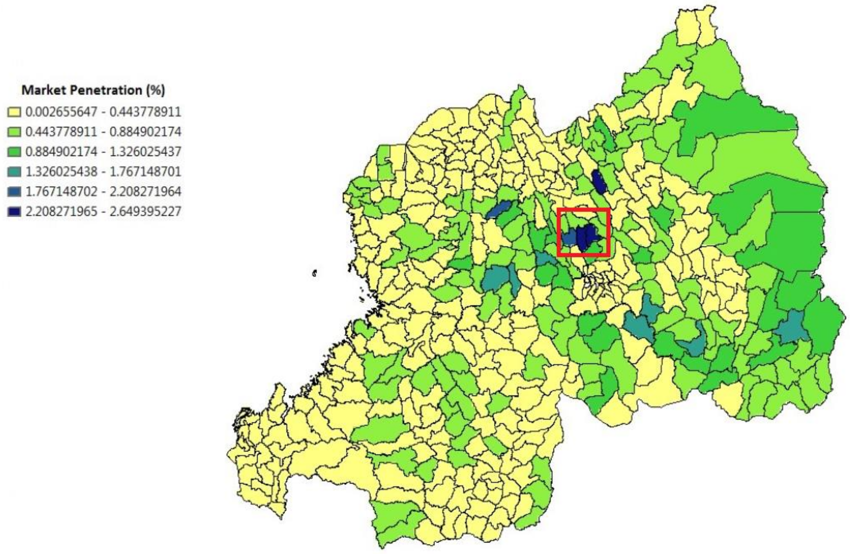

Figure 3-4. Location of the Case Studies Conducted. Yellow regions represent low rates of SHS penetration, while the green regions represent higher rates of penetration. The dark blue color symbolizes places where SHSs are widely popular. The red square on the map indicates location of the case studies conducted.

In order to determine the quality of services currently offered by SHSs, and the requirements of an SPM platform for interconnecting SHSs in off-grid Rwanda, interviews with customers relying on BBOXX installation were conducted in Ruli village (12 customers) and Musega village (16 customers). Those residing in Ruli village were mainly domestic customers with basic lighting systems and phone chargers. Households were spread across the village with no centralized location where the concentration of houses was particularly high. None of the users interviewed in Ruli village used BBOXX SHS to run a local shop. Electricity from BBOXX unit was occasionally used to support farming businesses after the sunset.

Topography of Musega village was significantly different. Most houses were concentrated around a central point of the village. Many BBOXX customers in Musega village used their installations to run small businesses such as pubs or small shops. It was revealed that some local pubs were equipped with TVs which were supporting small businesses by offering entertainment activities within the community.

The group of BBOXX customers interviewed was dominated by men, with 22 out of 30 responses. Research proved that SHSs technology is equally popular amongst youth (15–25 years old) and elders (60 + years old).

3.4. Demand Surveys with Householders relying on BBOXX SHSs

All SHSs owners interviewed in Ruli and Musega villages have been BBOXX customers for less than 36 months, implying that pay-as-you-go contracts requiring regular payments at least once every month still applied to each one interviewed. During field studies, the only upgrades offered by SHSs distributors were small TVs, radios, irons or more LEDs. Surveys used for the field studies are presented in the Appendix A.

3.4.1. Feedback from BBOXX SHSs users

Based on the field work conducted and interviews with numerous SHSs users in Rwanda, villagers were satisfied with services offered by BBOXX, mainly due to significant improvement in light quality over previously used kerosene lamps. After installation of SHSs, security in the village has also improved due to introduction of external lights in front of houses. Some users complained about the lack of capacity offered by BBOXX SHSs. This may be a result of the low voltage disconnect threshold level, locking the system whenever its allowed daily capacity is exceeded. In some cases, high amounts of capacity within BBOXX SHS is still available; however, the system operator does not allow users to access this unless they upgrade their contract and payment plan. As a result, some families do not show willingness to add more appliances to the system, as they are unaware of this extra “locked” capacity that a BBOXX SHS is capable to offer.

For users running local shops, income generation opportunities were increased due to the provision of basic energy access, allowing them to trade in the evening as well host social events with TVs for several hours every day.

3.4.2. Measuring Willingness to Pay for Larger Devices

Studies indicating aspirations for scaling-up with electric demand were performed by conducting set of surveys within selected sites. The majority of SHSs users indicate that refrigeration systems as the most desired high-power device (after lighting and phone charging offered within base SHS). Some residents also aspire to use TVs (bigger than those currently offered by BBOXX). To estimate willingness to pay for these appliances, a pay-as-you-go fee was proposed within the community. Estimated costs to be paid by potential interconnected SHSs prosumers willing to upscale their electric demand were comprised of two tariffs: PAYGO **-** valid for the first three years from purchasing of a device (this would be charged once every month). The second tariff would apply after the end of the three-year PAYGO contract to cover costs of energy required to supply appliances as well as maintain assets connected to the microgrid. The estimated tariffs were defined with a support of BBOXX team and proposed tariffs are presented in the Table 3-3.

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Table 3-3. Proposed fees for upgrading systems.

APPLIANCES	**PAYGO FEE PER MONTH FOR 36 MONTHS**	**FEE AFTER 36 MONTH PERIOD**
40” TV	RWF 13450 ($14.85)	RWF 6500 ($7.18)
FRIDGE	RWF 16000 ($17.65)	RWF 10700 ($11.80)
40” TV + FRIDGE	RWF 22900 ($25.30)	RWF 14700 ($16.20)
FAN	RWF 5000 ($5.50)	RWF 5000 ($5.50)
DVD PLAYER	RWF 500 ($0.55)	RWF 500 ($0.55)
SEWING MACHINE	RWF 11600 ($12.80)	RWF 11600 ($12.80)

The algorithm proposed by BBOXX to find estimated prices for new appliances is presented below:

$$\text{PAYGO (per month)} = [(\text{cost of appliances}) / 36\,] * 200\% \qquad \text{Equation 3-1}$$

Based on Equation 3-1, payments for new appliances are distributed over a period of 36 months (just like typical tariffs applied for BBOXX SHSs). Within this period, the revenues resulting of new appliances distribution need to be 100% higher than cost of appliances purchased (profit margin indicated by BBOXX). Other aspects affecting proposed pay-as-you-go tariff are related to cost of energy required to supply fridges, TVs, etc. Estimated amount of energy was multiplied by average cost of electricity of $1.50/kWh (calculated for MeshPower microgrids). This amount was added to overall pay-as-you-go tariff to find overall willingness to pay within Ruli and Musega Villages. Results presenting aspirations to connect new electric appliances are illustrated in Figure 3-5.

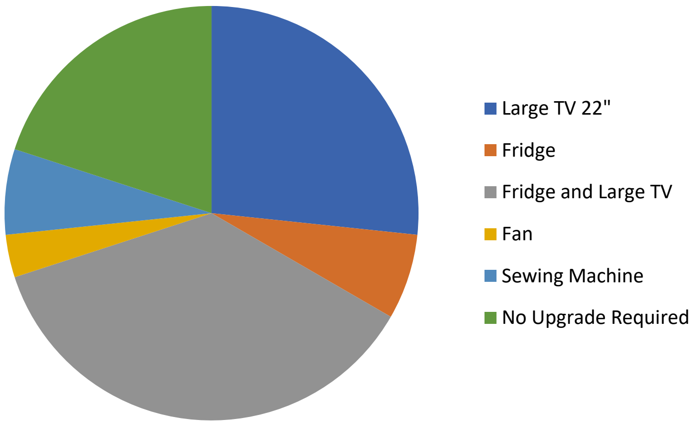

Figure 3-5. Aspirations to Add Larger Appliances other than Currently Available

The majority of those living with SHSs show a strong willingness to purchase devices such as fridges or big TVs for prices introduced in the surveys; therefore, the introduction of smart interconnected SHS microgrids will only make sense if these appliances can be accommodated and supplied. As such, any interconnected SHS microgrid should, at a minimum, be able to accommodate 50W peak load for a typical small fridge as well as 40” TV (more details on these appliances in the next chapter of the thesis). Other observations associated with the surveyed data presented in Figure 3-5 are shown below:

- According to Figure 3-5, willingness to add a sewing machine for income generation activities was not a popular choice, mainly due to lack of elementary knowledge of using these systems. Some people show willingness to add these devices to their electrical demand only if training will be provided.

- Around 60% of those who showed willingness to add refrigeration showed an interest in using some of its cooling space for rental, believing they could generate extra income by sharing their fridges with other users in the village. As a result, relatively high costs for refrigeration units could be split between two or more households and adaption of fridges could be much more efficient. Further difficulties concerning this method of appliances sharing may result from determining which user sharing the fridge is going to possess it. Such analysis could become a subject for further analysis regarding fridges and other high-power devices.

- Interestingly, fans as cooling systems were not amongst popular choices. Villagers often asked how the quality of life can be improved by introducing these systems as they were not familiar with these devices. BBOXX team indicated that fans are significantly more popular in regions with higher average temperatures than Rwanda, such as Pakistan, where standard BBOXX systems contain a fan together with lighting systems and phone chargers as part of a standard product specification.

- A group of BBOXX customers using SHSs upgraded to accommodate a small 8 W DC TV declared that they would be very interested in upgrading to a new, larger version if it was possible to terminate their previous PAYGO contract for small TVs. New TV would be therefore used as a replacement of an old, small system.

All users interviewed prefer PAYGO for SHS contracts, as in most cases paying full upfront costs for these installations would not be possible. This enables payment of clean electricity tariffs that equates to the cost of energy previously associated with kerosene lamps and phone charging.

Similarly, all BBOXX customers interviewed present high interest in participating in the local energy market, to either allow the affordable connection of high-power appliances, such as fridges or TVs, or to generate income through the export of electricity to their neighbors.

One common issue that interviewees lacked was a clear understanding of was maintenance services provided by SHSs. People do not appreciate the benefits of paying a compulsory maintenance fee after the termination of the 3-year PAYGO contract. This could be a result of a lack of technical knowledge and understanding in relation to the expected battery lifetime, where it will typically lose capacity after 3 or 5 years since the installation (all customers interviewed had their systems for less than 3 years at the time of the interviews). As a result of introducing the maintenance fee for 7 years following termination of the initial PAYGO contract, users are able to replace faulty elements of SHSs whenever it is needed.

The rate of maintenance fee is approximately \$3.50/month which is one of the aspects to be considered while providing interconnections between SHSs. As a result of sharing electricity and gaining new income from exporting surplus generated, maintenance fees could be reduced to support monthly expenses within household with low financial capacities.

3.5. Discussion of the Field Work

Although feedback provided while interviewing families relying on SHSs in Rwanda was very positive towards new bottom-up electrification paradigm and shows genuine interest in adding new loads to the local demand, there are several implications which need to be considered before introducing the new smart energy networks concept in rural villages of the country. These implications can be categorized as economic, technical and social.

3.5.1. Economic Implications

The introduction of a bottom-up electrification concept requires deep consideration of the business plan, due to potential risks as well as new streams of revenues this technology can bring.

Investment Uncertainties

Although results gathered from case studies conducted in Rwanda show a significant willingness to upgrade existing SHSs to introduce local energy markets, issues remain with verifying accurate willingness to pay for larger appliances. Results of the case studies proved a high interest in the introduced concept, but it does not give full confidence of the capabilities to pay for listed appliances. This could be overestimated due to significantly higher costs of ownership for fridges and TVs for the basic SHSs offered so far. According to Christopher Baker-Brian, only around 2% of all BBOXX customers permanently fail to pay for SHSs, which would result in systems being returned to the distributor. In order to fully understand potential for a smooth multi-tier transition within interconnected SHSs microgrids, installation of such networks as well as monitoring is required. This would clearly give verification of the proposed concept.

Design of Appropriate Tariffs

Designing a micro transactions scheme and tariffs for those who are willing to add new electrical appliances and those exporting electricity to the network might be challenging as it is required to consider different market players (prosumers either exporting or importing electricity). Those with a net energy export need to gain benefits proportional to the rate of energy exported to the microgrid and cannot be charged for use of local network if no new appliances are being added. One way of recovering costs for net exporters is to connect them to the local pool of electricity and give them access to income generation just after certain amount of energy is exported from their system. Once this is completed, income for exporting electricity will start being billed for the user. This type of incentives should encourage local power producers to use electricity only for crucial activities to maximize its export. Payments should arise mainly from net energy importers, consuming electricity for larger energy appliances. The fee should also consider costs of interconnections and SPM system installed within each household. As a result, with the optimal introduction of new energy markets, all participants should gain benefits, either monetary (those with net energy export) or resulting from new appliances which could lead to new income generation opportunities.

Future demand growth estimation should also be considered while designing accurate tariffs. Costs of microgrid expansion in the future also need to be consider in the pay-as-you-go tariffs to provide smooth adaption of new generation and storage capacity without changing applied tariffs is one of the aspects requiring deeper analysis without changing initial contract between microgrid operators and end users.

3.5.2. Social Implications

Introducing new equipment such as fridges or TVs and increasing the levels of energy access offered to communities with only Tier 1 access, could also result in new social impacts which are introduced in this section of the thesis.

Development of a New Electrification Plan

Firstly, it is important to carefully identify the group of villagers that could potentially connect to form an interconnected SHSs microgrid. It is essential to build a new electrification plan for the whole village and beyond, and to define the rate at which demand growth should/could occur, as well as which households can connect first. Providing new appliances for every family presenting willingness to use them could result in system failure, mainly due to real ability to pay performed by people with very limited financial capacity. Growth in electrical demand would require installation of extra generation and storage to the system as existing might not be sufficient which would be associated with additional capital costs to be covered.

One of the solutions is to upgrade SHSs demand incrementally. First, by offering high-power appliances s to those who were regular with payments for the initial PAYGO contract in the past. This kind of arrangement could also introduce newly perceived inequalities and feelings of prioritization towards one group of customers over another, leading to a lack of willingness to participate in the local energy market at all and widespread disenfranchisement and disengagement.

New Appliances shared between two or more houses

There are potentially positive impacts associated with the provision of affordable supplies for larger electrical appliances. By adding a fridge to one of the households, refrigeration space could be shared between two or more families, reducing overall cost per head of using these devices. This kind of adoption of new devices could provide faster and more efficient transition within the access to electricity multi-tier framework, as well as having positive economic and health impacts through the reduction in food waste. Subsistence farmers and agro-businesses can also preserve goods for longer between harvest and consumption or taking to market.

Growth of new businesses in the villages

Introduction of new appliances could stimulate growth of new businesses in off-grid villages. People could therefore open new refrigeration hubs, barber shops, local cinemas or simply upgrade their existing businesses by new range of services offered, for example by selling cold drinks which could be supported by introduction of new refrigeration units. Growth of small businesses can also introduce competition between prosumers. As a result, some net power exporters may not be willing to provide electricity to for users that offer competitive services due to installation of new high-power electrical appliances. These studies require further analysis and possibly appropriate planning tools considering all possible businesses in the village, their income generating activities and many more.

3.5.3. Other Potential Barriers

Other barriers could result from lack of awareness of power ratings of electrical appliances currently used in the off-grid environment. This could be a particularly challenging aspect when connecting larger appliances to the system. Each SHS has its rating indicating maximum power output that could be exported from the battery before internal SHS protection trips. As a result, it is important to equip potential customers with appliances that could be easily energised from the microgrid, while not exceeding maximum ratings of the system. This would suggest that all appliances like fridges or TVs should be fully provided by the network system operator and no other appliances should be added to the system, especially those which were not approved by the microgrid operator.

3.6. Interconnected SHS Microgrid vs. Investments in Larger SHSs for Scaling-up the Demand

Although interconnected SHSs microgrids could introduce new opportunities in the off-grid sector, it is important to show their benefits over other potential solutions currently available, that is, the installation of new SHS capable to support high-power appliances.

While upgrading the individual SHS generation and storage capacity within a village may require significant investments in generation and storage (approximately 200W system as opposed to 50W supporting lighting and phone charging, according to Figure 1-9), it would not involve investments in the distribution system. However, one of the major issues associated with this approach is a lack of capacity to utilize all generated energy or that produced by neighboring systems. As a result, standalone systems would normally require more capacity installed per head to satisfy the worst-case demand scenario.

Section 3.6 presents differences in required capacity for interconnected SHSs microgrids and standalone SHSs capable of supplying Tier 3 level energy access and appliances. The data used to build the comparison are based on a village with 20 SHSs located in Ruli village, where field work conducted in March and April 2018 was undertaken.

Statistics were created to present typical demand variations for two scenarios. The first considering standalone systems (with currently available technologies) and assumed that systems can share electricity in the local energy pool. It was found that the average energy consumption per household for the considered sample group was 51.69 Wh/day per household. The average standard deviation for energy consumption for individual SHSs was found to be 12.28 Wh/day.

The second scenario evaluates interconnected systems where electricity is equally shared between all prosumers. Under such setting it is expected that the typical demand is more “predictable” due to load being shared between SHSs users. The average standard deviation of a daily energy consumption within a group of 20 interconnected systems was therefore found to be 2.36 Wh/day per household. This reduction in demand variations has been achieved by supporting power prosumers with high energy demand by those who remain with electricity surplus. As a result, typical demand uncertainty under scenario considering interconnected SHSs equally sharing load is significantly lower than under scenario where all systems operate as individual installations.

A reduction in demand diversity for interconnected SHSs networks could significantly decrease the need to install extra generation and storage to the network to maintain a similar level of reliability of power supply as that presented by standalone systems after upgrading appliances to Tier 3. This could ultimately result in an overall system generation and storage expenditure cost reduction which has potential to provide smoother multi-tier transitions than in the case of incrementally upgrading standalone systems with new capacity.

The next stage of the analysis includes assessment of a scenario where systems currently deployed are upgraded by a small 12V 50 litre DC fridge, consuming 200 Wh/day, which is a new rate of increase of average system demand per household with an upgraded system. The variations of demand in energy consumption for refrigeration systems is still unknown. Some households could use it for storing food which would result in fridge being turned on most of the time. Others can use it for income generation activities. In such case, people could offer cold drinks in the village during time when shop operates and switched off at night. To present further benefits of interconnections while introducing refrigeration, rate of demand variations within households with Tier 3 energy access was assumed to be the same as ratio of standard deviations over average demand within Tier 2 and Tier 1 households measured earlier. As a result, further comparison presenting generation requirements to provide electricity for interconnected SHSs scenario as well as stand-alone SHSs arrangement has been established. It was estimated that to maintain a high level of power system reliability at 95% days a year (taken as an example) based on demand variations for 20 households in Ruli Village, the fridge upgrade could be offered for up to 11 of the 20 BBOXX systems, with no need to install additional generation or storage capacity within the interconnected SHSs networks. Under a scenario where 11 out of 20 SHSs are upgraded by new generation and storage capacities with no interconnection, significantly higher levels of cumulative generation capacity are required. This is due to systems being oversized to match individual demand diversity under stand-alone (non-interconnected) system. Generation capacity required was identified by scaling up daily standard deviations of individual SHSs energy consumption by the magnitude of fridge average energy requirement (200 Wh/day). The results indicating capacity required to power 11 fridges in the villages under stand-alone and interconnected scenario are illustrated in Figure 3-6.

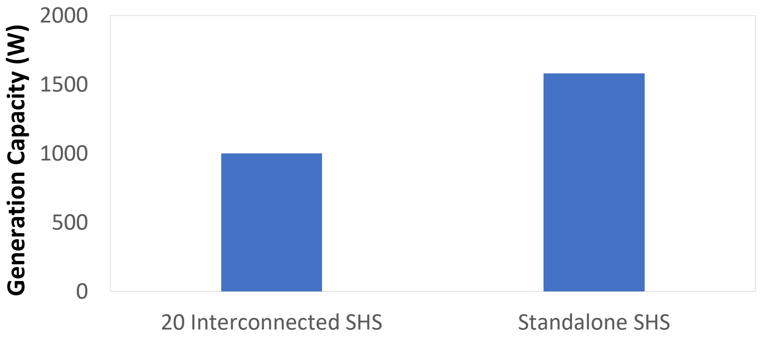

Figure 3-6. Generation required to supply fridge for 11 BBOXX Customers while maintaining average reliability of power supply at 95%

Upgrading currently deployed SHSs into new with higher generation and storage capacity would require higher investment costs in PV modules (~1.6 kW installed in oppose to 1kW already deployed) as well as batteries, even though there is still a significant portion of energy available in the village, produced by SHSs, which currently goes to waste. As a result of this surplus of electricity as well as strong demand diversities between household demands, people with existing SHSs installation could make use of existing generation capacity to power refrigeration systems for significantly lower cost than while purchasing new SHS with significantly bigger capacities. New expenditure would be limited to installation of low voltage interconnections between households and refrigeration systems.

3.7. Summary of the Feasibility Assessment conducted in Rwanda

Studies presented in Chapter 3 introduce the concept of bottom-up electrification within rural communities of Sub-Saharan Africa, and in particular the transition from Tier 1 to Tier 2/3 that can be enabled through interconnected SHS microgrids. The case for this was evidenced through analysis of data that were gathered and analyzed for villages supported by off-grid solutions offered by BBOXX.

The introduction of this new rural electrification paradigm could vary from country to country. In Rwanda, the most popular SHSs are based on the 50W PV (BBOXX) or 80-100W PV (Mobisol) system. Interconnecting them to form a community microgrid can improve overall performance of energy storage batteries and extend its' life cycle due to equal demand distribution within all interconnected systems. Most standalone SHSs produce significantly more electricity than typical household requires for basic Tier 1 appliances. It is proposed that interconnecting SHSs allows surplus of electricity to be fully utilized, and potentially supply higher power devices which currently cannot be accommodated using typical standalone SHSs.

Studies present that the most desired electrical appliances in off-grid villages in Rwanda are fridges and TVs, declared by 84% respondents. To date, the only method of adapting these systems to accommodate these higher load devices is through the introduction of new generation and storage capacity, requiring significant upfront costs.

Based on analysis provided in Chapter 3, bottom-up electrification has a potential to introduce smoother and scalable transition for growing demand, simply by providing interconnections between existing assets. It is estimated that interconnected SHSs microgrids requires around 35% less generation capacity than standalone systems to keep similar average reliability of power supply of 95%. This is mainly a result of strong demand variation between household, as measured based on installations in Rwanda. As a result, instead of offering new generation and storage technologies (requiring substantial upfront costs) to adapt growing demand, new appliances could be supplied by unused electricity within a community microgrid. Due to widespread communication technologies available in East Africa, such network can be simply monitored to understand when to adapt further generation/storage to meet growing demand.

Interconnected SHSs microgrids also introduce additional levels of power supply security as electricity can be supported by multiple prosumers. Studies presented in Chapter 3 suggest that maximizing number of interconnections within a microgrid can boost overall security of supply, ultimately reducing expenditure costs of generation and storage required (per household) by the system to meet growing demand.

Bottom-up electrification approach could be beneficial for many communities with limited access to electricity in Rwanda where SHSs are widely popular. The overall results might be different to presented in Chapter 3 while considering other countries in SSA, where types of off-grid systems have significantly distinct technical specification to those deployed by BBOXX in Rwanda. In some markets off-grid solutions could be dominated by pico-solar systems, which have just enough capacity to power a single light bulb and a phone charger This would imply that to provide multi-tier energy transition, interconnection between prosumers supported by addition of new generation and storage capacity would be required, making such transition significantly more difficult to achieve than among BBOXX customers. Despite such difficulties, off-grid sector experiences strong drive from pico-PV modules into bigger SHSs with significantly higher generation capabilities, indicating greater potential for the interconnected SHSs networks in the future.

Having identified opportunities as well as challenges associated with introduction of the bottom-up electrification on a SHS level, it is needed to indicate further design requirements for the controller capable to provide such bottom-up transition. Technical specification is given based on appropriate high-power appliances assessment as well as analysis of the internal control system within BBOXX SHSs. Details listing principles of operation of the interconnected SHSs microgrids supporting Tier 3 appliances are introduced in the Chapter 4.

4. Smart Power Management (SPM) and its Applications

Functionality of the SPM interconnecting SHSs and supporting the most desired appliances within off-grid communities requires deep analysis of the technology currently deployed in field and its limitations. It also requires appropriate analysis of market for electrical appliances to be supported which gives appropriate hardware specification for future development of the Energy Box.

Principal parameters controlled by the SPM are power out/in-flows between prosumers interconnected within the community and voltages - on the microgrid network and supporting new, high-power devices. Furthermore, different modes of operations are introduced to maximise electricity utilisation during sun peak hours, when high proportion of energy goes to waste.

4.1. Main Aspects considered while introducing SPM

Before introduction of a new SPM system, major technical requirements need to be precisely highlighted. These aspects have crucial impact on design and functionality of the interconnected SHS networks to support new appliances connected within off-grid environment. The principal features are required to provide affordable and scalable transition in electricity consumption supported by appropriate smart network infrastructure maintaining safe balance between supply and demand. The most important technical characteristics of the SPM considered in this thesis include:

1. DC vs. AC for new high-power appliance to be adapted to the interconnected SHSs microgrids.
2. Features of the new distribution network providing touch-safe, plug-and-play operation.
3. Adoption of New Distributed Energy Storage devices to the System utilizing electricity which currently goes to waste.
4. Compatibility of the SPM system with the existing SHSs infrastructure.
5. Communication within the Energy Box.
6. Demand Side Management (DSM) features.

4.1.1. DC vs. AC for High-Power Appliances

The market for refrigeration systems as well as TVs (the most desired appliances in off-grid Rwanda) is currently dominated by AC appliances, mainly due to the prominence of the AC power grid. Due to broad applications around the world, AC appliances are significantly cheaper than DC. Despite this fact, it is still worth considering DC as a viable option for off-grid electrification, mainly due to their high efficiency and ease of adaption for 12V batteries with solar installation [95], [96]. Evidence suggested that DC fridges are more than 20%–30% more efficient than AC which could be a crucial factor for further off-grid systems deployment where generation and storage is strictly limited typically by the size of solar panel and battery system [97]. DC appliances could also introduce more energy savings which results in investment cost reduction for generation and storage capacity in the local energy network.

To date, majority of SHSs currently being deployed in SSA support 12V DC appliances which normally operate withing the 12V battery range of 11.5V and 14.5V [98]. These devices include mainly lighting, phone charging, radios and small TVs, as specified in Chapter 3. Providing DC appliances within networks of interconnected SHSs would also be the most cost-effective due to elimination of power inverter stage which would add additional complexity in the design which would drive costs of the bottom-up transition up, creating barrier for many people across the Global South who could potentially make use of the proposed solution. Introduction of a power inverter may also reduce system reliability since devices providing such DC/AC conversion often require frequent maintenance and replacements [99]. As such, it was assumed that optimal bottom-up transition supported by the Energy Boxes should support electricity for DC appliances only.

The biggest drawbacks of using DC loads are associated with lack of supply chain for these kinds of appliances in most Sub-Saharan Africa countries where AC appliances dominate. During field work conducted in Rwanda in 2018 and 2019 it was revealed that the only DC appliances available on the local markets with electronics are LED bulbs, phone chargers and mini radios. As a result, new appliances such as TVs or fridges would need to be provided by the microgrid operators.

4.1.2. Appropriate Network Architecture

Although AC networks have been dominant around the world, DC systems can introduce significant benefits over AC in terms of reducing capital and operational costs while being used for off-grid electrification [100]. The main benefit of using DC networks in the context of interconnected SHSs is their simplicity in control. Such technologies do not require tuning to a given frequency and phase which is mandatory if network relies on AC. Module synchronizing SHS with the DC grid would therefore be simpler with a lower number of power conversion stages than while introducing AC system requiring DC/AC module provided by the inverter as well as AC/AC introduced by the local transformer to synchronize SPM with the microgrid voltage at standard 230V (typical household voltage level in Rwanda) [101], [102]. As a result of more complex power management scheme introduced while performing DC/AC conversion, operation of SPM and communication system on a single core processor requires higher computational speed and greater energy consumption than while providing single DC/DC conversion. Considering small generation and storage capacities within SHSs it is important to provide a microcontroller (μC) of the minimum power consumption. Evidence suggests that some microcontrollers operating at 60 MHz consume 450mW whereas those with higher computational speed of 150 MHz require nearly 900mW, resulting in consuming approximately 5% and 10% of total daily energy generated by a SHS (such as BBOXX analyzed in Chapter 3) being purely used to drive the μC itself [103], [104]. As a result of all these technical challenges to supply Energy Boxes within existing SHSs, DC network architecture was chosen to be optimal to provide interconnections between SHSs.

4.1.3. Smart use of High-Power Appliances and adaption of Distributed Batteries

Loads supported by the SPM system can be divided between two categories. First, user-controlled such as those currently introduced within SHSs. These typically include light bulbs, phone chargers, radios which draw power whenever user connects them to a power supply. Other types of loads are controlled in a "smart" manner where power is delivered proportionally to the capacity available within the microgrid – known as active loads in this thesis. This is particularly important feature for microgrids experiencing higher electricity production than demand, surplus of power produced can be addressed to appliances which can operate more effectively by drawing higher quantities of electricity. Similar technique can support adaption of smart charging scheme for external, distributed batteries. Surplus of energy generated by interconnected SHSs can therefore be accumulated to support electric demand of a household after the sunset, when generation capabilities of the microgrid are low and cost of energy could be higher. As a result of SPM features maximizing electricity utilization during sun-peak hours, total reliability of supply could be maximized. Furthermore, costs of the system usage could be reduced by relying mostly on electricity directly generated by the solar panels, bypassing the batteries. Details on how these control strategies have been attained are presented in the Section 4.2.

4.1.4. Compatibility with the Existing SHSs Infrastructure

New SPM modules are required to operate considering existing SHS infrastructure. Proposed way of providing power supply to the SPM system is via connection directly to one of the 12V DC output pins of the SHSs. That way, SPM system has a capability to monitor unregulated voltage of the battery to manage power flows between SHS and distribution network. Parameters read by the SPM indicating internal 12V battery dynamics need to be sufficient to provide full functionality of the networks of interconnected SHS.

4.1.5. Information and Communication Technology (ICT) Requirements for SHS Microgrids

Communication and remote monitoring aspects are also worth considering when designing new smart control for interconnected SHSs microgrids. It is required to capture available generation and demand data by the microgrid operator to understand when capacity in the system should be upgraded due to growing demand in the microgrid. Furthermore, local network operator is required to send commands to each system deployed in field to disconnect end user from energy consumption while payment for energy consumption has not been completed. Other monitoring features should give a fundamental understanding of rate of energy exchanged by each user and at its tariff (daily or night energy consumption). As such, appropriate functionality of the local energy market and information exchange between prosumers and system operator must be attained a regular basis.

4.1.6. Demand Side Management (DSM)

Smart DSM scheme in charge of maintaining balance between supply and demand within the network of interconnected SHSs is one of the fundamental aspects required to be incorporated into each Energy Box. In the events when generation is low and power consumption is high due to introduction of new appliances, DSM is required to disconnect loads in the microgrid step-by-step, before tripping undervoltage protection system within SHSs which could ultimately disconnect SHSs within the microgrid initiating blackouts in the village. As a result, proposed DSM architecture requires clear separation between existing SHS 12V output port (where standard low power appliances such as LEDs and phone chargers are connected) and 12V port providing electricity for new high-power devices including fridges and TVs. Such configuration is presented in Figure 4-1 where Energy Box controller is directly supplied by a SHS. Electricity exported from the SHS is therefore used to boost microgrid voltage and to serve new appliances within the microgrid. 12V busbar supporting new high-power appliances can disconnect them at any time to provide appropriate DSM functions. Details explaining appropriate sequence of disconnecting loads in the system are presented in the Chapter 5.

4.1.7. Appropriate Energy Box Architecture

Introduction of appropriate power flows management in the network requires detailed explanation of functionality of power converters. Figure 4-1 reveals that Energy Box is supplied by the SHS 12V DC port to energize its hardware components including gate-drive circuits, communication systems and remote monitoring with a micro finance function as well as CPU system itself governing all the functions listed. The Energy Box controller is therefore “recognized” by the SHS as new load and functionality of SHS remains intact.

Direct connection of Energy Box to SHSs gives opportunity to understand operating conditions of the SHS. This is primarily due to unregulated 12V battery terminal of the SHS (no power conversion between battery and 12V output port) which gives capabilities to understand voltage levels of the battery by the SPM. As a result, state of charge of the SHS could at any time be estimated by the SPM which therefore has a capability to export higher power quantities from SHSs with high SoC than those which typically remain with power deficit. Simultaneously, based on SoC estimation appropriate load shedding can be initiated which is a part of DSM scheme introduced in Section 5.7.

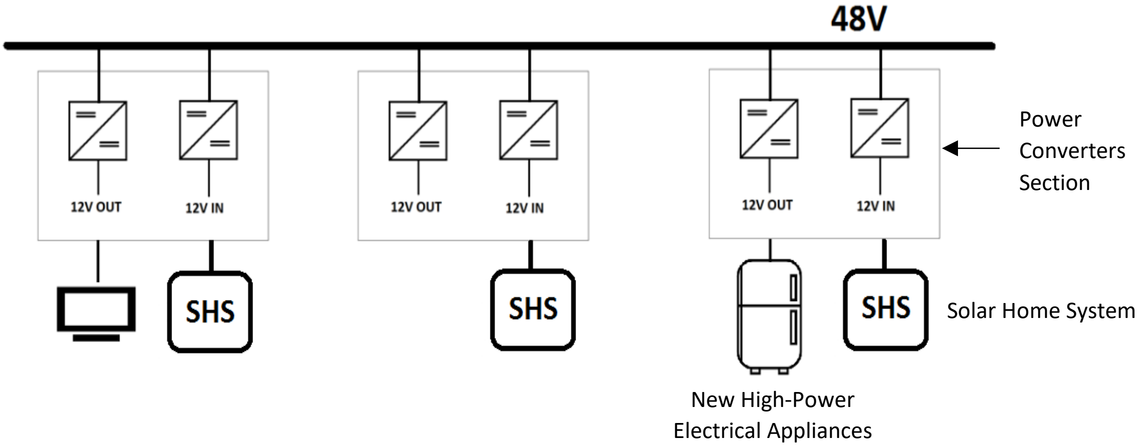

Figure 4-1. Proposed interconnected SHS microgrid infrastructure

Before developing system arrangement as indicated in Figure 4-1 and introducing hardware design and control algorithms, other configurations for exporting/importing electricity from SHSs and controlling microgrid voltage were considered. First architecture to comply with such interaction is illustrated in Figure 4-2 and represents a bidirectional buck/boost converter. By introducing such power converters configuration, SPM could be given capabilities for exporting energy whenever the SoC of the system is high and importing when SoC of the batteries is low using a single power conversion stage. Although this configuration seems to be “natural” including bidirectional operation of the system providing desired operation and therefore, improving overall system efficiency, it may not be adaptable to most SHSs on the market due to lack of capabilities for charging SHSs from 12V output terminal. According to Felix Boldt, designer of Mobisol SHSs and current managing director of Solarworx, charging batteries through 12V output ports can damage SHSs and prevent users from utilizing even the basic power appliances such as LEDs or phone chargers.

Other limitations resulting from introduction of the configuration indicated in Figure 4-2 may arise from difficulties with adaption of external batteries directly connected to the 12V SHSs output port. Distributed batteries would therefore initialize operation in parallel to existing SHS storage which voltage is currently purely governed by SHSs internal charge controller. Connecting two batteries in parallel (SHS and new external unit) without any regulation between could initialize high current flow between both which could result in tripping of the protection system of SHSs or even damaging it.

Other drawbacks resulting from adaption of the bidirectional power converters configuration illustrated in Figure 4-2 are associated with adaption of the DSM scheme. Under scenarios when microgrid cannot provide sufficient capacity for TVs and fridges, all appliances including lighting and phone charging will tend to remain disconnected which can significantly reduce overall acceptance of interconnected SHSs networks across the Global South.

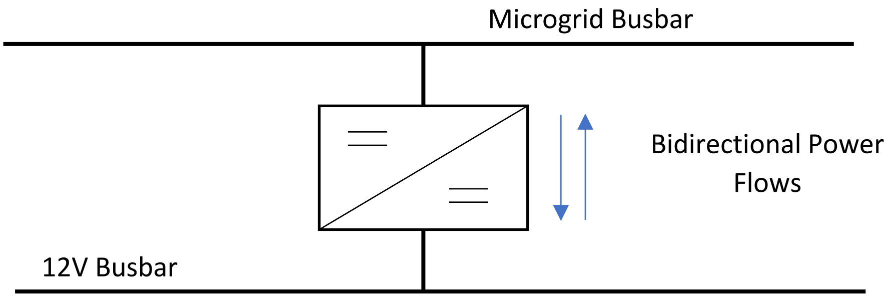

Figure 4-2. SPM with a Bidirectional Power Converter Configuration

Other configuration presented in Figure 4-3 involves introduction of another power converter decoupling 12V busbar at the terminal of SHS. Separation between 12V busbar for new high-power appliances and 12V SHS terminal gives chance to connect and provide control capabilities required for charging external batteries. Such configuration also supports load prioritization and capability to control 12V output busbar independently from the SHS internal power management system.

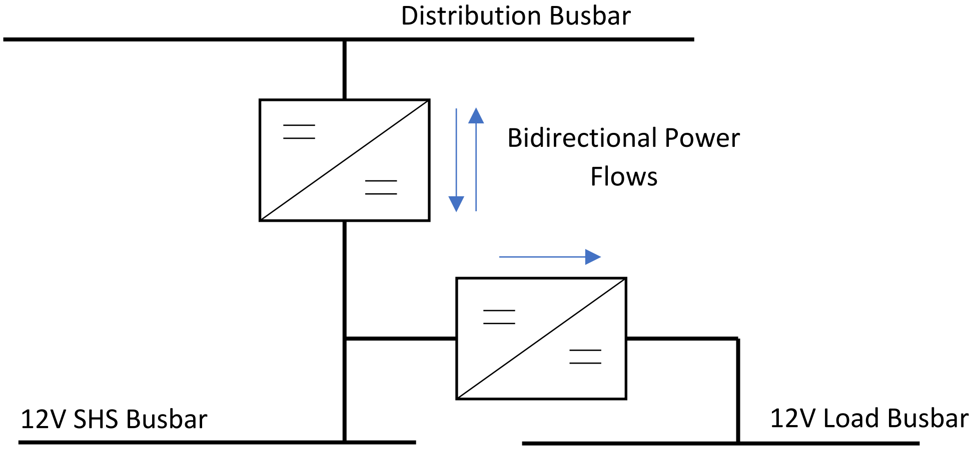

Figure 4-3. Other Configuration of the Power Converters for SPM

The issues regarding system presented in Figure 4-3 remain with complexity of the proposed arrangement. Importing power from the microgrid to use it for larger devices would require coordination of two power converters in series through two DC-DC converters to supply 12V load busbar where larger appliances are connected. It would also imply higher power losses at each of two stages of power conversion. Other difficulties may result from lack of voltage regulation capabilities at the 12V SHS terminal. This eliminates droop control technique from being a solution to appropriate power flow management within the system and makes power control difficult to achieve.

4.1.8. Power Control Consideration

Exchanging electricity between prosumers using shared DC distribution network could be achieved by providing droop control technique taking busbar voltage as a reference signal [105]. This allows safe operation of the microgrid where reference voltage can be dynamically varying, based on conditions in the network and within SHSs. As such, higher microgrid voltage reference points can be setup by SPMs connected to SHSs with electricity surplus. As a result, this group of SHSs would export higher quantities of electricity than other systems in the microgrid. As such, balance between electricity supply in the system could be maintained. One potential issue arising while adapting droop control arises while introducing resistive nature of the distribution line affecting the perceived reference voltage at each location of the microgrid, thus resulting in variance of this reference voltage across these nodes. This is especially the case for two locations separated from each other by a long distance. In such cases, electricity sharing will not be proportional to the aggressiveness of the droop control gain and systems providing voltage support close to the load would tend to provide more power than they were initially intended to. One way of mitigating these issues is installation of oversized cables between prosumers. Due to relatively low power requirements for TVs and fridges, voltage drops between microgrid nodes can be maintained low and optimal power sharing between prosumers can be maintained. Although oversizing cables would minimize issues with voltage variations along the network, it would require additional expenditure costs. Alternative techniques used to avoid capital intensive methods of providing interconnections consider introduction of adaptive droop control methods which are introduced in Section 4.4 of this thesis.

4.2. Introduction to Appliances supported by the Interconnected SHSs Microgrids

Operating within isolated microgrid with limited generation and storage capacity requires fundamental analysis of market for efficient appliances. Field work performed in Rwanda amongst 28 households currently relying on BBOXX SHSs indicates that the most desired appliances after lighting and phone charging include refrigeration systems and TVs.

Analysis of 12V DC appliances for off-grid electrification shows great differences in technical specification between devices in terms of their power and energy consumption as well as adaptability to off-grid environment. This section of the thesis presents the most adequate appliances for off-grid DC microgrid in the Developing World. Appliances considered in the studies were identified with a support of BBOXX which is currently supported by manufacturers developing highly efficient systems. Performance indicators of such appliances was therefore used to optimally scale the Energy Box for a bottom-up electrification.

4.2.1. Selection of Appropriate Refrigeration Systems

Introduction of refrigeration within interconnected SHSs networks can be particularly challenging as fridges typically operate 24 hours per day which can drain significant portion of energy stored within batteries and gradually reduce their operational duration. Moreover, power consumption of typical 12V fridges is significantly higher than for appliances installed within basic SHSs units. Simultaneously, due to limited power provided from each SHS, it is important to introduce fridges that respect all the technical constraints imposed by the SHS and Energy Box integrating them to form a microgrid. The final model of the fridge selected for interconnected SHSs is Embraco 100 liter unit. The fundamental features considered while selecting this model are revealed in sections below.

Low Energy Consumption

Connecting appliances with higher energy consumption than generation could result in reduction of overall SHS reliability which could significantly affect overall acceptance of the proposed bottom-up transition in the Developing World. Moreover, inadequate refrigeration could result in necessity for installing additional generation and storage modules within the local energy network supporting such appliances. Alternatively, novel refrigeration systems with high cooling efficiency and sufficient isolation can present greater adaptability to networks of interconnected SHSs. Such fridges, despite requiring higher expenditure costs, present greater operating capabilities within off-grid environment and do not require oversized distribution network, generation, storage or energy meter to support them.

Other features considered while selecting appropriate 12V DC fridges are associated with capabilities to provide smart control strategies to adjust power consumption and temperature while providing balance between generation and demand existing in the microgrid. As a result, higher rate of power could be consumed by the fridge during periods when SHSs are full and remaining generation potential of the PV modules goes to waste. Consequently, fridges installed within the villages could be used as a form of energy storage consuming higher quantities of energy during sun peak hours to minimize electricity usage after the sunset, while relying on batteries. Other application where dynamic control over fridge power consumption could be used is while introducing new business opportunities for local grocery shops in rural regions of SSA. Interviews with small entrepreneurs during field studies in urban Rwanda reveal that fridges installed to sell cold drinks can purely operate between morning and evening and there is no requirement to provide electricity for cooling at night. As a result, reliance on a battery system could be minimized. Meanwhile, power consumption could be initiated in the morning to chill drinks and sell them when demand is the highest – in the afternoon.

Limited Inrush Current

Low inrush current drawn by the fridge compressor could significantly benefit the network of interconnected SHS. Such current is initiated each time the compressor is energized. Its magnitude is normally significantly higher than rated current. This is the effect of coils installed within each refrigeration system which during start-up period draw high amount of electricity. Example of a power consumption profile for a compressor-based AC fridge without a soft starter is presented in Figure 4-4 [106]. Similar issues regarding high start-up current are associated with 12V DC fridges. According to Amaury Fastenakels, Chief Marketing Officer at BBOXX, SHSs with capabilities to support fridges require additional soft-starter circuit in order not to exceed maximum current allowed by the system while energizing the fridge. This is valid for 100 liter 12V DC fridge produced by BBOXX, currently highly popular mainly in the Goma region of DRC [107].

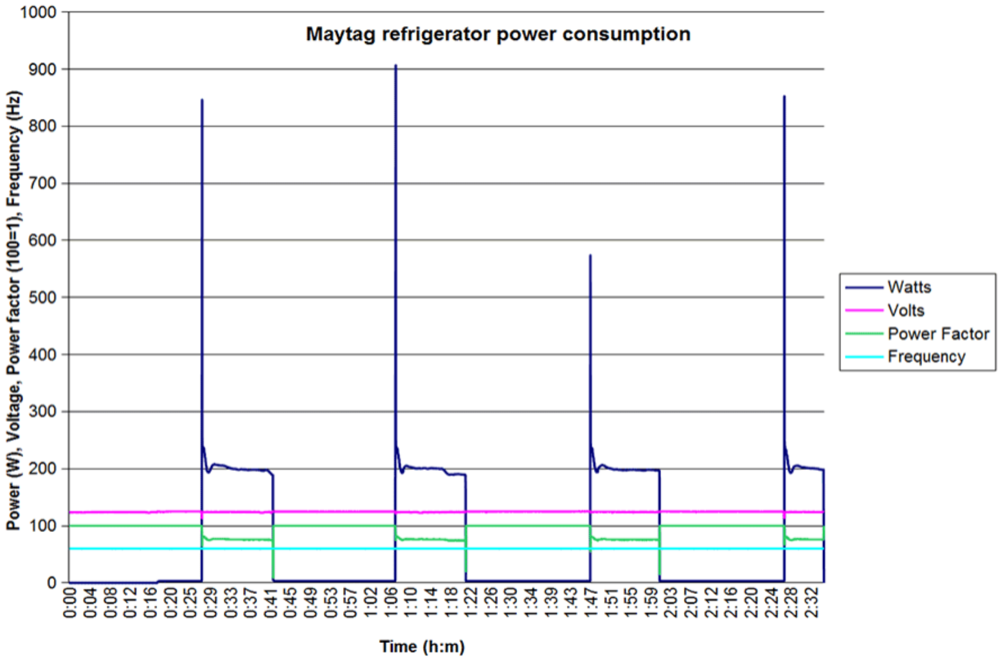

Figure 4-4. Power Consumption Profile for a Fridge with no Soft-Starter Capabilities

As seen in Figure 4-4, maximum power consumption of the fridge can be several times higher than rated and would require controller providing interconnection between SHSs being significantly oversized, driving overall costs of the microgrid high. Simultaneously, power outflows from SHSs to support refrigeration systems could be too high which would eventually trip overcurrent protection within SHSs, disconnecting full system from electricity use, even for basic appliances including lighting and phone charging.

Based on deep market research and interaction with numerous fridge suppliers as well as SHSs providers, it was assumed that the most compatible model to be introduced within networks of interconnected SHSs is Embraco Solar-Fridge. It presents adequate soft-starter capabilities shaving inrush current resulting from energizing the compressor unit. The maximum current draw by such fridges is 2.5amps – significantly lower than specified for most other 12V fridges available on the market. As a result of great compatibility with off-grid systems, Embraco refrigeration system selected for further bottom-up electrification analysis, The 100 liter model is illustrated in Figure 4-5.

Figure 4-5. Embraco Solar Refrigerator, 100 litres

Specification of the two Embraco solar fridge (50 liter and 100 liter) is presented in the Table 4-1 [108].

Table 4-1. Embraco Off-Grid Refrigeration System Specification.

Model	**Embraco 50 liter**	**Embraco 100 liter**
Peak Power Consumption (W)	30 (adjustable)	30 (adjustable)
Daily Energy Consumption	<150 (Wh/day)	<180 (Wh/day)
Operational Voltage Range	9 – 16 V	9 – 16 V
Insulation	High Density Polyurethane	High Density Polyurethane
Refrigerant	Isobutan (R600a)	Isobutan (R600a)
Cost ($)	230	300

Optimal operation of the Embraco systems can be maintained by designing appropriate communication interface between the microgrid (or Energy Box) and fridge itself. This can be achieved with a support of the functionality developed by Embraco. As such, Energy Boxes “having understanding” of overall balance between supply and demand in the microgrid can adjust power consumption setpoints accordingly. This interaction can be developed by utilizing RS232 protocol which ultimately can modify temperature and power consumption set points of the fridge. Layout of the connector supporting communication and providing power supply is presented in Figure 4-6.

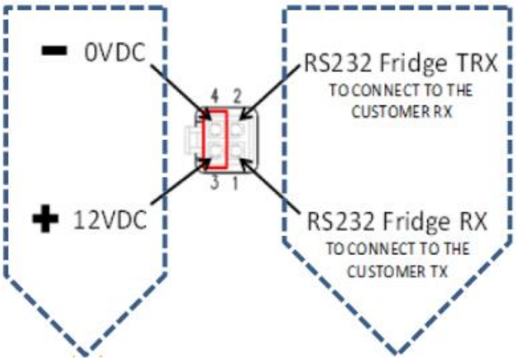

Figure 4-6. Embraco Fridge Connector Pins

Although adoption of RS232 interface enabling interactions between the SPM and the fridge has a great potential to balance supply and demand in the microgrid, it has not been implemented within the scope of work presented in this thesis. As such, all tests using 100-liter Embraco Solar Fridge were based on default settings for power consumption of 17.8W and temperature setpoint at 4 Celsius degrees.

4.2.2. Adaption of a TV within Interconnected SHSs Microgrids

TVs are amongst the most desired (next to the fridges) appliances among people currently relying on SHSs who show willingness to scale-up their electric demand. Within the villages visited during field studies in Rwanda some BBOXX customers use 8” 12V DC TVs. Bigger TVs supported by 250W BBOXX SHSs are occasionally installed in urban locations of Democratic Republic of Congo (DRC) where overall financial capabilities to pay for SHSs are higher than in Rwanda – according to Christopher Baker-Brian [109]. These systems are usually used as a back-up to highly unreliable power supply in the region. Power consumption of such 22” TV is 20W [110].

To date, PAYGO tariff for 8” TVs in Rwanda is approximately 12$/month for 12 months which is substantially higher fee than offered purely for LEDs and phone charging. As a result, many users investing in small BBOXX TV are those who have already completed their initial PAYGO contract and show financial capacity to further expand their demand. TV payback time of 12 months is determined according to warranty given for TV sets.

4.3. Incorporating Batteries to the SPM System

Field work performed in Rwanda analyzing potential for the bottom-up electrification proved that market for 12V lead-acid batteries (either deep-cycle or car batteries) is well developed and purchasing 12V battery can be completed in most big cities. This is primarily a result of high number of applications for such batteries as well as increasing awareness of capabilities established by off-grid solar systems which typically support 12V devices in rural regions of SSA. Within the design of the Energy Box (see Figure 4-1) such batteries can be connected to a 12V busbar from which new high-power appliances are energized. As a result, prosumers equipped with new batteries can import electricity when surplus of energy in the microgrid exist. It can be therefore utilized after the sunset, without affecting overall reliability of SHSs interconnected within the network. Such interaction is achieved primarily due to 12V output terminal of the Energy Box being fully controlled by the SPM, independently from SHSs. Charging sequence of external batteries is achieved by gradually increasing voltage of the 12V terminal resulting in transferring higher rates of power from the network towards the energy storage itself. Such procedure is required to respect maximum power transfers as well as 12V battery charging profiles. Details explaining integration distributed batteries within the microgrids of interconnected SHSs are presented in the Chapter 5.

4.4. Microgrid Voltage Control Strategy

Adaption of the Energy Box interconnecting SHSs to form a local microgrid requires analysis of the limitations within each SHS. It is crucial that system equipped with SPM has capabilities to bypass internal control system of the SHSs to provide electricity exchange between prosumers. Analysis presented in Chapter 2 indicates that rearranging hardware configuration of the SHS is currently forbidden by some SHSs providers (like BBOXX) and can lead to SHSs being disconnected. As such, the only possibility to support network of interconnected SHSs is by utilising one of existing ports within SHSs. According to SHSs specification, there are three ports available:

- PV Input – input port where solar panel is connected. Once electricity is generated by the solar module, voltage of this port adjusts to find optimal conditions maximising electricity generation. Techniques is known as MPPT (Maximum Power Point Tracking).

- 12V output terminal – port supplying most appliances available within SHS. This includes lighting or TVs.
- 5V output terminal – USB port supporting some low power appliances such as phone chargers, radios.

Out of three types of ports available within each SHS, integration of the Energy Box could be achieved by utilising one of 12V terminals. Connection to PV Input to energise SPM would initiate problems with the internal control of SHSs which would rise a risk of SHS not transferring maximum power from the PV module to the battery due to undesirable interaction with the MPPT. Moreover, PV Input terminal port supplies electricity only when solar module produces energy (during day). On the other hand, connection of Energy Box to one of the 5V USB terminals allows extraction of low power rates (typically few watts) and is not a solution to effectively export energy from the SHS. As a result, the optimal way to form interconnected SHSs microgrids is by connecting Energy Boxes directly to 12V output terminals of SHSs, as indicated in Figure 4-7.

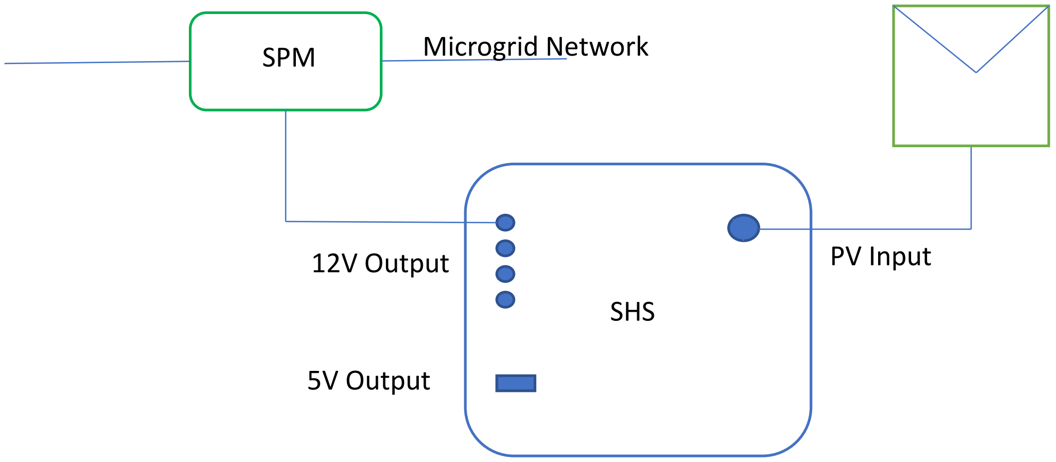

Figure 4-7. Solar Home Systems with a Connection to SPM and local Microgrid System

Connection between SPM module and SHS as presented in Figure 4-7 gives adequate understanding of SHS SoC due to nature of lead-acid batteries which voltage levels are proportional to battery charge level [111]. This technique to estimate SoC is frequently used by SHSs operators, mainly due to its simplicity. High voltages at the battery terminals (around 13V or higher) indicate that the system is either charging or it is already operating at high SoC. For low voltages (around 12V) indicating low SoC, load shedding can be initiated to protect from reducing their overall life-cycle.

Studies performed while developing SPM model for interconnected SHSs are based on the battery profiles valid for BBOXX SHSs. Figure 4-8 illustrates voltage and SoC relationship. Data presented were shared by the BBOXX technical team supporting studies.

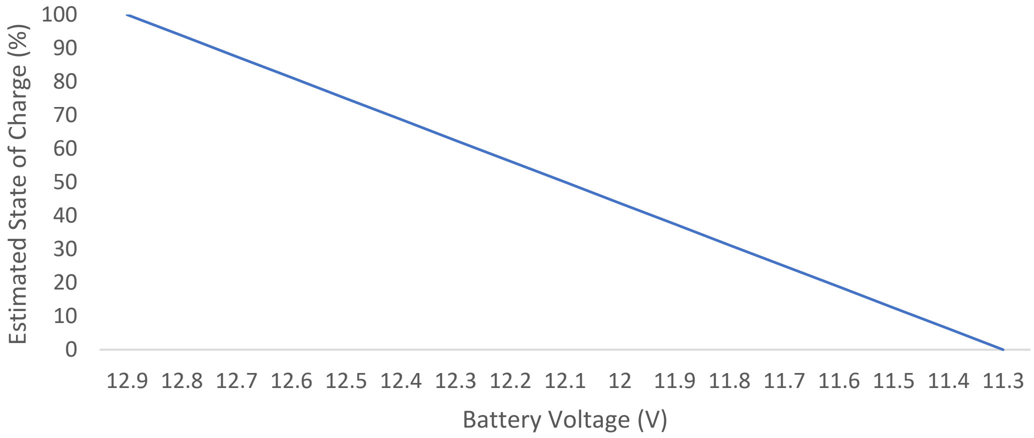

Figure 4-8. Estimated SoC of the BBOXX battery based on voltage measurement

For 12V lead-acid batteries prevalent in many off-grid SHS, charging voltage typically increases beyond 12.9V (maximum indicated in Figure 4-8) and can reach up to 14.5V [112]. This stage of charging is known as “bulk” when maximum power produced by the solar module is transferred to the energy storage. Identifying estimated SoC based on battery voltage level is therefore inaccurate. Once maximum recommended voltage is obtained, charge controller switches into absorption state to maintain fixed level of 14.5V (for BBOXX systems). This phase lasts for as long as charging current drops below certain value (200mA in case of BBOXX SHSs). Once this occurs, battery level drops to 13.5V until supply within the SHS is higher than demand. Full lead-acid battery charging sequence is presented in Figure 4-9 [113].

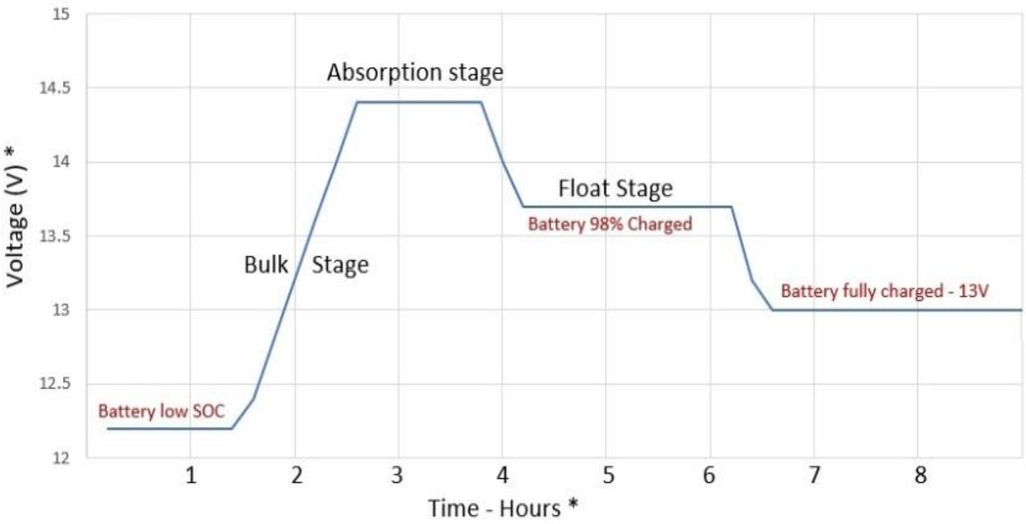

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Figure 4-9. Charging Cycles of a Lead-Acid Battery

Recognizing battery voltage levels by the SPM is crucial while managing power within the microgrid system. At each stage different control functions are executed to satisfy requirements of the local energy network; keeping balance between supply and demand as well as initiating load shedding when it is required.

According to Figure 4-9, charging of battery starts from around 12.3V where estimated state of charge is around 50% - minimum recommended for lead-acid systems to keep system at optimal operation. This typically occurs at night, when SHS is not charged by the PV module. In such events, SPM should tend to reduce power export from the SHS to maintain minimum capacity for basic appliances including phone chargers and lighting systems. Simultaneously, power demand within networks of interconnected SHSs is expected to be primarily supplied by SHSs with high SoC of the batteries to maximise duration of system operation without initiating load shedding. In the events when overall demand is still too high and SHSs are exposed to low SoC levels, DSM system should tend to disconnect high-power appliances, starting from “microgrid zones” where electricity deficit is the highest.

Once solar module starts generating electricity, battery reinitiates charging cycle resulting in voltage boost. As a result, SPM system can start supplying more significant portions of electricity from the SHS into the network, allowing appliances to be reconnected. Once electricity storage level reaches nearly 100% (see Figure 4-9), voltage suddenly drops and remaining power production within the SHS goes to waste (in standalone operation). As a result, Export Surplus Mode activates to effectively prioritise electricity export from SHSs with full batteries over others (still charging) in the network. As such, rate of electricity utilisation in the microgrid could be maximised.

4.4.1. Microgrid Voltage Control based on Estimated Battery State of Charge

Maintaining balance between supply and demand between all SHSs interconnected can be achieved by appropriate control of the microgrid. Within the proposed SPM system, it is obtained by an introduction of dynamic management of the network voltage setpoint adjusted at each Energy Box controller which is ultimately governed by the boost converter. As a result, each SPM supplied by SHSs with high SoC has a capability to maintain higher network voltage setpoints than those with low SoC within such network. As such, prosumers experiencing higher amount of electricity stored within batteries are prioritised while contributing to overall electricity demand in the system. Such functionality could be maintained by introducing correlation between SHS SoC and microgrid voltage level. This linear relationship established for the SPM is presented in Figure 4-10 and assumes that range of microgrid network varies between 44 and 48V (maximum rated voltage allowed within off-grid microgrids in Rwanda [114]).

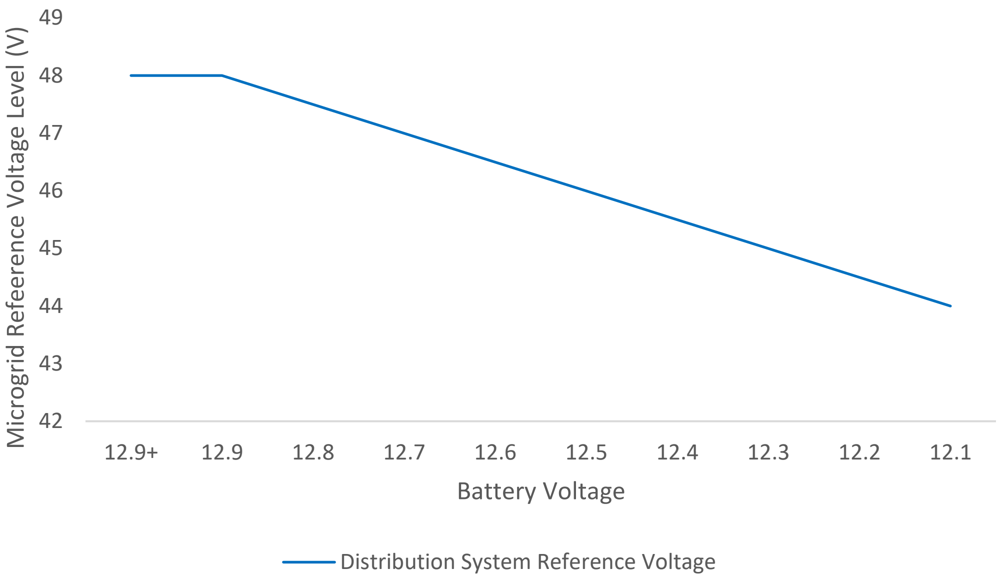

Figure 4-10. Microgrid System Reference Voltage Level based on Battery Voltage Measurement

As seen in Figure 4-10, reference voltage level of the microgrid network is directly proportional to battery voltage level between 12.1V up to 12.9V, according to Equation below:

$$V_{\text{Dist. Ref.}} = 48V - (12.9 - V_{\text{Battery}}) \times 5 \qquad \text{Equation 4-1}$$

where $V_{\text{Dist Ref.}}$ is a value representing distribution network voltage set point, V_{Battery} is a battery voltage. Equation 4-1 confirms that voltage control of a microgrid system is always proportional to SHS battery level, which results in prioritizing SHS with higher battery levels while supporting new load connected to the system. The scope defining such linear relationship between battery voltage and microgrid reference point (specified as “5” in the Equation 4-1) could be modified depending on the microgrid operator requirements as well as network specification. For systems with cables of high cross-section area (similar to low voltage distribution networks cables deployed in Rwanda with cross-section area of 35mm^2), typical voltage drops between prosumers are expected to be low and appropriate voltage adjustment can be achieved by maintaining low gains. Under a scenario where distribution cables have low cross-section area and high resistance (for example 1.5mm^2 copper cables used by MeshPower), obtaining appropriate balance between SoC of the SHSs in the network would require higher slope defining relationship between SoC and microgrid reference voltage. Lack of such aggressive gain may prevent SHSs to equalise SoC which ultimately could prevent users from introducing new electrical appliances, despite having high amount of energy available in the microgrid. This can overstress some SHSs within the proximity to the demand and prevent other SHSs to support this load.

Proposed microgrid voltage control can be adapted to all SHSs relying on 12V lead-acid battery systems. Further investigation is required to be considered while introducing lithium-ion batteries which costs are significantly being driven down mainly by wide development of electric vehicles and various portable devices [115], [116]. As such, appropriate microgrid voltage reference value could be specified depending on the total amount of electricity exported by the user per day. As a result, internal control of the SPM would be required to sum energy that is being exported for the whole duration of a day. The procedure could be reset each time voltage on the lithium-ion battery enters exponential zone when voltage of the battery is substantially beyond rated value, indicating high state of charge [117].

4.4.2. Voltage Control to Export Surplus of Energy

Under very specific scenario where SHSs fully completes charging routines and still have capability to produce electricity (but not to store it), additional control technique is applied. Under such scenario, the SPM can boost voltage beyond 48V - maximum microgrid voltage, according to Figure 4-10. As a result, system increasing distribution voltage beyond 48V are prioritised in supporting load in the microgrid by utilising electricity which otherwise would go to waste. Under such control scheme, direct interaction between SHS internal management system and Energy Box is introduced. SHS aims to maintain battery voltage at 13.5V (in case of BBOXX systems) for as long as surplus of electricity is produced whereas SPM manages system to reduce this voltage level down to 12.9V (associated with 100% SoC, based on relationship presented in Figure 4-10) by exporting energy from the SHS. Once battery voltage drops below 12.9V indicating operation below SoC of 100%, Export Surplus Mode is deactivated, and system returns to standard Voltage Control operation within voltage ranges indicated in Figure 4-10. Furthermore, SPM returns to its normal operation and synchronises microgrid within the range of 44-48V.

The summary of two control strategies for the boost converter are presented in the Table 4-2 below.

Table 4-2. Features of the Microgrid Network Voltage Control Strategies

Technique	**Voltage Control**	**Export Surplus Mode**
Maximum Voltage Reference (V)	48	50
Maximum Power Allowed (W)	20	35
Condition	Normal Operation	Battery Fully Charged

Together with activation of the Export Surplus Mode, buck converters importing electricity (see Figure 4-1) change their operation strategies. Its output voltage set point which at any other time is set to 12V (voltage where high-power appliances are connected), starts gradually increasing which essentially results in delivering more power to batteries connected to the buck converter output terminals. During this period, power imported is controlled in order not to exceed 50W (maximum recommended for BBOXX SHS) as well as to maintain voltage within 12V battery charging levels.

Summary of voltage levels at each stage of the SPM during different modes of operation are presented in Figure 4-11 and Figure 4-12.

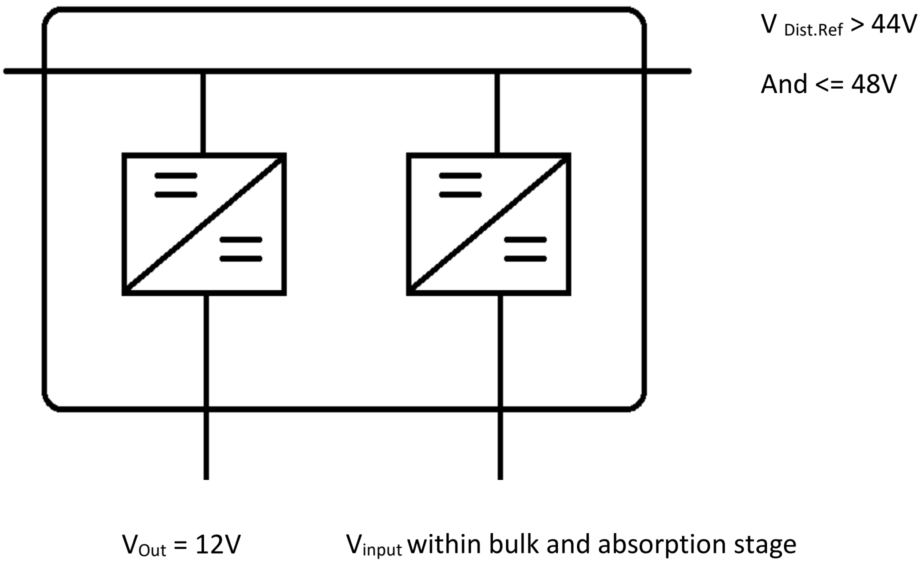

Figure 4-11. System Parameters Under Voltage Control Mode

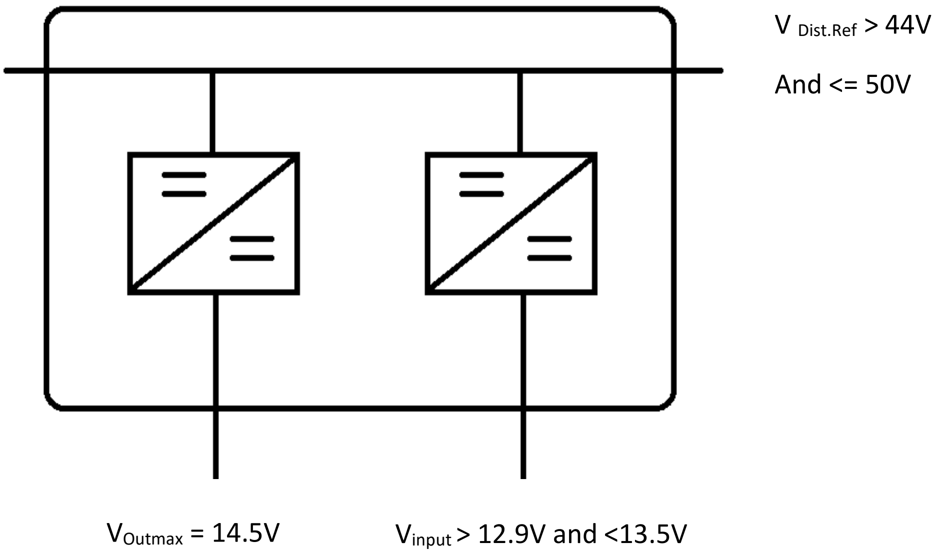

Figure 4-12. System Parameters Under Export Surplus Mode

The proposed Export Surplus Mode is a smart function activated whenever SHSs operate at full batteries. SPM system governing power flows gives chance to prioritise electricity produced by SHS over others, in order to match existing demand in the microgrid. As a result, SHSs which normally remain with the energy deficit are given a chance to reduce power outflows and consequently store it for further use. The practical implementation of this SPM functionality on power converters is presented Chapter 5.

4.6. Summary

Analysis performed in Chapter 4 presents selection of appropriate appliances to be supported by the networks of interconnected SHSs. It primarily focuses on adoption of refrigeration systems as well as TVs which are considered as the most desired devices among the families currently relying on SHSs, as revealed in Chapter 3. Appropriate appliances have been selected with respect to their compatibility with off-grid DC systems operating with limited generation and storage capacity requirements defined by the prosumers' installations. Specification of such appliances gives understanding of the minimum technical requirements for further design of the Energy Box. Such consideration is a base for further analysis presented in Chapters 5 and 6.

Chapter 4 gives further indication of the features essential to provide compatibility between the SHS as well as Energy Box. These are explained by giving insights to limitations as well as opportunities introduced by SHSs, focusing on BBOXX models. Studies reveal how integration of Energy Box using existing SHSs can be successfully achieved without structural reconfiguration of the assets currently deployed in field. Furthermore, appropriate power management is presented which indicates optimal strategies to develop desired control features within the network of interconnected SHSs. Such concept gives opportunity to maintain equalised SoC of the SHSs' batteries within the microgrid to maximise operational duration of the systems. Moreover, smart techniques to export surplus of electricity generated by the SHSs are revealed to prioritise electricity distribution produced by SHSs with fully charged batteries. Verification of all these SPM techniques is detailed in Chapter 5 where technical models of the controller are presented based on Matlab Simulink models established. Further work revealed in Chapter 5 indicates hardware design aspects of the proposed controller to create the final product – the Energy Box.

5. Development of the Energy Box Controller providing SPM Functionality

Development of the Energy Box providing interconnections between prosumers requires comprehensive analysis of electronic components as well as control schemes governing power flows between SHSs. Fundamental features of the SPM system as well as electronic circuits specified for the Energy Box were initially modelled in Matlab Simulink. Studies undertaken indicate various operating conditions to which system might be exposed while powering new electric appliances in rural off-grid villages across SSA. Furthermore, hardware components providing those control features have been selected and combined to develop the final product, ready for field tests in Rwanda.

Chapter 5 starts with explanation of Energy Box modes of operation, from pre-synchronised state which is activated as soon as the Energy Box is energised. SPM is therefore required to support voltage on the microgrid network by exporting electricity from the SHS without violating maximum power outflow limits dedicated by the internal protection system of the SHS.

Following SPM starting sequence explanation, steady-state control functions to govern microgrid network are described. Each sub-control mode within this sequence introduces different degrees of voltage dynamics. These are defined by primary control mode - providing optimal voltage management to satisfy voltage limit constraints on the microgrid network once step change in load is applied and secondary control recovering microgrid voltage back to its optimal setpoint. Chapter 4 revealed SPM functionality to export surplus of electricity generated within SHS which requires synchronisation between boost and buck converters within each Energy Box (see Figure 4-1). Such control loop is directly combined with the secondary mode of operation of the power converters.

Final section of Chapter 5 includes hardware design of the proposed solution. This covers all necessarily considerations while developing the physical model of the Energy Box as well as code generation to provide all functions required by the system. Code efficiency is validated with a support of Real Time Operating System (RTOS) to indicate feasibility of CPU serving multiple tasks in parallel [118]. As a result, all control loops are regularly executed within specified sampling time. Following explanation of code generation capabilities for a design of SPM, practical implementation as well as product design process is explained.

5.1. Power Export – Operation of the Boost Converter

The simplest (and the cheapest) approach of designing interconnected SHSs microgrids is by introducing functionality that allows SPM to understand conditions of each SHS by controlling microgrid voltage levels. Such procedure eliminates necessity for communication modules between SHSs which would increase production costs as well as energy requirements for Energy Boxes. Associating SPM control algorithms according to microgrid voltage levels can provide all functions required by the microgrid listed in Chapter 4. First model established indicates operation of the boost converter – section of the Energy

Box in charge of exporting electricity from the SHS. Simulink model of such system is presented in Figure 5-1.

The technical model of the system presented in Figure 5-1 is comprised of a battery unit, boost converter and section of a local distribution network model. The battery is characterised according 12V lead-acid 17Ah (such as those used by BBOXX in Sub-Saharan Africa) specification. It is therefore directly connected to two resistors in parallel which are terminated by the input of the boost converter – stage where electricity is exported from the SHS to the microgrid system. Resistors between the battery and boost converter are modelled to represent 1 metre of 0.75mm^2 copper wire which was selected to connect SHSs with the Energy Box.

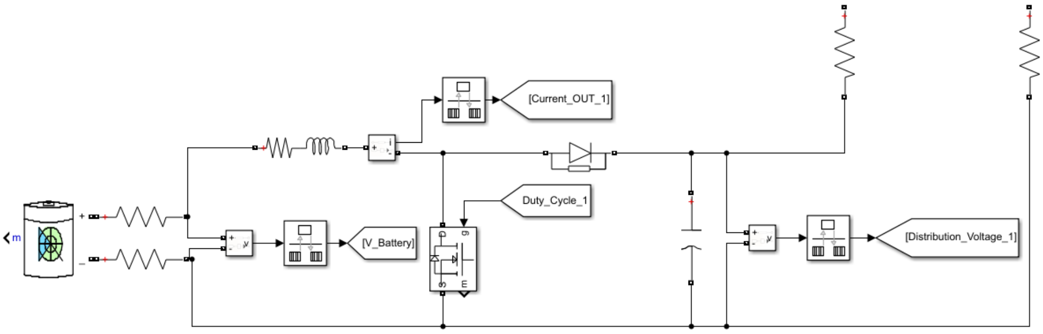

Figure 5-1. Boost Converter Model to Export Power from the SHS.

Proposed boost converter illustrated in Figure 5-1 is terminated by 50 metres of 1.5mm^2 cable which provides interconnection with another power converter of the same topology as in Figure 5-1. Elements of the boost converter in the model include [119]:

- Inductor - storing magnetic energy of moving electrons and releasing it to increase voltage on the output capacitor
- Diode – located between microgrid voltage busbar as well as 12V input to the converter keeping separation between two voltage levels sections

- MOSFET - switching on and off at the frequency of 20 kHz which ultimately results in energising inductor circuit.

The parameters of components of each element are illustrated in the Table 5-1 below.

Table 5-1. Selected Parameters for the Boost Converter

Element	Parameters
Cable for SHS connection	0.75mm^2 cable of 1 metre
Inductor	400µH at 2.5amps, 0.05 Ohms
Capacitor	5600µF of up to 50V DC
Schottky Diode	Froward Biased Voltage of 1.05V

The model takes three measurement signals – battery voltage (V_Battery), distribution network voltage (Distribution_Voltage_1) and current between the battery and local microgrid network (Current_OUT_1).

Design presented in Figure 5-1 could potentially be improved by replacing a diode (see Figure 5-1) with another MOSFET element [120]. Although introduction of MOSFET could significantly reduce overall losses while providing electricity to the microgrid, it would require additional analysis to provide coordination between MOSFETs to prevent short-circuit between battery 12V terminal and ground [121]. As a result, in order to reduce complexity of the circuit providing SPM between prosumers, model includes design involving a diode between 12V (battery) and 48V (microgrid) busbars.

All measurements are sampled for the purposes of the simulations at 4 kHz which is equivalent sampling frequency of the CPU governing Energy Boxes. The input to the model controlling boost converter is labelled as Duty_Cycle_1 (see Figure 5-1) which provides PWM modulation to control MOSFET regulating current flow between the battery and microgrid.

Before steady-state operation of the system is obtained, each SPM is required to synchronise with the microgrid. This is performed by the pre-synchronisation soft-start mode introduced within each Energy Box. This mode of operation is initiated as soon as SPM becomes energised by connecting 12V output terminal of the SHS with the Energy Box. Once SPM gains understanding of estimated SoC of the SHS, SPM initialises appropriate control functions defining duty cycle for the converter to manage power outflows and effectively support microgrid voltage. Once this is completed and voltage of the local network reaches minimum threshold level set by the SPM algorithms, Energy Box becomes synchronised and enter steady-state mode of operation. Consequently, boost converter maintains stability of the microgrid voltage and keeps it within the minimum and maximum levels allowed for as long as network operates within safe conditions (when no faults is detected) and where balance between demand and supply is maintained. As revealed in Chapter 4, voltage on the microgrid system varies depending on the SoC of the batteries as well as balance between demand and supply within the network. The minimum steady state voltage level is set to 44V and is prevalent during periods when demand exceeds supply and overall SoC interconnected SHSs is low. In case of surplus of energy being generated in the network, distribution voltage can boost up to 48V-50V to prioritise electricity utilisation from SHSs with full batteries over those which are still charging. In parallel to voltage control settings, power outflows measurements are taken to keep maximum current outflow below the SHS protection threshold. Full algorithm sequence including modes of operation for the boost converter is illustrated in Figure 5-2 where V_d* corresponds to measured microgrid voltage, V_b* indicates battery voltage measured, and P_e* reveals power exported from the SHS to the microgrid. V_{ref} and Pemax indicate reference voltage on the microgrid network as well as maximum allowed power export from the SHS.

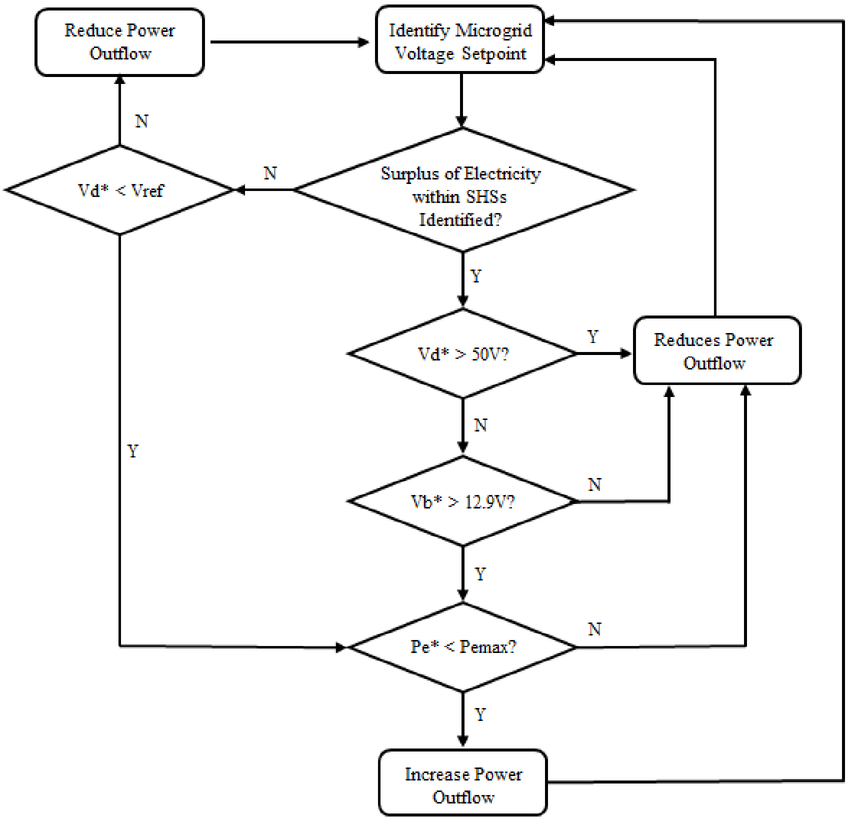

Figure 5-2. Control Strategy of the Boost Converter during Steady-State Operation

According to Figure 5-2, for as long as SHS does not present evidence to produce electricity surplus, SPM governs duty cycles of the boost converter based on two measurements: microgrid voltage and power exported from the SHS. Figure 5-2 confirms that once distribution voltage drops below desired reference level (defined according to relationship presented in Figure 4-10), SPM tends to boost it up without exceeding maximum power outflows resulting from increased duty cycles. In the events when surplus of electricity produced is identified, SPM enhances power outflows maintaining their maximum allowed ratings. Simultaneously, rate of power exported must consider battery voltage measurement which during this time cannot drop below 12.9V in order not to export electricity stored within the battery unit. Detailed demonstration of boost converter performance under steady-state is presented in Sections 5.3 and 5.4.

5.2. Starting Sequence of the Boost Converter

Before SPM reaches its steady-state operation, it is required to maintain appropriate synchronisation strategy to provide desired interaction with the microgrid. In order to keep safe operation at such pre-synchronised stage, soft-starting techniques are proposed. They maintain smooth power management process without exceeding maximum current outflows allowed by the SHS. Such strategy is particularly important in the events when SHS with high SoC is connected to the microgrid. As a result, minimum distribution reference voltage threshold of its SPM could be higher than actual voltage on the microgrid. As a result, attempt to boost voltage could activate internal SHS overcurrent protection and disconnect all loads connected to the SHS.

5.2.1. Operation under the Pre-Synchronisation State

Once Energy Box is connected to SHS, duty cycle of the boost converter in charge of exporting electricity activates. Control algorithm in charge of system synchronisation is presented in Figure 5-3.

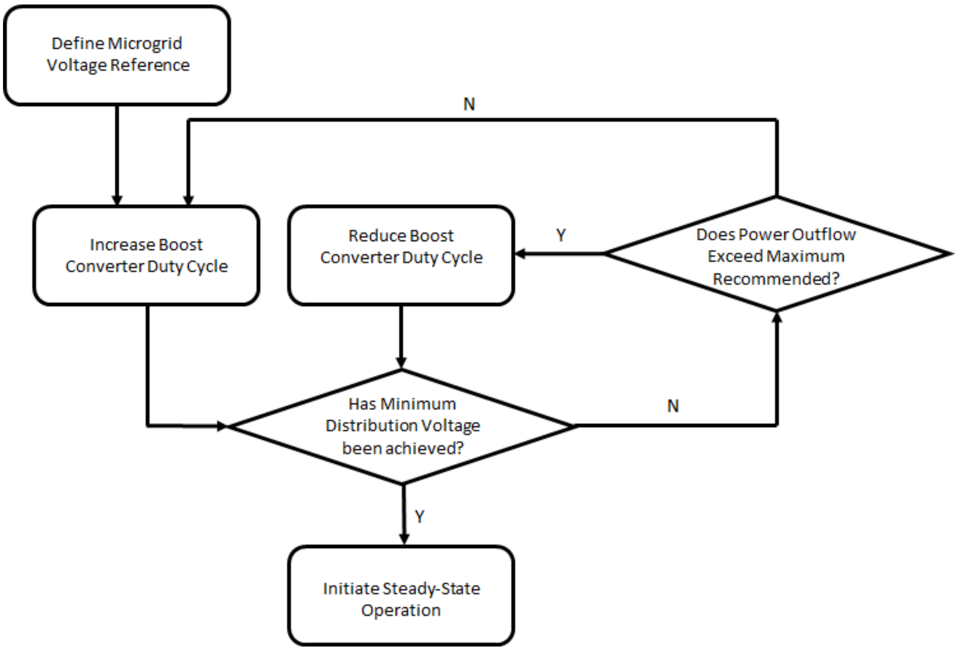

Figure 5-3. Pre-Synchronisation Operation of the Boost Converter

According to algorithm presented in Figure 5-3, duty cycle of the boost converter increases only under two conditions. First, in the events when measured microgrid voltage is below optimal distribution network voltage reference set-point. Under such scenario, smart operation of interconnected SHSs microgrids indicates that newly connected SHS within the network has higher SoC of the batteries than systems currently interconnected. As a result, such SHS is therefore required to contribute higher amount of electricity to the network than other SHSs previously interconnected with lower SoC. These conditions are to be maintained for as long as SoC of the batteries are equalised between all SHSs interconnected. During such events, power is maintained below maximum recommended of 20W. For SHS of high SoC being connected to the microgrid, high power outflows will promptly reduce battery voltage (and equalise it with SoC of other systems interconnected) which ultimately provides transition of SPM operation from the pre-synchronised to steady-state.

5.2.2. Starting sequence under no-load conditions

Energising microgrid and providing transition between pre-synchronised to steady state has various impact on the microgrid voltage dynamics. Under a scenario where no load is connected to the microgrid, boosting voltage to a reference value can be achieved rapidly without need to significantly increase in duty cycle. Example of SPM operation under such condition is revealed in Figures 5-4 and 5-5 which present duty cycle of the boost converter and microgrid measured voltage respectively.

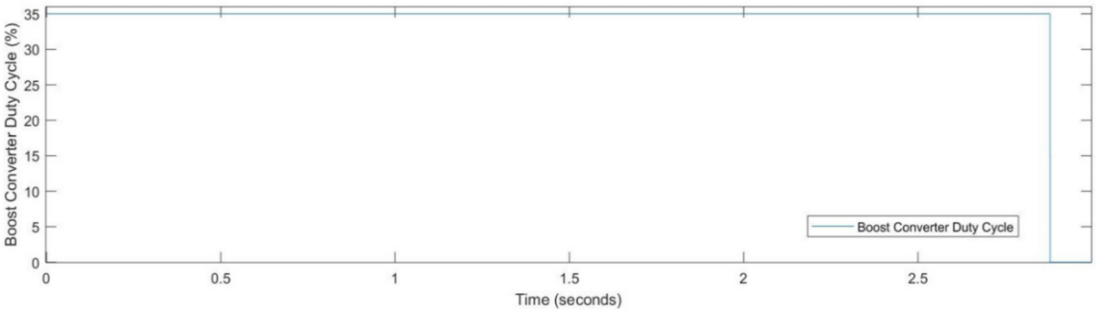

Figure 5-4. Duty Cycle of the Boost Converter Under No-Load Conditions

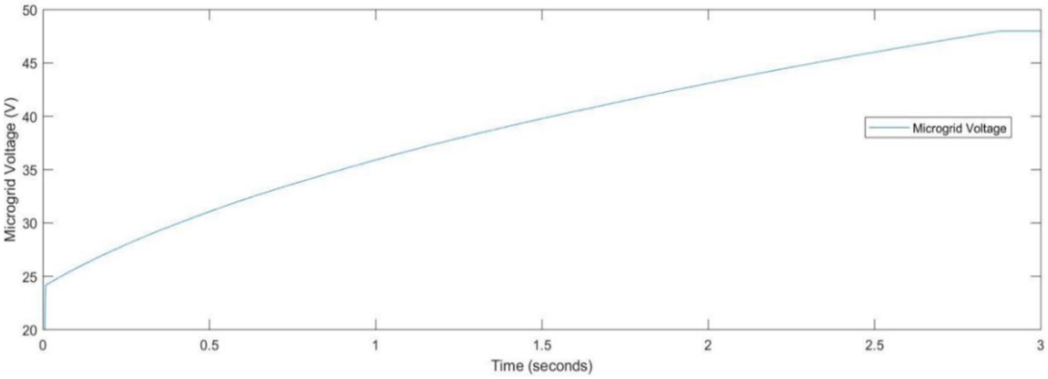

Figure 5-5. Microgrid Voltage while Energising the System Under No-Load Conditions

For a system operating under no load, duty cycle typically does not go beyond initial level of 35% (set in the model) and full charge delivered to the output capacitor of the boost converter is stored instantaneously. Once the reference voltage is reached, system becomes synchronised and duty cycle drops to keep optimal voltage level for as long as there is no evidence of new loads being connected.

5.2.4. Starting Sequence with Load Connected to the Microgrid

Reaching synchronisation with the microgrid network is more challenging when one or more prosumers import electricity. Under such condition, duty cycle is required to increase beyond initial 35%. This indicates that higher rates of electricity are being exported from the SHS to reach minimum distribution network voltage threshold which would ultimately provide synchronisation between the SPM and microgrid itself. Once appropriate voltage level is obtained, power outflow drops, and steady-state operation of the SPM is initiated. Figures 5-6 and 5-7 present operation under such condition and indicate voltage profile measured as well as duty cycle respectively. The simulation has been performed considering resistive load being connected to the output terminals of the boost converter. Synchronisation between SPM and microgrid has been achieved 5.6 seconds after activating the system and maximum duty cycle of the converter increased from 35% (set up at the initial state) to approximately 45%.

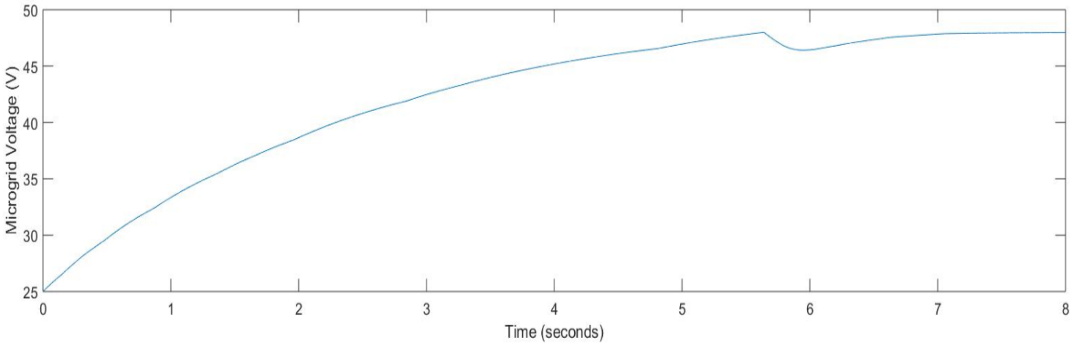

Figure 5-6. Voltage Profile of the Microgrid System.

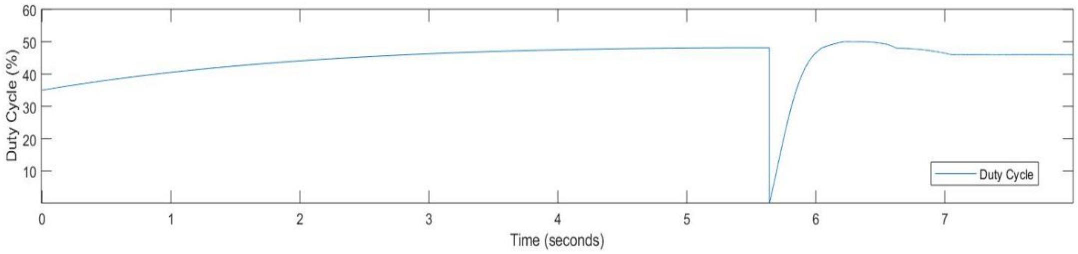

Figure 5-7. Duty Cycle after Energizing the Circuit under Load Condition.

Based on Figure 5-6 and 5-7 illustrating dynamics of the soft-started under load conditions it can be assumed that appropriate microgrid distribution voltage of 48V has been reached approximately two seconds later than under no load scenario (see Figure 5-5). Over the period of 5.6 seconds boost converter’s duty cycle has increased from 35% to 45%. This moderate change in duty cycle shows that controller aims to increase microgrid voltage without rapid change in current outflow from the SHS to the microgrid network.

Lack of such soft-starter stage could prevent prosumer with high SoC of the battery from connecting to the microgrid of interconnected SHSs where majority of users maintain low SoC. As a consequence, newly connected SHS would tend to boost voltage to higher reference setpoints to reach minimum voltage threshold by exceeding maximum current outflow limits. With an introduction of soft-starter techniques, the maximum current during initialisation presented in the studies was found to be 0.75A which is significantly lower than maximum allowed by BBOXX SHS of 3.5 amps. As a result, under proposed control arrangement, SPM systems can effectively synchronise with the network without violating technical constraints introduced within existing SHSs. Once SPM reaches such synchronisation, microgrid control at steady state is initiated.

5.3. Voltage Control during Steady-State Operation of a Boost Converter

This section presents operation of the voltage control loops which are introduced to support stability of the microgrid network after SPM switches from the pre-synchronised to steady state. Appropriate control techniques are therefore defined to provide capacity for new high-power appliances connected to the network and supplied from numerous SHSs simultaneously.

Microgrid voltage control techniques are divided between primary and secondary. The first (Primary Control) acts as soon as step change in voltage on the distribution network is detected by the SPM. Its fundamental task is to maintain microgrid voltage within its limits in the first hundreds of milliseconds after high-power load is connected.

Secondary control follows the primary. It is introduced to recover microgrid voltage back to optimal level, minimizing distribution losses. As a result, appropriate power flows between SPM systems are established, prioritising electricity provision from SHSs with high SoC over others, with low SoC. As a result, overall performance of all batteries within interconnected SHSs is equalised, increasing overall operational duration of the system.

Full control loop of the voltage control during steady state operation when no surplus of electricity produced by the SHS is detected is presented in Figure 5-8. Such approach measures voltage on the microgrid system (V_d*) and compares it to reference of the system. It therefore passes through the PI controller providing primary and secondary control features [122]. Output signal (e*) obtained is therefore added to a function damping constant power oscillation (f*), using virtual resistor method taking current outflow (I_{out}*) as a reference signal [123], [124].

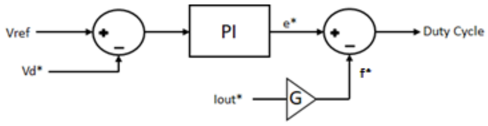

Figure 5-8. Steady State Microgrid Voltage Control Loop

Based on the voltage control loop illustrated in Figure 5-8, once distribution voltage (V_d*) drops, indicating new load connection to the microgrid, the difference between reference voltage and its actual value increases which essentially enhances duty cycle of the boost converter.

Functionality of such control loop is presented in the next experiment where constant current load of 0.15 amps is connected at the output terminal of the boost converter as presented in Figure 5-9. Figures 5-10 and 5-11 indicate microgrid voltage dynamics as well as power outflow from the SHS to the microgrid. The load was connected after 1 second from the simulation initialisation.

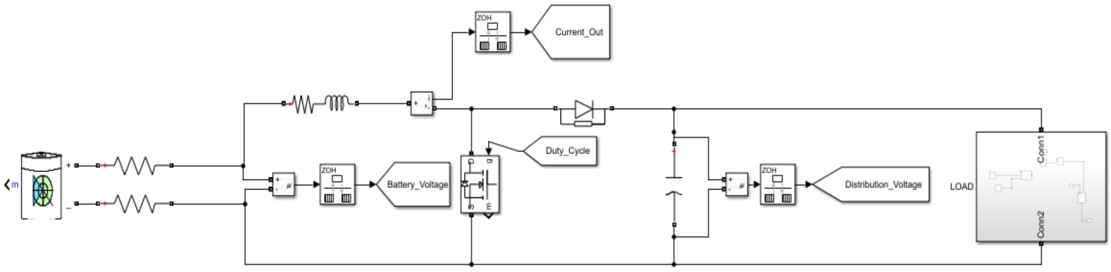

Figure 5-9. Primary Control – System Arrangement

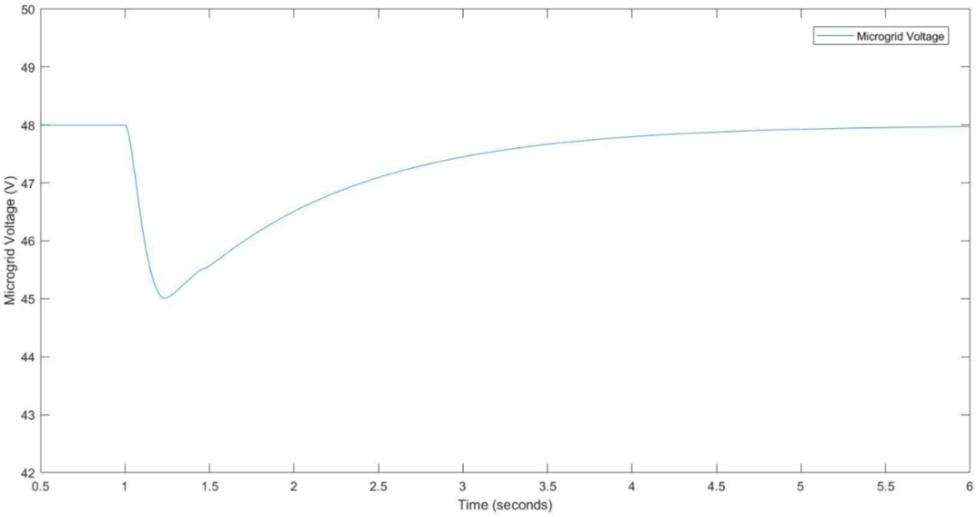

Figure 5-10. Microgrid Voltage Profile after Load Request

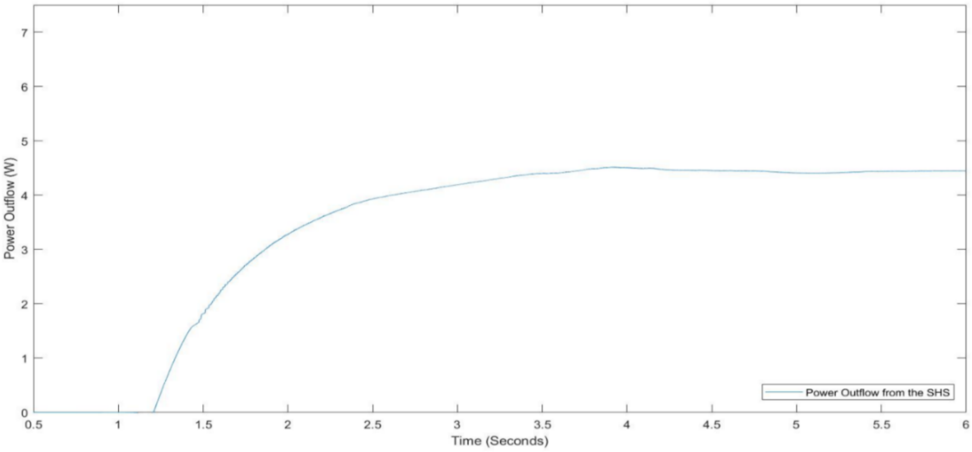

Figure 5-11. Power Outflow of the Boost Converter after Load Request

As illustrated in Figure 5-10, for voltage drops below the reference point of 48V (reference voltage for batteries with SoC of 100%), converter starts exporting power from the SHSs to maintain voltage within 44V-48V. Figures also suggest that after experiencing voltage drop, microgrid system returns to appropriate operation by recovering voltage to optimal level (set to 48V in this case).

5.3.1. Power Sharing between two Systems

Demonstration circuit developed to present dynamics of the boost converters in the events where two SHSs share the same load is presented in Figure 5-12 (boost converter 1 highlighted in orange whereas boost converter 2 in blue). Battery units of both systems are set to have 95% of the full charge. Converters outputs are linked through a local distribution network modelled according to parameters for 80 meters 1.5mm^2 double core copper cable (highlighted in green in Figure 5-12) – cables typically used in 48V DC microgrids installed by MeshPower.

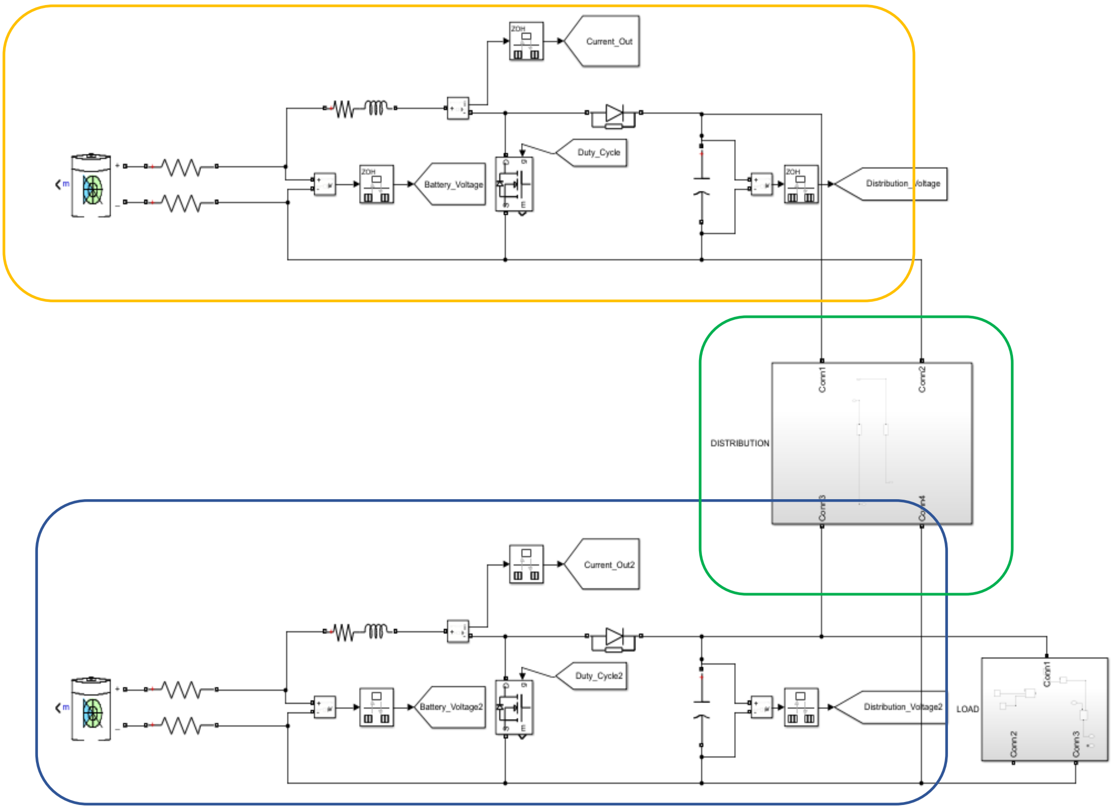

Figure 5-12. Simulink Model of two Boost Converters sharing Electricity to Support Load of 0.5 Amps

Load connected directly to output terminal of the boost converter 1 is requested after 0.5 seconds of starting the simulation. The results presenting power sharing between systems to support the battery are indicated in Figure 5-13. Figure 5-14 illustrates voltage dynamics of the microgrid under investigated scenario.

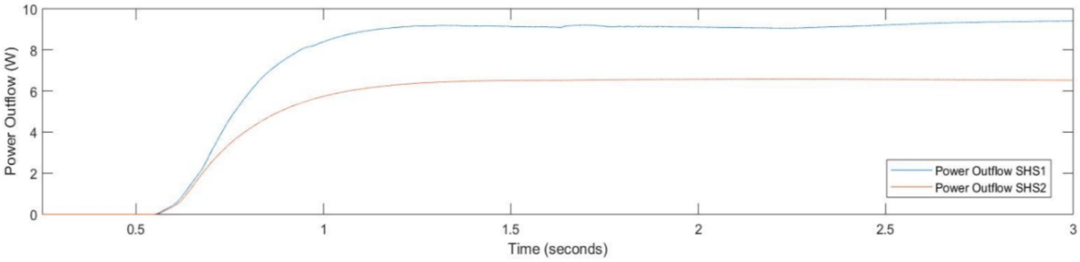

Figure 5-13. Power Outflows between two SHSs supporting Load.

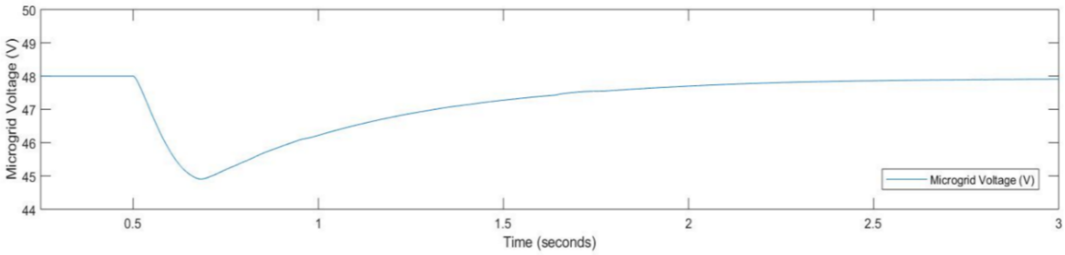

Figure 5-14. Microgrid Voltage Profile after Addition of the Secondary Control

According to Figure 5-14 , after connecting new load to the system voltage goes down to approximately 45V. Within next 1.5 seconds it recovers back to around 47.9V which is a reference voltage point of the distribution system for both systems.

The situation differs under scenario where SoC of each SHS is different. As a result, optimal microgrid voltage level tends to be higher for SHSs with high SoC than those which battery voltage levels are low. To present such interaction using shared power distribution, one SHS battery was set to 100% SoC whereas the other to 60%. As a result, optimal control of the SPM should tend to cover most demand of the SHS with full battery, as long as overall power outflow does not exceed maximum recommended of 20W. Figure 5-15 illustrates the initial condition for the considered scenario.

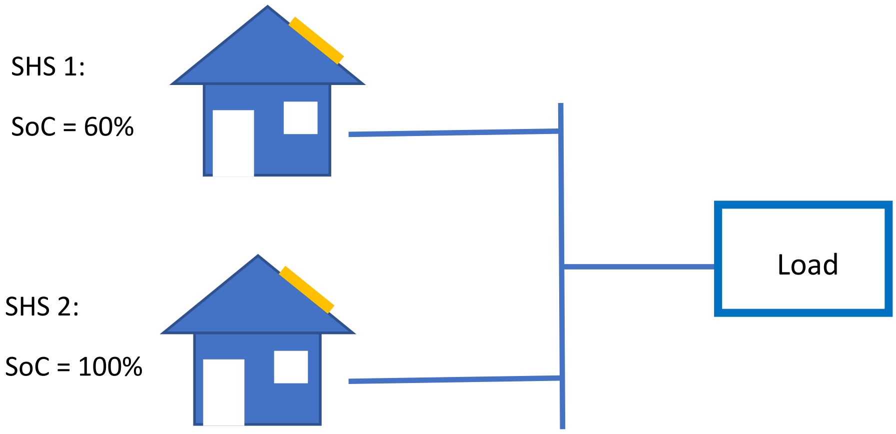

Figure 5-15. Interconnected SHS Arrangement for Load Sharing between Two SHSs with Various SoC

Investigated case considers connection of two loads to indicate appropriate operation of the SPM. First load was introduced after 0.5 seconds and was set to 0.3 amps. After 5 seconds another load of 0.3 amps was connected. As a result of connecting second load, overall power demand within interconnected SHSs network significantly exceeded 20W (maximum rate of power recommended for export by a single Energy Box) and was therefore shared between both systems. Power outflows under these conditions are presented in Figure 5-16 whereas voltage profiles in Figure 5-17.

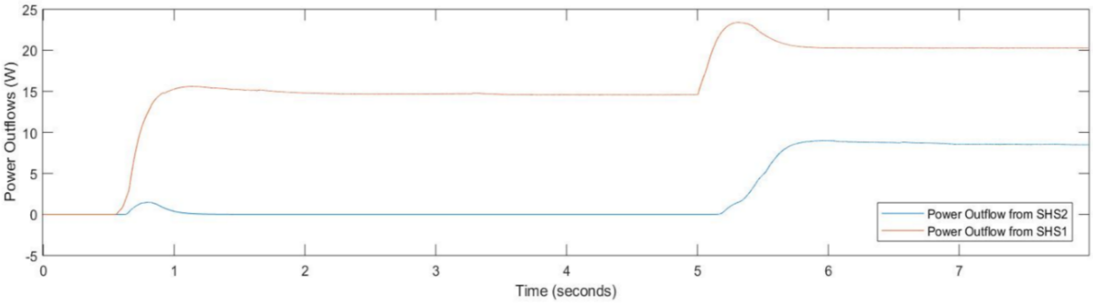

Figure 5-16. Power Outflows from two SHSs with different SoC.

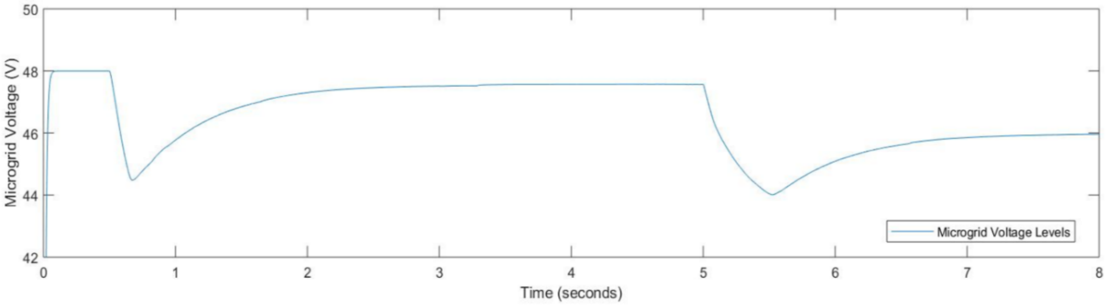

Figure 5-17. Voltage Profiles supported by two SHSs with different SoC.

As presented in Figure 5-16, following the first power request (after 0.5 seconds), SHS1 provides approximately 14W to the microgrid load whereas SHS2 does not cover any of the existing demand. This is a result of interaction introduced between SHSs which tend to equalise SoC between all interconnected SHS by boosting microgrid voltage primarily by systems with a surplus of electricity. The graphic visualisation of the power provision while reaching steady-state after first load is request is illustrated in Figure 5-18.

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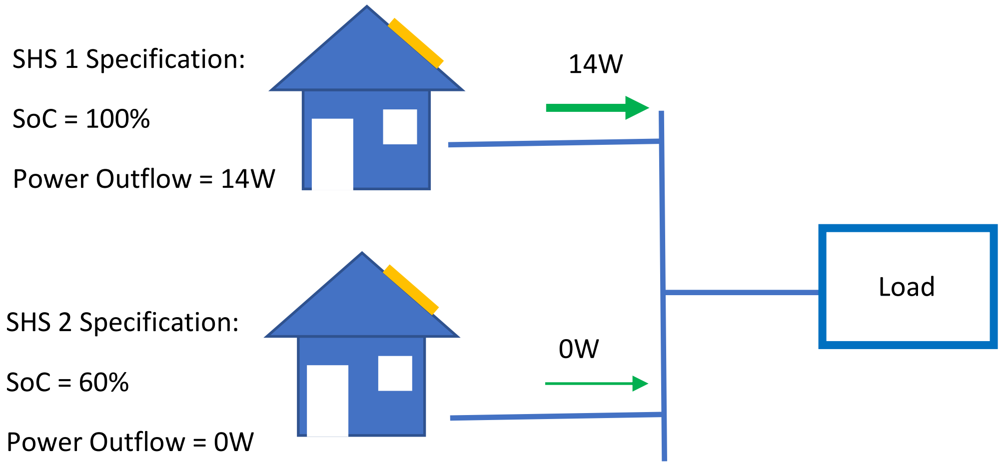


Figure 5-18. Two SHSs with different SoC sharing Demand of 0.3A connected to the Microgrid

Once load doubles to 0.6 amps, power exported from SHS1 increases up to the maximum recommended of 20W and remaining demand (approximately 8W) needs to be covered by the SHS 2, despite its low SoC. Simultaneously, voltage on the distribution network falls from 47.8V to 46V which is a new SHS 2 reference microgrid distribution level. Visualisation of power sharing under such scenario is presented in Figure 5-19.

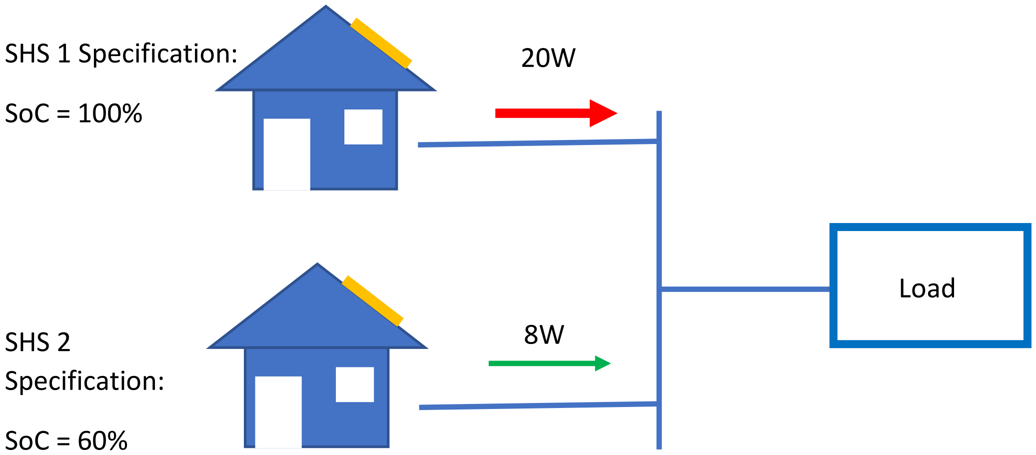


Figure 5-19. Two SHSs with Different SoC sharing Demand of 0.6A connected to the Microgrid

As a result of the SPM introduced between interconnected SHS presented in the experiments in Section 5.3.1, each of the systems interconnected controls power flows in such way that resulting SoC of the batteries tend to be equalised. Meanwhile appropriate control systems maintain maximum power outflows from each SHS in order not to exceed allowed power outflow ratings. As a result, most new high-power load is supported by SHS which remain with the energy surplus, unloading SHS with low SoC which has a positive impact on overall lifecycle of the batteries.

5.4. Export Surplus Mode executed by the Boost Converter

As introduced in Chapter 4, Export Surplus Mode is activated whenever SPM detects surplus of electricity generated within the SHS. As a result, electricity exported from such system is prioritised while supporting new high-power appliances in the microgrid. This gives opportunity to fully charge batteries within SHSs that typically are exposed to higher demand and reaching high SoC during sun-hours takes significantly longer.

Initiation of the Export Surplus Mode is typically indicated by following SHS battery charging cycles. For lead-acid batteries, charge controllers typically reduce battery voltages from approximately 14.5V down to 13.5V when state of charge is close to 100%, as seen in Figure 4-9. Under such condition, Energy Box is permitted to boost voltage of the microgrid beyond 48V in order to maximise utilisation of electricity that would otherwise go to waste.

Export Surplus Mode has been introduced together with the secondary control loop of the boost converter. It essentially increases duty cycle for as long as there if evidence of energy surplus generated by the SHS. This is achieved by continuous monitoring of the battery voltage. For BBOXX SHS, as long as potential to produce electricity exists, charge controller tends to boost battery voltage up to 13.5V (assuming the battery completed all charging cycles). Once SPM starts exporting surplus of electricity, battery voltage drops. Simultaneously, SHS controller tends to compensate it by providing higher quantities of electricity from the solar module to the battery system aiming to recover voltage back to 13.5V. Such operation applies for as long as battery voltage is beyond 12.9V (estimated 100% of battery SoC). Once voltage drops below 12.9V, Export Surplus Mode terminates, and SPM returns to its normal operation.

Together with exporting surplus of electricity from the SHS, SPM is required to monitor power flows in order not to exceed maximum safety limits. In such case, maximum power allowed by SPM to export electricity is set to 35W. Once system spreads this amount of power across the network, boost controller stops increasing outflows in order not to trigger overcurrent protection of the SHS set at 3.5amps per each 12V output terminal within BBOXX system.

Other constraints respected by the SPM operating within Export Surplus Mode are related to maximum voltage limitations allowed within the proposed microgrid arrangement. Under a scenario where significant number of SHSs in the community remain with energy surplus and overall surplus of energy is higher than demand, voltage of the microgrid starts increasing. As a result, each Energy Box module is therefore required to reduce power outflows as soon as maximum voltage of 50V is measured.

The secondary voltage control scheme with addition of Export Surplus Mode functionality is presented in Figure 5-20.

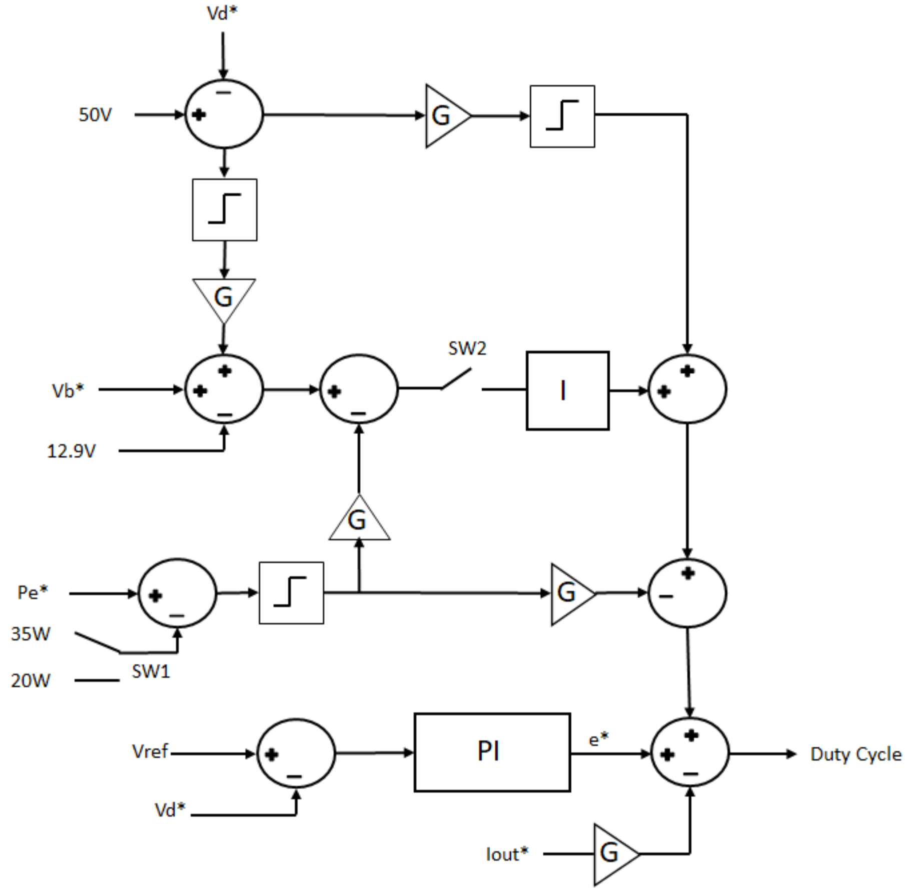


Figure 5-20. Microgrid Voltage Control with Export Surplus Mode Functionality

Export Surplus Mode is a combination of standard control function used to control microgrid voltage at the desired level proportional to the SoC of the battery (presented in Figure 5-8) as well as other major subsystems maintaining appropriate voltage on the microgrid and SHS battery. Power control loop has been supported by a switch element (SW1) which changes SPM maximum power outflow setpoints between 20W (when no surplus of electricity within the microgrid is detected) and 35W when system operates under the Export Surplus Mode. Once this mode of operation is activated, switch 2 (SW2) closes and output of the Integrator (I) gains direct control on the boost converter duty cycles. As a result, output of the Integrator has capability to boost voltage up to 50V, at the same time maintaining minimum battery voltage level of 12.9V as well as maximum power outflow of 35W.

Functionality of the SPM supported by Export Surplus Mode is presented for the configuration between two SHSs interconnected (such as illustrated in Figure 5-12), sharing a single load. Both SHSs start operation at SoC lower than 100%. After 3 seconds SHS 1 switches into Export Surplus Mode and increases its power outflow which essentially allows SHS 2 to charge its battery faster due to lower amount of electricity being exported to cover existing demand. After 5 seconds, demand increases further initialising maximum power outflows allowed of 35W from SHS 1. Power profiles under such scenario are illustrated in Figure 5-21 whereas voltage of the microgrid is presented in Figure 5-22.

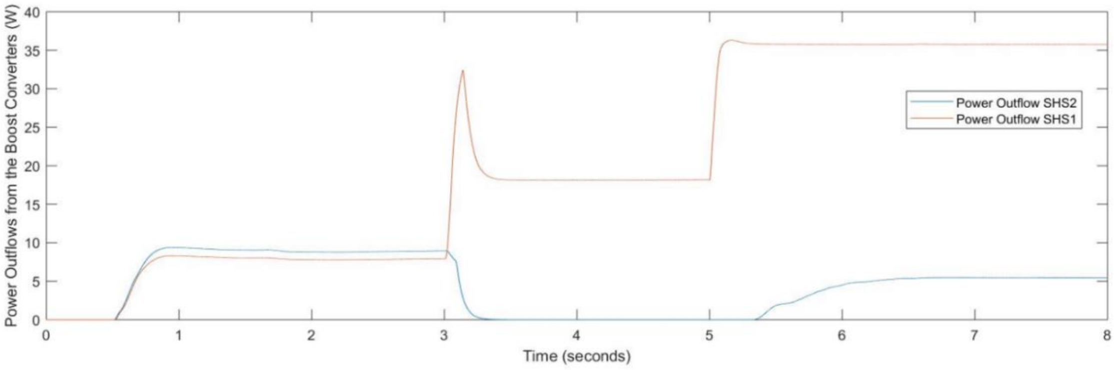


Figure 5-21. Power Outflows after Activation of the Export Surplus Mode

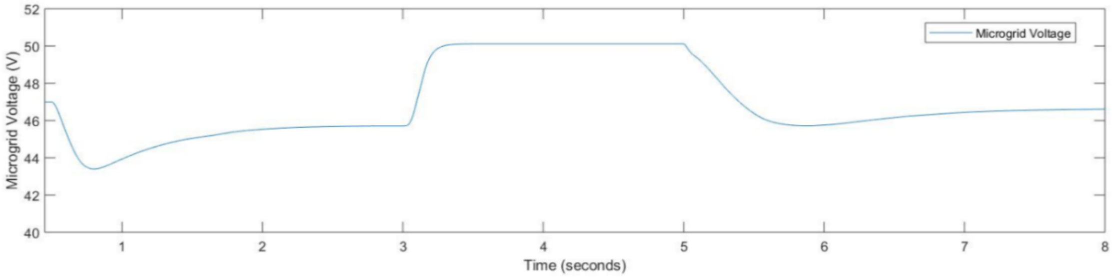


Figure 5-22. Voltage Profile of the Microgrid System under Export Surplus Mode

According to Figure 5-21 and Figure 5-22, between second 3 and 5 voltage of the microgrid increased up to 50V indicating existence of electricity surplus in the local network. Power outflow from SHS 1 for a short period of time (approximately 200 ms) can reach up to 33W. Such power spike produces fast increase of the microgrid voltage. After this transition, full demand is covered by SHS 1. It is also evident that voltage boosts up to 50V which indicates further existence of electricity surplus. After 5 seconds, demand increases again. As a result, distribution voltage drops down to approximately 46.5V indicating that surplus of electricity is either no longer available or has been fully utilised by the loads in the microgrid. It is also evident that maximum rate of power supported by SHS1 is 35W and remaining electricity deficit (approximately 5W) is covered by SHS 2, as indicated in Figure 5-21.

Although coordination schemes providing power control within a network supported by numerous distributed batteries have been already established by introducing adaptive droop control methods adjusted by SoC measurements [125], proposed SPM presents how practically this can be achieved purely based on understanding battery dynamics. Such method is particularly important while considering networks of interconnected SHSs where addition of a smart controller providing electricity exchange between prosumers does not give capability to precisely estimate SoC based on Coulomb counting method [126]. Moreover, adjustable microgrid voltage setpoints introduce a capability to adjust power export according to overall SoC of the batteries, even within low-cost networks with relatively high impedance resulting in significant voltage variations among nodes in the microgrid.

Proposed operation of the boost converter does not require any reconfiguration of the SHS and gives capabilities to export all surplus of electricity within the SHSs to support other electrical appliances in the local community network. Further studies indicated in Section 5.5 present relationship between smart operation of the boost converter and consequently appropriate power management system developed within the buck converter supporting new high-power appliances as well as external batteries.

5.4.1. Export Surplus Mode under Limited Charging Current

So far, Export Surplus Mode of operation has been presented where one of the SHSs is full and still has a capability to generate 35W (maximum power outflow in the Export Surplus Mode) or higher. Different functionality is performed while SHS produces lower rate of electricity than 35W. In such case SPM is required to monitor battery voltage to satisfy minimum voltage level of a battery under the Export Surplus Mode of 12.9V. Such operation is illustrated based on analysis of two systems interconnected with each other as indicated in Figure 5-23. For the experiment presenting functionality of the Export Surplus Mode under limited charging current, it was assumed that SPM installed within SHS 1 detects electricity surplus. The system is also exposed to a charging current of 1.5amps at 12V.

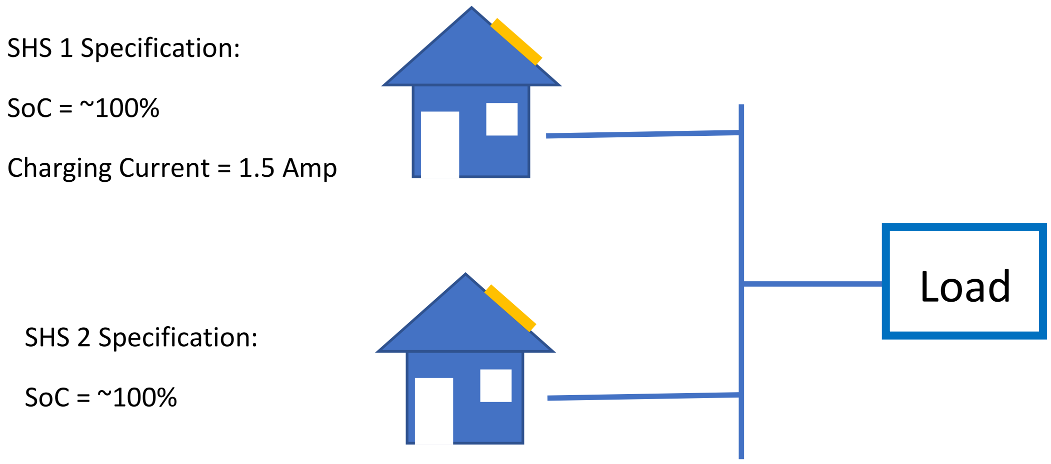


Figure 5-23. Starting Test Conditions for two SHSs interconnected before Export Surplus Mode under limited Generation

Initially both systems have high SoC of the batteries, close to 100%. Load is requested after 1 second. After 11 seconds, SHS 1 switches into Export Surplus Mode. As a result, full generation potential to produce electricity by SHS1 can be used to support demand in the system. Power outflow profiles for such scenario are illustrated in Figure 5-24 where SHS 1 represents unit that enters Export Surplus Mode after 11 seconds. Microgrid voltage profile is presented in Figure 5-25 whereas Figure 5-26 illustrates voltage at the input terminal to the boost converter (battery voltage).

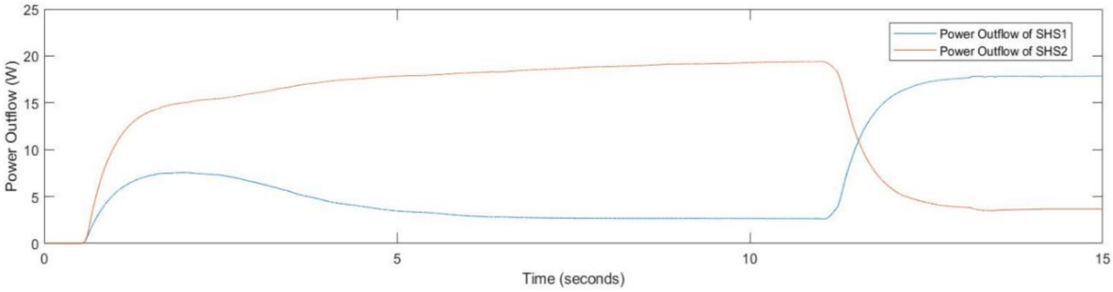


Figure 5-24. Power Outflows and limited Generation capabilities within Export Surplus Mode

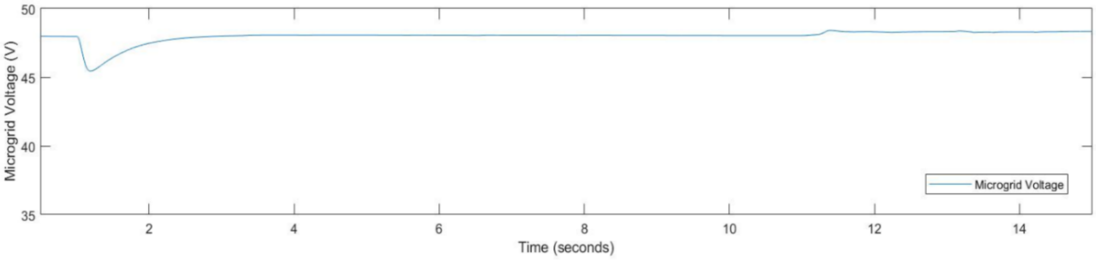


Figure 5-25. Microgrid Voltage Profile under limited Generation capabilities within Export Surplus Mode

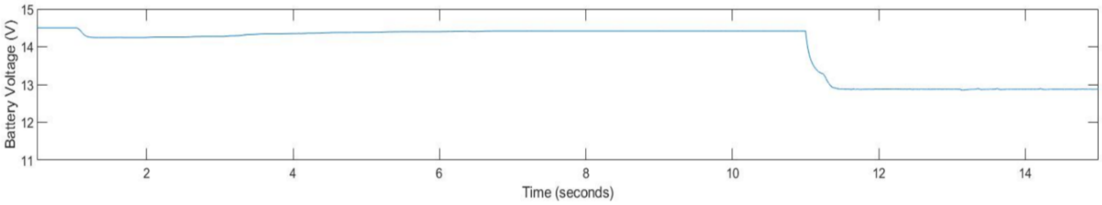


Figure 5-26. Boost Converter Input Voltage under Export Surplus Mode for SHS 1

Figure 5-27 indicates that for the first 10 second (before SHS 1 enters Export Surplus Mode) electricity is shared between both prosumers. SHS 2 supports significantly higher proportion of electricity (up to 18W) than SHS 1 (approximately 3W). This uneven load sharing between two SHSs with similar SoC is a result of differences between distribution network voltage measurement for each system due to measured microgrid voltage at each of two sections of the system. This is a result of resistive nature of the distribution network as well as load being connected within a proximity to SHS 2.

After 11 seconds SHS 1 entering Export Surplus Mode boosts voltage on the microgrid network to utilise surplus of electricity (see Figure 5-25). As a result, power outflow of SHS 1 which was initially contributing significantly higher portion of electricity to the local demand decreases. It is also evident that once Export Surplus Mode is activated, overall voltage on the SHS battery does not go below 12.9V (see Figure 5-26) which indicates that only surplus of electricity produced is being exported to the microgrid system.

Power flows contributions from each of the Energy Boxes after reaching steady-state in the considered scenario with limited power for export are presented in Figure 5-27.

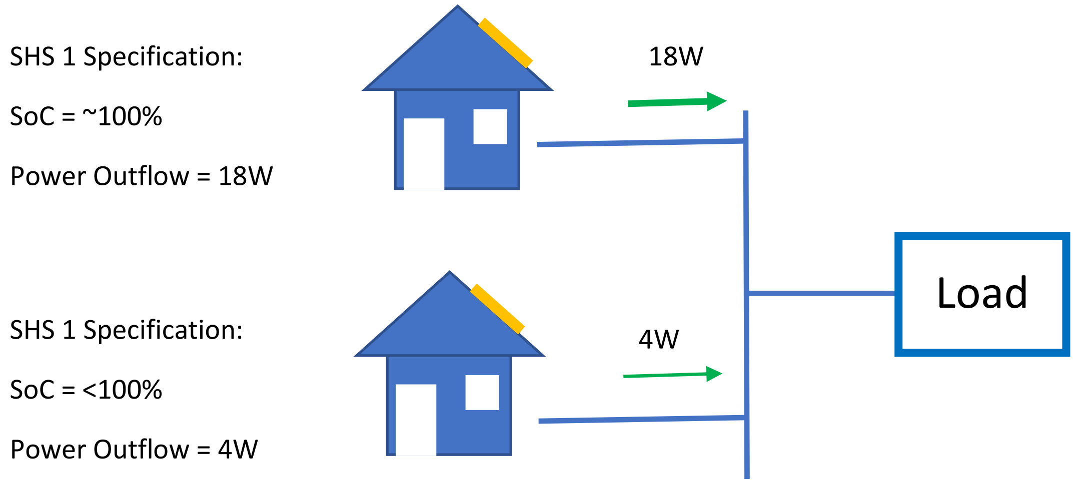


Figure 5-27. Surplus Export Mode Power Flows under Limited Generation

The experiment proves that intelligent power management between SHS can maximise utilisation of electricity in the microgrid of interconnected SHS by prioritising electricity distribution from resources wasting significant portion of electricity. Simultaneously, energy stored in the battery unit is not used in the Export Surplus Mode of operation due to continuous monitoring of the SHS. Similar control features could be applied to lithium-ion battery based SHSs which are characterised by different voltage profiles than lead-acid systems. As such, Export Surplus Mode could be initiated each time battery enters exponential zone of operation. Power outflows supported by the boost converter would therefore initiate voltage reduction to rated value. As a result, lithium-ion battery based SHSs would charge up to SoC of approximately 90% and Export Surplus Mode would prevent system from storing higher portions of electricity [127].

Further consideration of Smart Power Management system is introduced in Section 5.5 presenting coordination between buck and boost converter in order to charge external batteries by the surplus of electricity produced within network.

5.5. Power Import from the Microgrid

So far, functionality of the boost converter exporting electricity from the SHS to the microgrid unit have been introduced. Further smart functionality is presented by the circuit in charge of importing electricity within the Energy Box – buck converter. Section 5.5 reveals principles of operation of such system which main function is to provide electricity from the microgrid to support high power appliances.

The range of voltages limits acceptable by most 12V appliances supported by the buck converter is typically within operating voltages of lead-acid batteries to which these appliances are normally connected. As a result, proposed converter introduced within each Energy Box is required to regulate its voltage output according to specification given for the appliances to be supported. For LEDs offered by BBOXX, the low threshold voltage level starts at 7V (based on the laboratory tests). Other devices such as TVs start their functionality from 10V DC, according to BBOXX technicians. Phone chargers operate at 5V and are supplied by a DC/DC voltage regulator. Embraco refrigeration systems selected for a bottom-up electrification operates within range of 9V and 16V [128].

In addition to 12V output port regulation after connecting new load, buck converter is also equipped with smart functionality which increase rate of power imported whenever surplus of electricity in the microgrid is detected. This may result in providing electricity to external batteries directly connected to the 12V output busbar supported by the buck converter. As such, electric demand within the household equipped with the Energy Box and new appliances can be supported by significantly higher portion of energy at night – when probability of power shortages is the highest due to lack of solar generation. The surplus of electricity is imported from 48V to 12V busbar only in the event when voltage on the distribution system exceeds 48V – indicating that overall generation in the microgrid surpasses demand and some SHSs interconnected are fully charged as well as present further capability to generate electricity. As such, buck converter boosts output terminal voltage beyond 12V which essentially can result in charging external battery unit if it is connected to the output of the Energy Box buck converter. Furthermore, the system is developed in order not to exceed maximum power to charge batteries of 50W (maximum power set-point for the Energy Box prototype). It is also required that the system operates within the safe voltage conditions for external 12V battery system. As such, SPM is required not to exceed 14.5V (maximum recommended voltage for charging 12V lead-acid batteries). Proposed control algorithm of the buck converter is presented in Figure 5-28 where V(HPA) is the magnitude of output voltage of the buck converter supporting high-power appliances, P_i* is imported power measured and P_{imax} is the maximum import power threshold allowed of 50W.

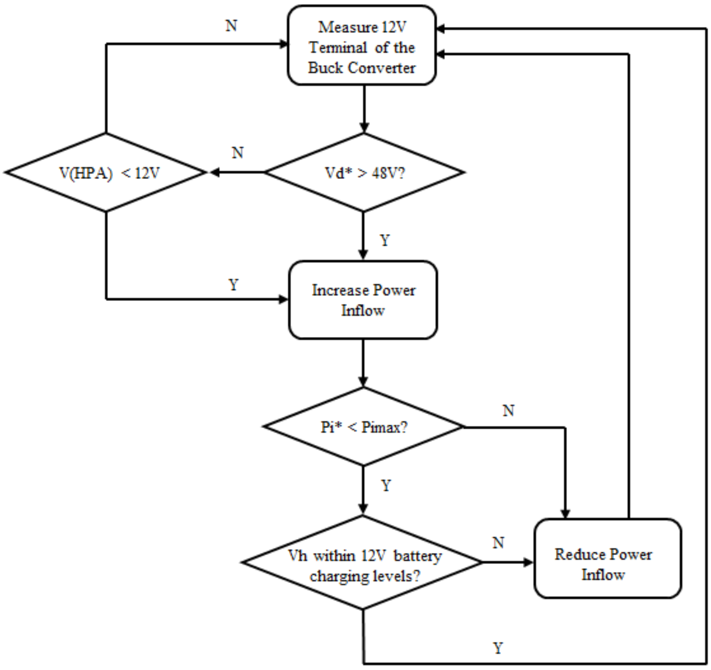


Figure 5-28. Control Strategy of the Buck Converter

Functionality of the buck converter is presented with a reference to the Matlab Simulink model in Figure 5-29. It illustrates the full topology of the Energy Box power converters including boost converter connected to the SHS battery (in charge of exporting electricity) as well as buck converter. Output of the buck converter is connected to the Controlled Current Source block which represents high-power loads such as refrigeration systems or TVs at 12V output terminal. Converters are also providing electricity to load at 48V network which is further interconnected with other systems in the microgrid through 50 metre of 1.5mm^2 copper wire.

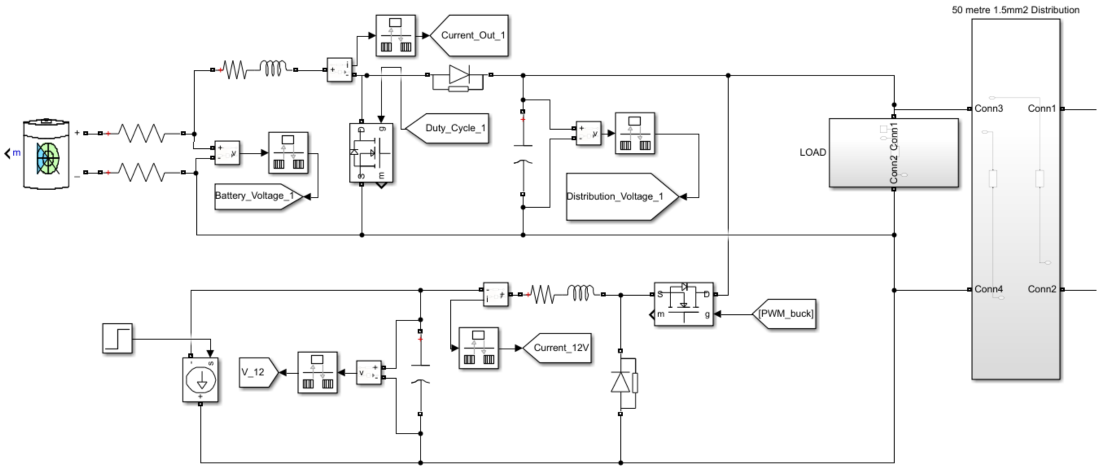


Figure 5-29. Buck and Boost Converter connected to the microgrid system

Signals measured by the buck converter include output voltage (V_12) where high power appliances are connected and current supporting them (Current_12V). The only signal controlling buck converter is PWM_buck which provides PWM modulation controlling current between the microgrid and appliances. Model indicating operation of the buck converter system could be further optimised by replacing diode with a MOSFET which would ultimately minimise losses while stepping down electricity from 48V to 12V. Such design was not provided in this thesis as it would require introduction of additional circuit governing MOSFET. As a result, losses reduction within Energy Box power converters is considered as a part of future work requiring optimisation. Although introduction of diodes instead of MOSFETs produces additional losses, it does not interfere with the functionality of the SPM. The specification of the buck converter parameters used in the model is presented in the Table 5-2.

Table 5-2. Buck Converter System Components Specification

Component	Specification
Inductor	300uH, 50mOhm
Capacitor	8200uF
Diode	Forward-biased voltage drop of 1.05V

5.6. Smart Operation of the Buck Converter

Functionality of the Export Surplus Mode has been described in Section 5.4. These features of the SPM are required to be directly linked with the smart control strategy of the buck converters importing electricity from the microgrid when surplus of electricity is detected. Section 5.6 reveals these features using model generated in Matlab Simulink (see Figure 5-29) indicating appropriate interaction between both power converters.

First scenario analysed considers two SHSs interconnected with each other initially under no load conditions. After 10 seconds of the simulation, one of the Energy Boxes switches into Export Surplus Mode which results in increasing microgrid voltage beyond 48V in order to extract surplus of electricity generated. At this stage, other Energy Box with external battery connected to output terminal of the buck converter start their charging routines. Such functionality is tested with a support of configuration presented in Figure 5-30 where SHS 2 is equipped with a 12V external battery. Microgrid voltage profile under such condition is presented in Figure 5-31 whereas rate of power import to charge the battery in Figure 5-32.

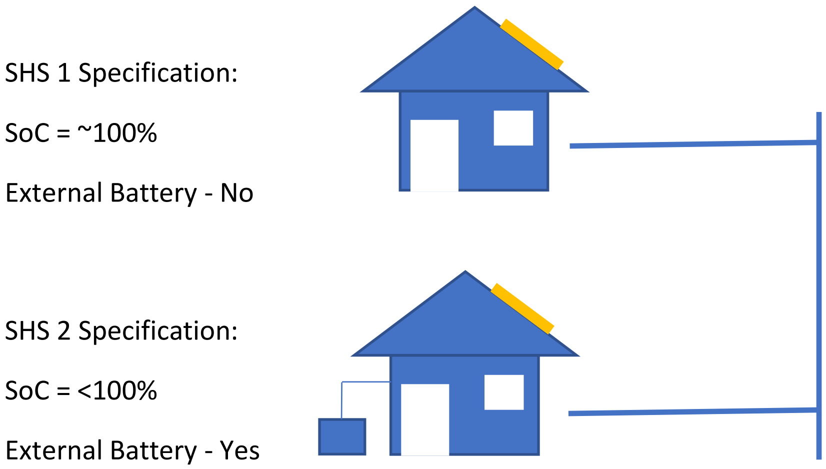


Figure 5-30. Microgrid Representation with SHS 2 equipped with External Battery

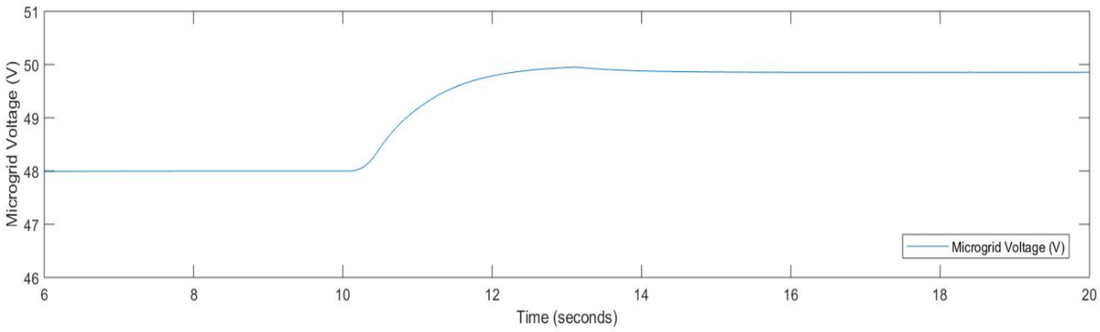


Figure 5-31. Microgrid Voltage Profile while Charging External Batteries

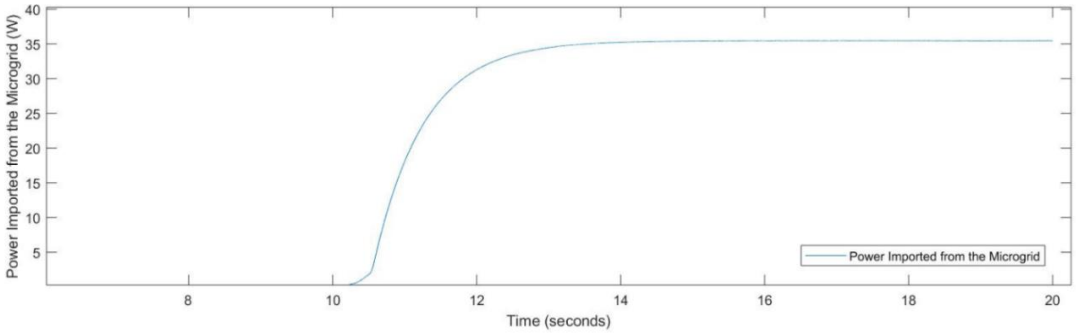


Figure 5-32. Power imported from the Microgrid System to Charge External Battery Unit.

Figures 5-31 and Figure 5-32 show a strong relationship between microgrid voltage and rate of power imported from the network. Graphs prove that for voltages below 48V, no power is delivered to charge external battery indicating that internal SHS battery is still charging, and no surplus of electricity generated is detected. As soon as microgrid voltage increases beyond 48V resulting from operation of the boost converter, power flow from the microgrid to external battery is initiated. As a result of such combination between functionalities of both power converters, distributed batteries can charge purely with energy produced within SHSs that completed their charging cycles. Such portion of energy would otherwise go to waste, under the stand-alone operation.

Such novel control of islanded DC microgrid with distributed generation and storage as a form of interconnected SHSs introduces optimal interaction between power prosumers without need to develop complex coordination before energising them. Instead, SPM purely relies on understanding dynamics of voltages within SHSs and “shares” information about the conditions of the system using microgrid voltage control algorithms. As a result of its simplicity, SPM concept gives opportunity to interconnected existing off-grid assets without need to configure them individually before being connected. Synchronisation between power converters in the microgrid while detecting electricity surplus in the system could significantly increase rate of energy utilisation in the network. As a result, new appliances requiring additional amount of electricity could be provided without need to install additional generation modules.

5.7. Demand Side Management (DSM) Functionality

Although many SHSs currently remain with high surplus of electricity which goes to waste, adaption of new high-power appliances within the microgrids of interconnected SHSs can introduce demand for energy, especially during periods of low energy generation (for example, during wet seasons). To provide safe operation of the microgrid, Demand Side Management (DSM) functions are introduced within each Energy Box. DSM is triggered once minimum allowed voltage on the microgrid network is detected which consequently indicates lack of sufficient power supply in the system.

Based on microgrid control functions explained in the Chapter 4, voltage of the distribution network interconnecting SHS is always proportional to estimated SoC of the batteries in the microgrid. Once this voltage is low, buck converter terminates its operation to preserves capacity for the most basic appliances such as lighting systems which are directly supplied by SHS without Energy Boxes. After initiating DSM and disconnecting high-power appliances, buck converters operations can be restored only when SHSs batteries present sufficient SoC - indicated by the microgrid voltage being recovered to 48V.

Demonstration of the DSM is performed by introduction of the buck converter Matlab Simulink model (see Figure 5-33 in blue) supporting resistive load of 10 Ohms (in green). Microgrid voltage is adjusted by the Controllable Voltage Source block (highlighted in orange). Distribution voltage has been set to vary across the simulation period to verify operation of the DSM.

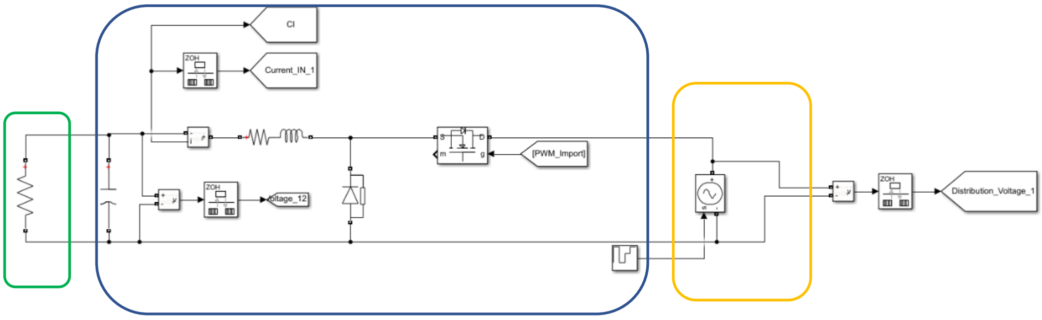


Figure 5-33. Demand Side Management Demonstration Circuit

Controlled Voltage Source governing microgrid voltage is set to represent four different states at one second intervals each, as indicated in Figure 5-34. Consequently, buck converter adjusts its operation depending on the microgrid voltage level, as seen in Figure 5-35 verifying voltage at the 12V output terminal.

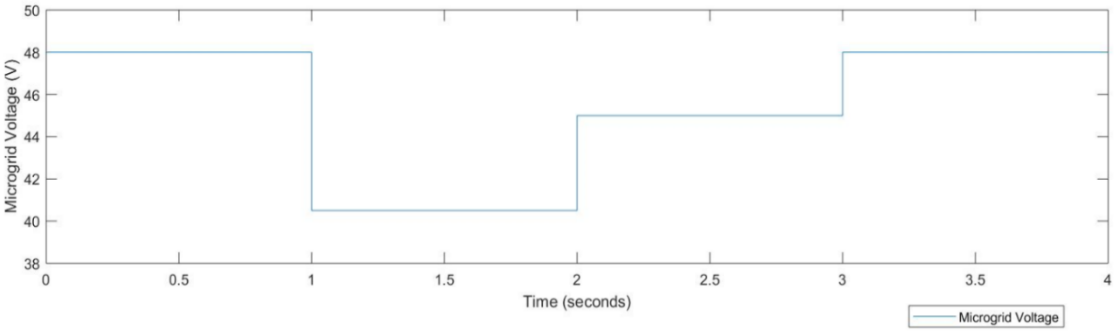


Figure 5-34. Microgrid Voltage Levels for DSM tests

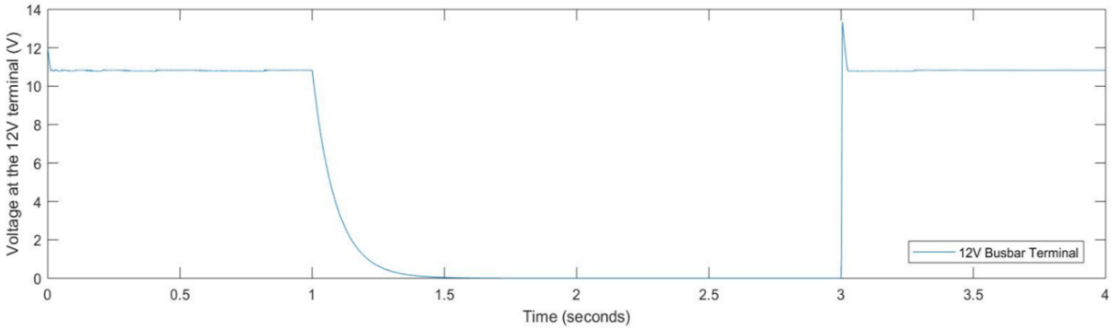


Figure 5-35. Buck Converter Output Voltages for DSM tests

As seen in Figure 5-34, initial microgrid voltage is set to 48V. Simultaneously, output of the buck converter is 12V, providing optimal operation delivering electricity for the resistive load. Once voltage on the microgrid system drops down below 40.5V (after one second), converter stops energizing its output busbar. It does not recover even when voltage on the microgrid returns to 45V after 2 seconds of the simulation. Functionality of the buck converter is restored after three seconds when microgrid system recovers back to 48V indicating sufficient amount of electricity to support new loads. As a result of this arrangement, SPM system always assures that enough energy is generated and stored to support high-power appliances before reconnecting them.

Although DSM presents capability to maintain balance between demand and supply in the microgrid, it also gives functionality to prioritise loads within the village. As a result, for appliances with higher priorities minimum threshold voltage to activate DSM could be reduced from 43V down to 42V or even lower. Consequently, DSM system starts disconnecting loads with low priority to always keep enough capacity for the most important appliances, such as refrigeration units storing medicals in low temperatures.

The example of load prioritising integrated in the DSM scheme is presented in the Table 5-3.

Table 5-3. Load Prioritizing supported by the Energy Box DSM.

Voltage Level	**Mode of DSM Operation**	**Actions**
48V-50V	Energy Surplus in the System	Distributed batteries charging, No load shedding
46V-48V	Normal Operation	Distributed batteries not charging, No Load Shedding
45V– 46V	DSM1	Disconnect low priority loads (TVs)
44V– 45V	DSM2	Disconnect high priority loads (fridges)
<44V	DSM3	Disconnect all Loads

5.8. Energy Box Hardware Design

To successfully deploy smart microgrids integrating interconnected SHSs, it is required to conduct deep circuit design analysis. It is needed to select appropriate equipment that can support all control functionality at the lowest costs.

The fundamental hardware elements of the system are boost and buck converters to control power flows, communication infrastructure to develop remote monitoring system sending data to the server to upload microtransactions for electricity and visualise power flows within the system, circuit protection to detect and isolate faults as well as microcontroller to perform all the functionality required. Section 5.8 presents details of all components selected to develop the final product – the Energy Box.

5.8.1. Design of the Boost Converter

Basic components for boost converter were described while presenting control strategies of such system. The same parameters of resistors, capacitors and inductors as simulated using Matlab Simulink models presented in Chapter 5 were therefore used for the laboratory demonstrator.

First element considered which is established to drive boost converter MOSFET is a gate drive circuit. Such model involves use of optocoupler isolating microcontroller PWM signal at 3V from the minimum PWM signal required to drive the semiconductor (approximately 12V - 15V, according to the specification). Such circuit is presented in Figure 5-36 where GPIO_00 is the PWM signal from the microcontroller and 12-48BOOST is equivalent to PWM at the magnitude of 12V battery connected (+12_BATTERY). In addition to circuit presented in Figure 5-36, 2.2kOhm resistor is added between Gate and Source of the MOSFET to effectively discharge any residual voltage between gate and source when the PWM signal is low. Source of the MOSFET of the boost converter is also grounded.

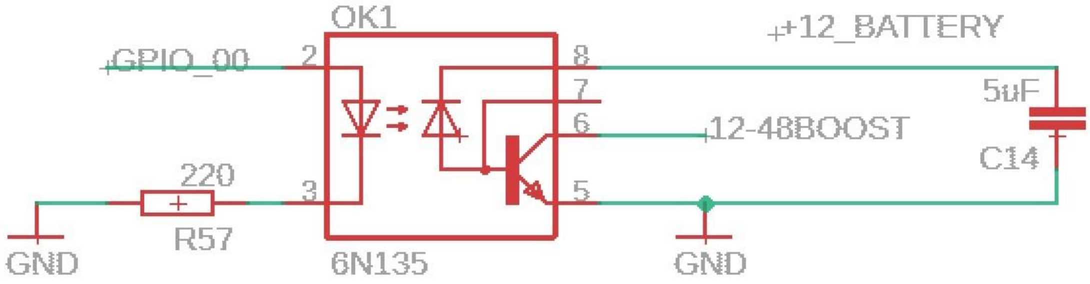


Figure 5-36. Gate Drive Circuit for the Boost Converter driving MOSFET

To make proposed solutions affordable for people residing in rural SSA with very limited financial capacity, components for the boost converter are required to be appropriately matched and analysed. The list of elements required to design boost converter within the Energy Box is presented in Table 5-4.

Table 5-4. Boost Converter Components and their Cost

Element	Cost (GBP)
Optocoupler Broadcom, HCPL-3120-000E	£1.23
N-Channel MOSFET, 4A, 60V NDT3055L	£0.59
Inductor, 400uH	£0.80
Capacitor 2200uF, 50V DC	£0.61
Total cost	**£3.23**

5.8.2. Design of the Buck Converter

To control MOSFET of the buck converter, appropriate PWM voltage is required to be generated between its gate and source terminals. This can be achieved with a support of isolated DC/DC switching regulator. Once optimal voltage level driving MOSFET is introduced, PWM frequency and duty cycle is dedicated by the microcontroller. The pulses to which MOSFET is exposed are therefore equivalent to those send by the microcontroller. The magnitude is determined by the switching regulator and is fixed at 15V, as presented in Figure 5-37.

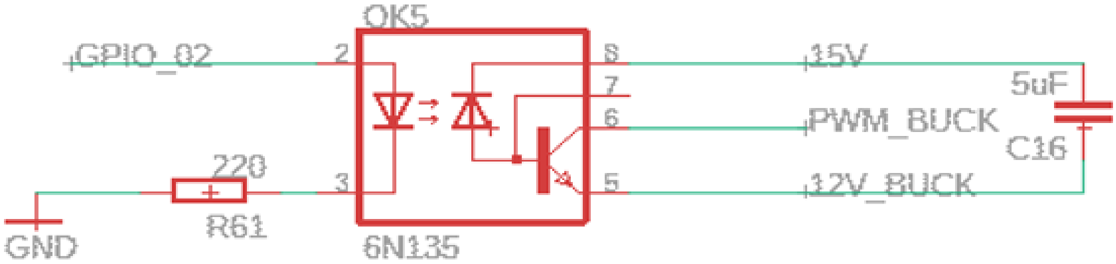


Figure 5-37. Opto-isolation for the Gate Drive Circuit of the Buck Converter

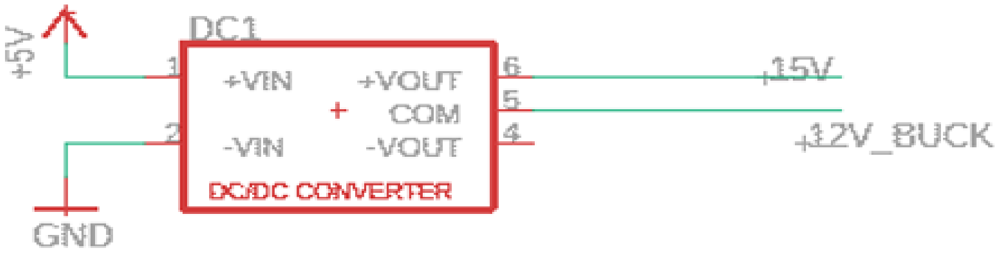


Figure 5-38. DC/DC Isolated Circuit providing 15V Gate – Source Voltage

Based on gate drive configuration presented in Figure 5-37 Figure 5-38, PWM signal produced by the uC (GPIO_02 signal) is equivalent to PWM_BUCK at the magnitude of 15V between gate and source of the buck converter MOSFET.

As a result of introduction of the isolated DC/DC switching regulator, buck converter configuration is more costly than boost converter making use of SHS battery voltage. This is essential, mainly due to technical requirements of the system introduced among households with no 12V SHS who wish to import electricity from the local pool of energy. As such, additional voltage source (between 12 and 15V) driving MOSFET is required. Cost breakdown of the buck converter is presented in Table 5-5 below.

Table 5-5. Cost Breakdown for the Buck Converter.

Element	**Cost (GBP)**
Optocoupler Broadcom, HCPL-3120-000E	£1.23
N-Channel MOSFET, 4A, 60V NDT3055L	£0.59
Inductor, 400µH	£0.80
Capacitor 8200µF, 16V DC	£0.64
Isolated DC/DC switching regulator NMA0515SC	£3.20
Total	**£6.46**

5.8.3. Communication Technology

Communication technology providing remote monitoring of the microgrid is an essential element installed within each Energy Box. Monitoring features give microgrid system operator knowledge on total energy requirements among prosumers. As a result, microgrid developers can maintain smooth multi-tier transition within the community by adding additional generation and storage step-by-step, in parallel to the growing demand. Other benefits resulting from the communication technology are associated with understanding rate of energy either imported or exported by each household. These data are then being uploaded to the server to bill each individual customer.

The low-cost module providing remote monitoring capabilities at each Energy Box level was SIM800L. It utilises GPRS network widely available in many African countries. The cost of such module is approximately £4 per sample. Additionally, SIM card is required to exchange data between the server and each Energy Box. It costs approximately £1 in Rwanda.

5.8.4. Circuit Protection Consideration

Design of a circuit protection could potentially give capability to isolate DC link which experiences a fault. As a result, power flows within the meshed microgrid could always be bypassed by utilising alternative branches of the system which are not exposed to faults. Under such scenario, damaged branch of the microgrid should be isolated for as long as fault is not removed.

Isolation of a faulty DC link could be achieved by introducing MOSFETs with capabilities to disconnect each of three branches for interconnections separately. Such arrangement, although providing higher reliability of power supply, could be impractical due to requirement of installation of three additional gate drive circuits (one for each connector within the Energy Box) governing MOSFETs. Consequently, proposed system would introduce higher power self-consumption. As a result, the final design of the Energy Box does not include function separating DC links. It is assumed that faults can be cleared by the internal protection system of SHSs. In such cases, all energy Boxes would become deenergised.

Other elements required to be introduced within the Energy Box consider protection of the reverse polarity within the DC system. This can be achieved by the introduction of p-channel MOSFET isolating the circuit as soon as “negative voltage” is detected [129]. Such capabilities have not been yet developed for the Energy Box prototype (within the scope of this thesis) and are subject for the future investigation.

5.8.5. Microcontroller Selection

The final microcontroller selection process was based on trial-and-error method. It was important to find an optimal chip which is capable to control all processes described in Chapter 4 and 5. To simplify prototyping, group C2000 Texas Instruments microcontrollers was selected. Their well-developed Automatic Code Generation capabilities integrated with Matlab Simulink made this family of microcontrollers preferable over other available on the market. As such, most code providing SPM functions was established by the Simulink models without necessity to write it manually. Initially, F28335 Delfino chip has been used. Based on the Real Time Operating System (RTOS) results it was assumed that other models with lower computational speed and power requirements can be adapted to control all functions desired. Such controller would also cost less than F28335 initially tested. Finally, F28035 Piccolo uC was used which fully supports all functions for interconnected SHSs microgrids [130]. The cost of F28035 chip is approximately £4 per unit.

Selected microcontroller was therefore used to test its functionality and performance while managing multiple processes simultaneously. To support these studies, tasks profiling features were employed which show performance of the code execution in a real time. As a result, it is possible to understand whether all control features are completed without violating computational constraints.

Such analysis provided for the SPM system introduced in this thesis and F28035 Piccolo microcontroller is presented in Figure 5-39.

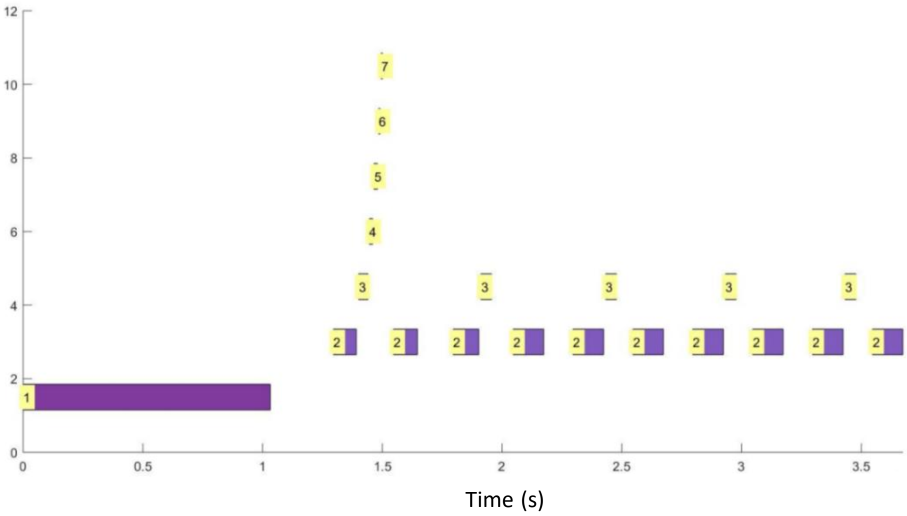


Figure 5-39. Screen Shot illustrating Task Execution Profiling

Figure 5-39 indicates different tasks (1,2,3,4,5,6 and 7) and their execution times (on the horizontal access). It is shown that different processes perform with various sampling times. Each individual control task in Figure 5-39 is explained in Table 5-6. Understanding of control loop execution frequency gives a good insight of how well the CPU is performing while providing all desired functionality within the Energy Box. These features of C2000 family were used to compare several uCs in order to find optimal model of the microcontroller considering computational speed, cost and power consumption.

Table 5-6. Control Loops for the Code Execution

Task Number	Function	Sampling Frequency
1	System Initiations	Executed Once
2	Current Sampling Loop and PWM Control	4kHz
3	Microgrid and 12V Output Voltage Sampling Loop	2kHz
4	Battery Voltage Measurement	200Hz
5	Storing Voltage and Power Measurements in the Buffer	60 seconds
6	Updating Cost of Energy LED	120 seconds
7	Sending Data to the Cloud	10 minutes

As seen in Figure 5-39, Task 2 is executed regularly at 4kHz which is the same frequency as specified for this task in Table 5-6. As a result, it was concluded that code is not violated within the period of operation investigated in Figure 5-39.

Task execution examination was conducted over significantly longer period than 3.5ms (as indicated in Figure 5-39) in order to verify if all control features are kept within optimal frequency specified by the SPM. Furthermore, after code deployment into hardware, no issues with control system have been identified, thus, it concluded that all tasks are executed without any code violation.

5.8.6. Other Elements of the Energy Box and PCB Fabrication

Other costs related to design of the Energy Box are related to SMD components such as current sensors, resistors, capacitors, PCB fabrication as well as enclosure design. Estimated costs for these elements are presented in the Table 5-7.

Table 5-7. List of Energy Box Components

Element	**Cost (GBP)**
PCB Design	£1.70
SMD Components (sensors, resistors)	£1.50
Enclosure Design	£4.00
Total	**$7.20**

5.8.7. 5V output terminal for USB charging port.

5V USB port is required to be installed in the Energy Box system, primarily to support charging of mobile phones by users who previously had no access to electricity. This requires a switching regulator stepping down voltage from 12V (buck converter output) to 5V. Such operation has been obtained with R-78E5.0-0.5 chip. The cost of the voltage regulator is approximately £3. Full circuit schematic is presented in Figure 5-40.

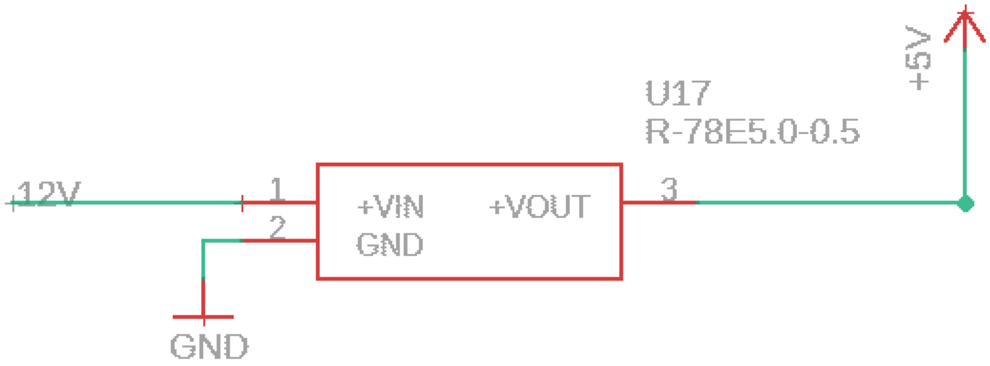


Figure 5-40. Circuit schematic for stepping down Voltage from 12V to 5V for USB connector.

5.8.8. External Power Supply Circuit

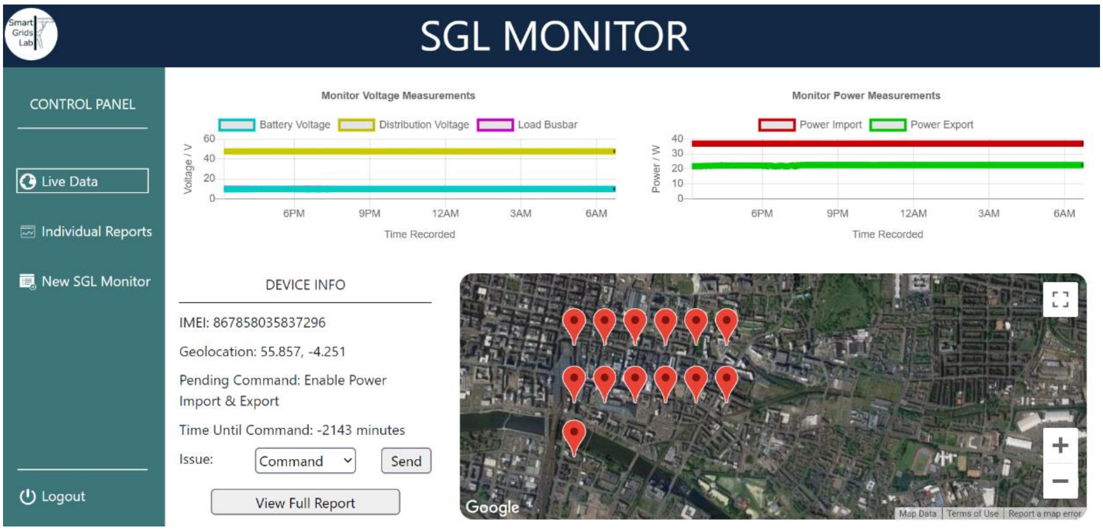
Similar circuit to the one seen in Figure 5-40 has been designed to provide 5V power supply for systems that are not connected to any SHS and electricity is purely imported from the microgrid system. In this case, power supply for the gate drive, GPRS and microcontroller is required to be provided from the microgrid network instead of 12V SHS port. As a result, switching regulator stepping down voltage from 48V to 5V is required to be installed. This can be obtained by installation of the SRX05S05 converter which input voltage acceptable varies between 9V and 72V whereas output voltage is fixed 5V. Such regulator costs approximately £9.

5.8.9. Energy Box Cost Summary

As a result, by summing up all costs required to assemble the Energy Box, it was assumed that PCB with all components listed in this thesis would cost approximately £25 per unit, making it affordable solution and competitive with typical smart meters installed in Rwanda ($60 per single unit, according to the interviews with villagers). For those who do not have SHS installed, cost of Energy Box fabrication would be at approximately £33. Considering financing schemes for off-grid electrification (users often pay for installations for a period 3 years), monthly cost of Energy Box could be well distributed and reduced in order to accommodate people with low-income generation. These costs could be further reduced while reaching appropriate scale which would give chance to purchase Energy Box in high quantities for low costs. Although cost of Energy Box can be maintained low, installation of LVDC networks interconnecting households might be a major difficulty. Selection of appropriate distribution lines can depend on several aspects and requires appropriate regulation. This could be particularly important while considering future microgrid connection to the main power network. Under such condition, appropriate support from the energy utility companies may be required introducing financing for the proposed microgrids which ultimately gives capabilities to support the whole range of appliances specified in the multi-tier framework for energy access [131].

5.9. Software Supporting System

Understanding of the consumption patterns amongst people relying on interconnected SHSs microgrids is a crucial aspect as it indicates how electricity in the system is distributed. It also provides information about overall balance between supply and demand in such network which is crucial aspect while introducing the multi-tier bottom-up transition. To provide such functionality, remote monitoring system was designed by the University of Strathclyde Computer Science student – Kyle Lawson. The system collects data provided by each Energy Box and stores them in a server for further visualisation and analysis. This is provided with an app specifically developed for the Energy Box. Integration between remote monitoring and SPM has been developed in Matlab Simulink where new C code has been implemented and executed every 10 minutes (frequency of sending data to a cloud). Each package of data contains information on voltages of the SHSs' battery, distribution network and of the output terminal of the buck converter as well as power flows between microgrid and each buck and boost power converter. All parameters are sampled every minute, hence, 10 measurements is sent to the cloud every 10 minutes. The data visualisation panel developed for the Energy Box is presented in Figure 5-41.



IMEI: 867858035837296

Geolocation: 55.857, -4.251

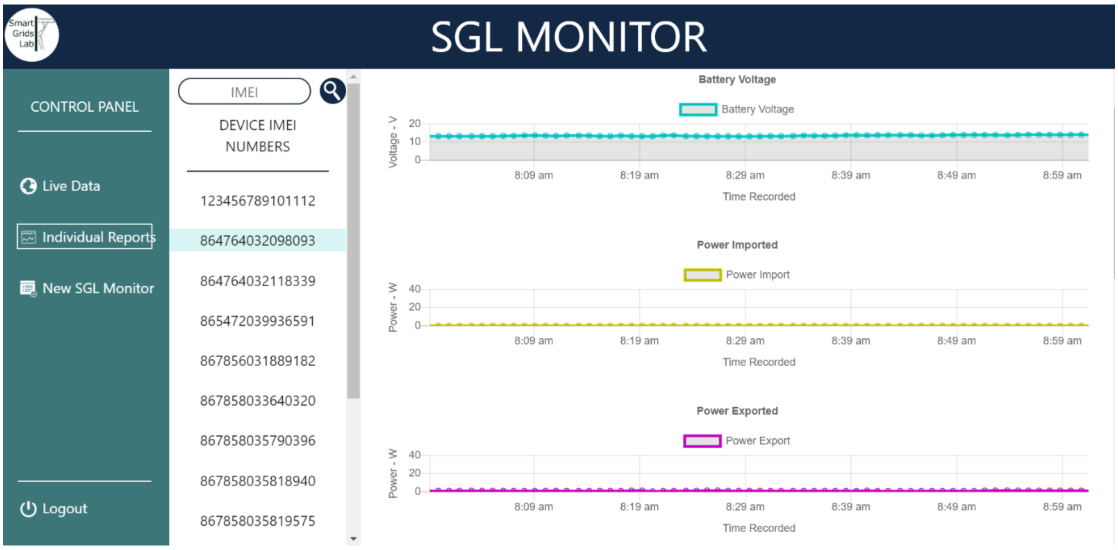
Pending Command: Enable Power Import & Export

Time Until Command: -2143 minutes

Figure 5-41. Remote Monitoring System Panel for Microgrid Networks of Interconnected SHSs.

Although visualisation of data is one crucial factor to understand customers' behaviour, the system is also equipped with certain control capabilities for each Energy Box. It could be completed by issuing commands which can deactivate functionality of the buck or boost converter. Disconnecting buck converter would prevent electricity import by customers not paying for electricity on time. Deactivation of the boost converter could be used when issues with the distribution network occur or when maintenance or expansions of the system takes place.

Remote Monitoring System app opens with the Live Data page where each Energy Box has its representation on the map introduced by pinpoints at the location of the installed system. After selecting one of them, data is visualised based on measured data for the specific Energy Box. Detailed data analysis can be performed after entering Individual Reports section. This can be seen in Figure 5-42 below.



DEVICE IMEI NUMBERS

123456789101112
864764032098093
864764032118339
865472039936591
867856031889182
867858033640320
867858035790396
867858035818940
867858035819575

Figure 5-42. Data Analysis Screen for the Energy Box

Figure 5-42 presents battery voltage data as well as power flows between SHS. The same page includes visualisation of load and distribution system voltages, amount of energy imported and exported over the whole day.

The list of IMEI numbers is unique for each GPRS module which are individually assigned to each Energy Box. This number is also used within the remote monitoring system app to distinguish users' identity. All data stored with the RM system can also be exported to .csv file for further analysis.

Proposed monitoring system is similar to those currently deployed by SHSs providers. It is crucial, particularly while providing access to electricity in locations with low accessibility. In such places, capabilities to meter energy usage per household as well as micropayments control without appropriate remote monitoring could be a major barrier.

5.10. Final Product Design

Section 5.10 presents final design of the hardware supporting all functions for the SPM module including power converters, microcontroller as well as GPRS system. The ultimate PCB design has been developed in Autodesk Eagle. Full schematic is illustrated in Figure 5-43. The system has one input connector to be supplied from the SHS on the right bottom side of Figure 5-43, three output connectors (two 12V and one 5V) on the bottom left of the picture as well as three 48V connectors (two on the left and one on the right) to share electricity with the neighbouring systems. The system supports F28035 microcontroller card, elements contributing to the gate drive circuit as well as GPRS. Additionally, pins for LEDs indicating cost of energy were introduced on the enclosure and are governed based on microgrid voltage level, introducing flexible pricing of electricity depending on balance between demand and supply, correlated with the voltage levels in the microgrid.

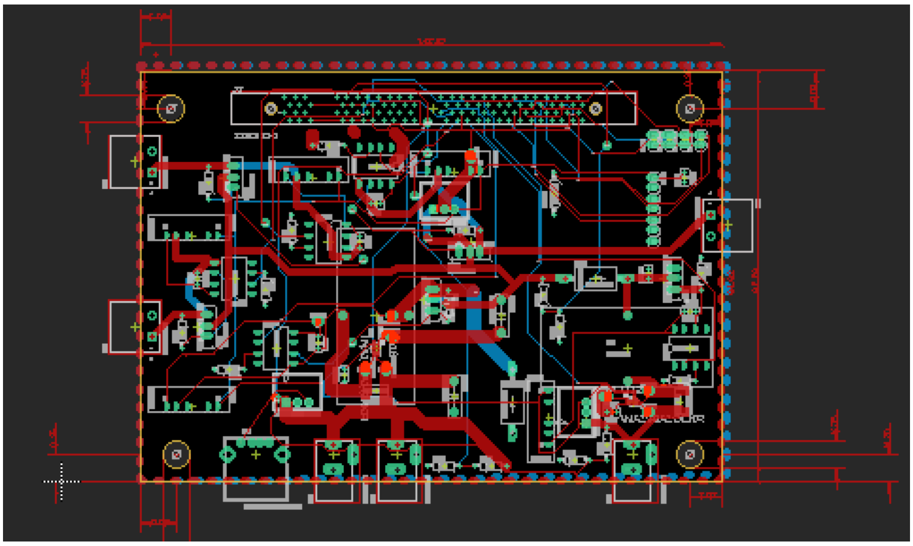


Figure 5-43. Final PCB Design supporting SPM Functionality

After manufacturing PCBs and placing all components on the board, final product has been developed and is presented in Figure 5-44 and 5-45.

Figure 5-44. Open Energy Box with all Components on the PCB.

Figure 5-45. Closed Energy Box with LEDs indicating Cost of Energy of the System

5.11. Summary of the Chapter

Functionalities of the SPM presented in Chapter 5 prove that appropriate electricity exchange between prosumers within the microgrid can be maintained without violating constraints of the SHS. Such transition can be purely based on analysis of the battery voltage dynamics. Technique presented do not require SHS rewiring or replacements internal control modules which is evident while adapting Solboxes – controllers used to interconnect SHSs in Bangladesh [132]. Furthermore, proposed SPM prioritises electricity supplied by SHSs which produce electricity surplus over others, remaining with energy deficit. Moreover, Export Surplus Mode gives opportunities to utilise electricity which normally goes to waste by charging external (non-included within SHS) distributed 12V batteries in the network. As a result, rate of electricity utilisation in the network of interconnected SHSs could be maximised. The Energy Box is also equipped with Demand Side Management which disconnects loads according to priorities set, purely relying on balance between demand and supply and SoC of the batteries within the system. Unlike some other DSM concepts available, the proposed DSM equipped within each Energy Box does not require any additional communications to disconnect loads in the network of interconnected SHS [133]. Proposed Energy Box controller prototype is primarily developed to present functionality of the SPM. As such, the final controller's capacity to import electricity from the microgrid might be bigger than specified in this thesis. As a result of oversizing it, low cost 12V fridges with higher power consumption than Embraco models (selected for case studies in this thesis) can be introduced which ultimately minimizes ownership costs of refrigeration units [134]. Despite further analysis required to optimize size of the buck converter by estimating future electric demand growth in rural Africa, proposed SPM control strategy can still be applied to interconnect SHSs to support various high-power appliances at the household level.

After designing the first prototype of the Energy Box, further research requires validation of the proposed bottom-up electrification concept. Results indicating performance as well as acceptance such microgrid system in rural Rwanda are presented in Chapter 6.

6. Field Tests in Murambi Village – Northern Province of Rwanda

To test expectations and see how the Energy Box worked in practice, a pioneer project was established in Murambi Village in the Northern Province of Rwanda. The research was conducted with a support of Fraser Stewart (department of Government and Public Policy at the University of Strathclyde) who developed a set of surveys to assess background of people currently relying on BBOXX SHSs. The outcomes of analysis give understanding of people acceptance of the proposed bottom-up electrification concept as well as indicate potential issues with the development of such electrification architecture. Murambi village was selected as a small community with a mix of residential households and small enterprises: with the aim to test system operating for people with different backgrounds. Although SHS technology is widely prevalent in this village, some families remain without any access to electricity at all.

In addition to wide demographic variance in Murambi, topology of the village selected also had a substantial impact on the effectiveness of interconnection and power distribution. Villages with high distances between prosumers may require higher initial investment costs for interconnections and may in turn also incur high losses while distributing power over a 48V DC system.

Focus groups were conducted in conjunction with local representatives and workshops were held to rise the awareness of the project and its objectives with the residents. Those who were interested in participating were then interviewed individually to ascertain their willingness to participate in the trial, their demographic profile and energy usage profiles. Eight participants were finally chosen: six households with their own SHS, one business also with its own SHS, and one household with no electricity at all. The average number of domestic household members was 5. Five of the six households owned a standard SHS from providers BBOXX, consisting of a 50W PV module and 12V 17Ah battery, equipped with two or three LEDs and phone charger, while one used a larger capacity Mobisol system (with an 80W PV module and 12V 120Ah lead acid battery) with only limited appliance demand, and so offered a relatively significant level of potential generation capacity for the microgrid. The business property, a local shop, also consisted of a standard BBOXX SHS supplying a small 12V DC TV. One household did not own a SHS and would represent the sole consumer in the interconnected SHS microgrid.

An Energy Box was installed in the house of each participant and connected to form a local microgrid. It is important to note that, for this initial trial, no money was exchanged between importers and exporters of electricity in the microgrid, to avoid any potential cost to those who had agreed to participate. While the team did not anticipate any losses given the volume of excess energy available, the decision was taken to monitor exchanges but to avoid any potential risks. Participants were incentivized with a small appliance (light bulbs and shavers) at the end of the trial.

An Energy Box was installed in the house of each participant and connected to form an interconnected SHS microgrid. It is important to note that, for this initial trial, no money was exchanged between importers and exporters of electricity in the microgrid, to avoid any potential cost to those who had agreed to participate. While no significant financial losses were anticipated given the volume of excess energy available, the decision was taken to monitor exchanges but to avoid any perceived risks that may discourage participants from interacting with the microgrid. Participants were provided with additional appliances to power (with this newfound surplus energy) such as fridge, shavers and new LEDs and some of them (shavers and LEDs) they could retain at the end of the trial.

Prior to microgrid installation, the team also conducted baseline surveys across villagers residing in the community, results of which are presented as follows. Villagers were asked to join a community meeting at a central shop, where translators conducted one-to-one surveys with those who were interested in the project (see Appendix B). A total of 38 people out of 80 in the village answered the survey, which was mainly focused on understanding the socioeconomic profiles of households, as well as budget and expenditures of families residing in a typical off-grid village in Rwanda. Firstly then, it was important to understand job type and typical income generation activities of residents (Figure 6-1).

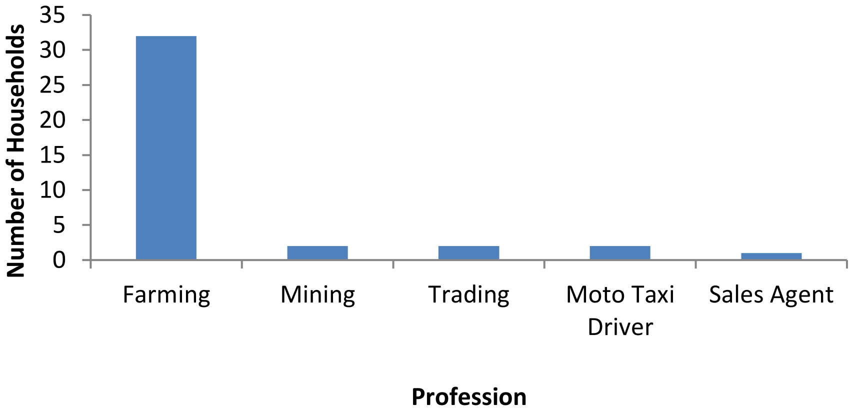


Figure 6-1. Profession per Household in Murambi

As with a majority of people across off-grid areas in developing countries, Murambi residents rely on farming as their primary source of income [135]. Significantly fewer villagers then live from mining, trading, sales, as well as providing basic transportation services in the form of MotoTaxis between villages and the main city of Kigali. Around 20% of those relying on farming also run local shops in the villages, where locally produced goods are sold. These small businesses are typically supported by SHS installations providing lighting after sunset, to maximize their overall business opening hours.

Domestically, households that rely on SHSs typically consume electricity for lighting and phone charging. Some families also have a small TV or radio, although these are few due to cost and capacity restrictions. In addition to the monthly payments for the SHS, families spend significant portion of their income on other sources of energy, mainly for cooking like wood or charcoal. Interviews with villagers show that the cost of cooking fuels has in fact been rising due to deforestation creating a scarcity issue in the area. Some families have thus had to switch from wood to more expensive sources for cooking like charcoal. Average monthly expenditures of people residing in Murambi are illustrated on the graph below.

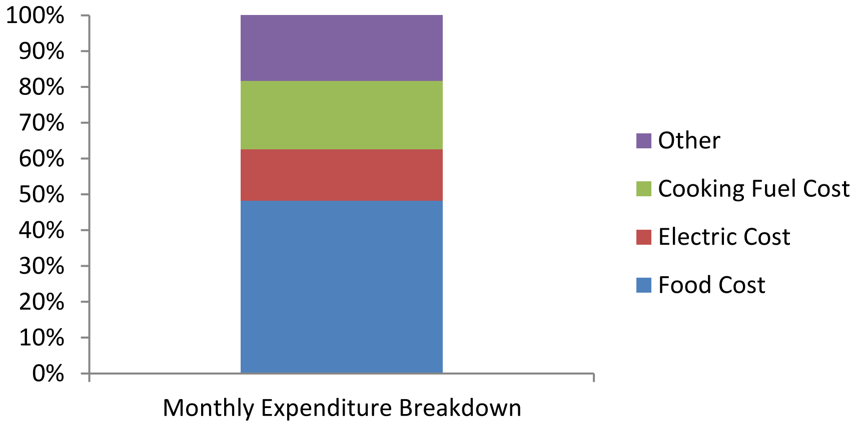


Figure 6-2. Average Monthly Expenditure Breakdown in Murambi

A significant portion (25-30%) of monthly expenditure for residents of Murambi is spent on energy between cooking fuel and electricity. In terms of SHS electricity alone, the expenditure as a proportion of overall income per household is illustrated in Figure 6-3.

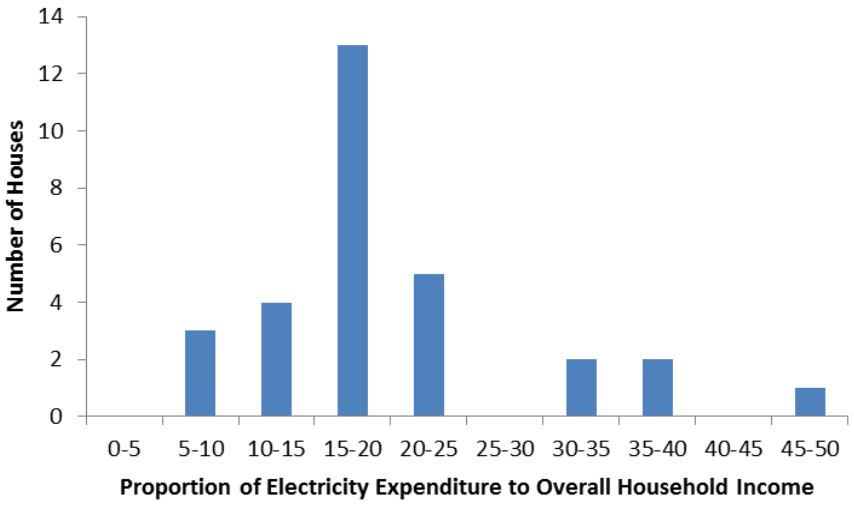


Figure 6-3. Proportion of monthly expenditure on electricity in Murambi

Without cooking fuels, most families in Murambi spend between 15-25% of their monthly income on basic access to electricity. This is over 30% for some households, usually for families who have upgraded their systems to run a TV unit. All BBOXX customers are then obliged to pay a maintenance fee of \$2.50-\$3 which covers the cost of repairs and replacement of damaged batteries; this applies also to those who have completed their PAYGO contracts. As a result, as soon as these PAYGO contracts end, total expenditure on SHS after first 3 years reduces, which tends to be when people begin to think about larger appliances.

These findings have a few immediate implications for the viability of interconnection. First, the costs of energy in these areas are substantial for those with their own SHSs (typically more than 15% of the income) and restrictive to those on the lowest incomes. Alternative means of electrification will thus be essential in ensuring that efforts are inclusive of people in those lowest income brackets. This can be provided by utilising latent excess generation of those with SHS to support families with the lowest income. Such interaction can provide more affordable energy access for people requiring basic energy access for lighting and phone charging. Meanwhile, SHSs users sharing their surplus of electricity can generate additional income by supporting their neighbours with electricity. This is consistent not just in Murambi, but across all villages surveyed.

6.1. Network design and consumption profiles of BBOXX customers in Murambi

With these factors in mind, a total of 8 households were subsequently interconnected in Murambi village. 220 meters of 2.5 mm^2 distribution cable was purchased to form these interconnections. Typical distances between buildings in the area of the village where the microgrid was deployed ranged from 5 to 20 meters. The topology of Murambi village and the microgrid layout are presented in Figure 6-4.

Figure 6-4. Topology of Murambi Village, Northern Province of Rwanda [Maps Data @Google, 2020]

In total in Murambi, there were 13 installed BBOXX units and one Mobisol with an 80W PV module and 12V 120Ah lead acid battery. Of these SHS households, participants for the trial were selected based firstly on their willingness to participate, as ascertained by our focus groups and interviews, and then based on the diversity of their demographic and energy user profiles. By the time of the study, some customers had already paid off their 3-year PAYGO contract, indicating that they have higher capabilities to pay for new electric appliances than those still paying monthly fees for SHS. Out of eight systems in Murambi village, one was a local shop, three customers were still in their PAYGO contract, one used a Mobisol system and one had no electricity at all. This would allow us to test the system across a range of different user profiles and needs.

To understand the potential to connect new appliances in the village, typical consumption patterns of BBOXX users in Murambi were then analysed – this consumption pattern analysis provided understanding of the overall surplus of energy within the network and, by extension, the overall potential to add new appliances to the microgrid without installing additional generation or storage capacity. Average energy consumption per day over two weeks in July (just before deployment of the microgrid) is illustrated in Table 6-1. Customer 1 was our business owner, who was using their BBOXX SHS to power 3 light bulbs, a phone charger and an 12V TV. All other users analysed were generating electricity to supply lighting systems, phone chargers and occasionally radios (data on the average rate of energy consumption were exported from BBOXX's Smart Solar remote monitoring system, which is installed in each SHS).

Table 6-1. Average energy consumption per day by participants with BBOXX systems (before introduction of interconnections)

Customer	Energy Consumption (Wh/Day)
1	72.29
2	50.11
3	62.39
4	56.19
5	54.55
6	33.11

From Table 6-1 it is evident that the typical energy consumption per BBOXX customer in Murambi is between 50 and 60 Wh/day. Yet, it is estimated that a 50W panel at the optimal inclination angle can generate around 210 Wh/day in the month of August (when field work was undertaken) [136]. Therefore, it is estimated that around 60% of generated energy amongst interconnected BBOXX SHSs in Murambi is not utilized. The total amount of surplus energy available from the six interconnected BBOXX SHSs alone is therefore estimated to reach around 880 Wh/day; electricity which could now be 'unlocked' and shared via interconnection. The microgrid was also supported by a Mobisol system, which has significantly higher generation and storage capabilities than the standard BBOXX SHSs (80W solar panel modules as oppose to 50W installed with each BBOXX SHS).

Introduction of new appliances in off-grid areas can bring significant opportunities to improve overall quality of living in rural regions of developing countries. From this analysis, it was decided that a refrigeration unit would be an appropriate appliance to test on the newly formed microgrid. Results from initial field surveys showed that a fridge was the most desired appliance on offer. Clearly, adoption of a new refrigeration unit could be challenging for individual households due to the high costs of these systems and limited capacity to pay. However, a majority of residents interviewed also showed a willingness to share a fridge with their friends and neighbours (the cost of such arrangement was not yet presented), which could make them more affordable. This could introduce a new 'community business' concept of refrigeration hubs within the interconnected SHS microgrids, where refrigeration units or other appliances such as TVs and laptops, can be promoted as a further incentive for people to connect to the microgrid. This represents a much more efficient use of energy than using fridges across individual households within the village, since the overall ratio of fridge cost to capacity is also significantly lower for fridges of greater volume. The energy requirement for cooling space per litre is also lower for larger refrigeration units (see Table

4-1). Therefore, the decision to trial refrigeration systems on the newly formed microgrid was based on a positive indication of willingness to pay amongst surveyed households.

A local shop owner, with a completed PAYGO contract for SHS and subsequent desire to expand his business through the provision of communal refrigeration facility, was furnished with this Embraco unit. The central village position of this shop made it a convenient location for shared/communal refrigeration which was then used to chill drinks for sale in the local business. Lack of willingness to share the fridge by such shop owner could result in deactivating buck converter of the Energy Box which would ultimately result in system being disconnected from use.

6.2. Field Results

To understand the impact of the SHS interconnection field trial using the Energy Box technology the system was monitored and energy consumption data captured as the trial progressed. A follow-up survey was then issued to users after the trial had finished. Focus groups with participants and other residents of the village were also conducted after the trial was over, as a means to gauging both the overall technological performance of the system from the end-user perspective, and the impact of the interconnected SHS on the three key socioeconomic factors outlined previously both individually for end-users and for the wider community (increased capacity, electrification, economic stimulus). Focus groups were semi-structured and open-ended, facilitated by a local contact in the village, and designed to be a free-flowing community discussion about the Energy Box and its effects. The survey contained ten questions designed to capture the users' experience of the interconnected SHS microgrid, made possible by the Energy Box technology. Half of the survey focused on the reliability of power supply in the network, willingness to add new devices to the system and potentially sharing them between users in future. The other half of the survey asked users about prospects of the technology, whether they would recommend the Energy Box and how they felt it could be utilized going forward. Structure of the follow-up surveys is presented in Appendix C. Results are presented as follows.

6.2.1. Acceptance of the Technology

The first question was designed to understand overall feelings among users towards the new technology in Murambi Village as soon as the trial had finished. Users were asked “on a scale of 1-10, how positive did you find your experience of the Energy Box overall?”. Results are presented in Figure 6-5. Overall, feelings among users about the Energy Box and the experience of interconnecting SHSs in Murambi village were clearly very positive, with an average score of 8.25 out of 10 and no negative responses to report. This positive response was echoed in our focus group discussions, where even non-users were positive about the trial having seen its effects, particularly in the running of the communal fridge. Interestingly, two villagers declined to participate in the trial in the first instance for undisclosed reasons but were encouraged by how the system had worked for those who received the system to the extent that they themselves enquired about being able to join the microgrid in future.

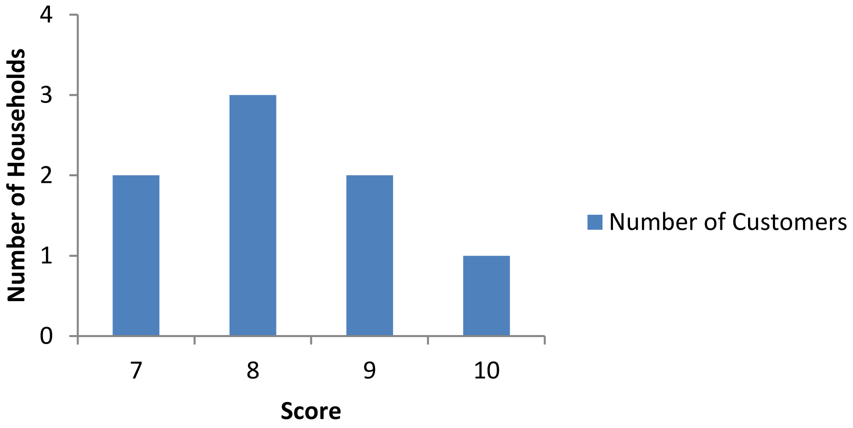


Figure 6-5. “How positive did you find your experience of the Energy Box overall?”

6.2.2. Reliability of Supply

The next set of questions related to the overall quality of power supply within the village during the Energy Box field tests. The users were asked whether, during the field tests, their electricity connection was more or less reliable than usual. In response, 2 out of 8 Energy Box users indicated that overall reliability of supply was better than their usual electricity supply (this naturally included the user who previously did not have access to electricity at all). All other users interviewed indicated that the reliability of their power supply remained the same as before installation of the microgrid. This might be a result of the high reliability of power supply from BBOXX systems, which are oversized for the average customer. Nonetheless, overall reliability of power supply remained at a similar level to what it was before the interconnection took place with no losses reported by users or detected via our remote monitoring system. Such high reliability of power supply as well as ability to connect new high-power appliances could be a strong factor for promotion of interconnected SHSs networks which can deliver electricity 24 hours a day. Utilisation of distribute energy systems (as a form of SHSs) could also unload the power network in the future, primarily in the events when it experiences the highest load and frequent power outages [137], [138].

6.2.3. Willingness to Participate in Upgrade

Users were asked a series of questions about their willingness to participate in a similar interconnected system in future, and ambitions for upgrading their current SHS to add new appliances. They were asked whether, based on their experience of the Energy Box, they would be willing to add more appliances in future, i.e. beyond the pre-existing desire among most people in off-grid locations to add new appliances. Respondents could then list appliances which they would be willing to adopt if connected to the existing microgrid. Results are presented in the pie chart (Figure 6-6. Preferred new appliances). It was found that users self-reported a strong desire to add new appliances based on their experience of the trial.

Amongst the villagers, TVs, shavers and fridges were the most desirable appliances. One user showed willingness to install an electric cooking device, mainly due to the high costs of traditional cooking fuels. The focus group discussion, including non-participants in the field trial, also reflected this desire – community members without the Energy Box cited the positive impact of the fridge system and a desire to upgrade their systems via interconnection.

From willingness to add new appliances, field trial participants were asked how they felt adding new appliances would affect the local economy. This question was also asked in the focus group session. All Energy Box users cited that new electrical appliances such as fridges or TVs would have a positive effect on growth of new businesses in the village. However, one noted concern about having no financial capacity for this even within a microgrid setting (this user was positive about the fridge share scheme but sceptical of being able to afford their own TV unit). Despite individual concerns of affordability for some appliances, however, all users declared willingness in continue participating in the microgrid. Most of them also declared willingness to share refrigeration units between each other to reduce overall cost of these systems.

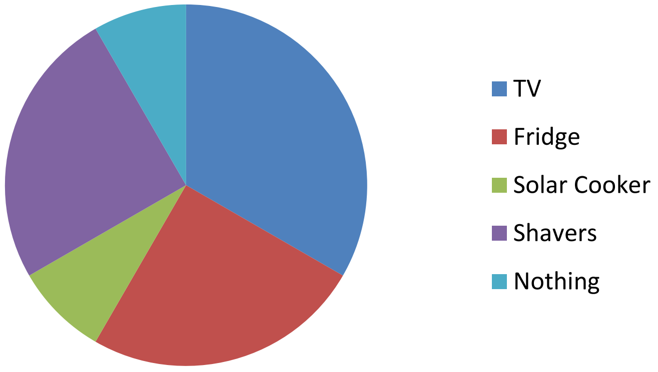


Figure 6-6. Preferred new appliances

Although interest in upgrading existing electric demand by new appliances within families in Murambi village is high, it is required to present further studies indicating real willingness to pay (WTP) for new electric demand. Further adjustments to determine real WTP can be introduced by using more comprehensive techniques such as Theory of Planned Behaviour [139], [140]. As a result, the outcomes of the research would present much more precise capabilities to purchase new electrical appliances amongst villages relying on rural microgrids. Such detailed analysis is required to be performed once appropriate business model for interconnected SHSs microgrid is established. As such, precise analysis of tariffs as well as PAYGO costs for new electrical appliances can be determined. Due to lack of regulations for microgrids in Rwanda (and most other countries in SSA) as well as absence of clear path to deploy microgrids in country, business model development for interconnected SHSs was not a subject for investigation in this thesis [141].

6.2.4. Fridge Share Scheme

Beyond the benefits for storing food and drinks, it was found out that the refrigeration system also provided a distinct economic boost to the village. After completion of field tests, the user with a refrigeration system reported that his sales, mainly resulting from offering cold beer, snacks and other refrigerated drinks, were significantly higher than before the Energy Box. With this extra income, the shop owner could pay for his extra electricity consumption from the microgrid (which would then provide additional income to those exporting their excess to the microgrid) and still have additional profit left over. This is encouraging news: the range of new businesses and economic stimuli that can arise from SHS interconnection is wide. Some villagers wanted to open a TV viewing shop to attract new customers, for example, while others wanted to open a new barber or grocery – interconnection was cited as a way to make each of these possible.


(a) (b)

Figure 6-7. Interconnected SHSs Users in Murambi Village – (a) Local Store equipped with 100l Fridge, (b) Household with basic Access to Electricity after Introduction of the Energy Box

6.2.5. Community Expectations

Finally, the study sought to understand the effects of the Energy Box on the quality of life - both individually and across the wider community. To do this, focus group participants were prompted to list the benefits they felt the microgrid had delivered in the village and the potential benefits that it could have in future. These factors were not directly or quantitatively measured, although user reports were still very enlightening. In line with expectations, the most commonly cited benefits were:

- Capability to generate new income by adding new electrical appliances
- Chance to study longer after sunset
- New streams of income from selling electricity
- More activity in local hubs (particularly where the fridge was installed)
- Connecting households with no previous access to electricity

Evidently, villagers had been aware of the Energy Box and the fridge installation, which had not only increased local business profits and increased local activity but had also increased study time among kids in the household who previously had no electricity whatsoever. Users were then finally asked how likely they were on a scale of 1-10 to recommend the Energy Box to other friends and family members. All responses were either 7, 8, 9 or 10 (see Figure 6-5).

6.3. Summary of the Field Work

The field trial outcomes were very positive, in terms of the key benefits that the Energy Box technology could deliver to a rural village community with a relatively densely populated distribution of pre-existing SHSs. Technologically, the system was stable and reliable throughout, when compared to the energy supply users had been accustomed to prior to the installation. While only two users cited and improved reliability of supply (one included the household who previously had no electricity at all), there were no reports of any detrimental effects to supply or service.

In terms of the three key socioeconomic areas, the trial also had significant positive impacts. The system unlocked the surplus generation and allowed for the installation of a larger appliance (the fridge). This larger appliance in turn acted as a stimulus to the local economy; increasing the income of the ‘fridge owner’ through cold drinks sales, and also SHS owners exporting energy to supply higher-powered appliances through the microgrid.

Other financial benefits for fridge users may come from the preservation of foods stuff either for future consumption themselves or for sale at market. However, it was notable that the villagers’ unfamiliarity with the fridge technology and its potential use would need to be addressed if the community was to maximize the benefit it offered.

Beyond the actual increase in economic activity, Murambi and neighbouring community members also cited that they would be willing to start their own new businesses, such as barbers and TV shops, based on the experience with interconnection in the village. Finally, the consumer household, previously without electricity, was provided a basic (Tier 1) supply, allowing them to power some LED lights and a phone charger, for evening study and improved communication. Interconnection thus presents not just the potential for unlocking of capacity for economic purposes but can be a very effective way to increase electrification rates and the associated individual and social benefits.

It is worth revisiting the fridge share scheme in a little more depth. Although in general the results of the fridge installation were very positive in Murambi, users did typically only use it for storing drinks – it was noted that not much food was ever kept there. During the focus group session, villagers explained that they were not aware 'the rules' about safe food storage and fridge hygiene. For this to be a fully effective model used elsewhere, outreach and education on these factors will be paramount. Worth noting is that two respondents also declared no willingness to share the fridge, citing a lack of trust in neighbours and a concern about others stealing food, which was not a widespread issue across all villagers, but something that may require more careful consideration in other places where social capital and trust are more precarious.

While this Chapter presents the findings of a relatively short-term field trial conducted across a limited population size, it does offer some interesting and encouraging insights into user behaviours and interactions with the technology, and the potential socioeconomic impact and technical feasibility of SHS interconnection and bottom-up rural electrification. However, the authors also recognize the limitations of the field trial and subsequent study results, and plan to use this experience to develop a more comprehensive randomized control trial and longitudinal study in the future. Moreover, further assessment of the bottom-up electrification is required to be performed including appropriate financial model for new, high-power appliances, as well as tariffs for electricity. As a result of such research, real impact as well as willingness to upgrade demand by using the Energy Box will be validated.

The trial was also conducted over a relatively short timeframe. While 4 of our 8 Energy Boxes remained in use after the trial was completed, to fully understand the longer-term socioeconomic effects, a baseline study followed by a longitudinal analysis of the socioeconomic impacts and technical reliability of the technology would be preferred. Plan for such studies, aligned with future field trials, are planned, and will form the basis of a future publication.

6.4. Conclusion

The Energy Box interconnection trial in Murambi yielded some interesting and encouraging results. Villagers reported an increase in the economic activity within the community, an ability to add larger appliances and an easy route to access to electricity for people who cannot afford their own SHS. These points have promising implications for development and inclusive energy access in line with the targets of SDG7. The ability of SHS interconnection to unlock latent surplus generation for more productive uses and to allow base-of-the-pyramid households to gain a foothold on the 'energy ladder', offers new economic opportunities for communities and improvements in the wellbeing and quality of life of extremely vulnerable communities across the Global South. Perhaps most pertinently for SDG7 and development efforts, is the ability of SHS interconnection to offer electricity at a lower cost than that of a distributed SHSs, which presents a viable avenue for inclusive electrification in some of most hard-to-reach areas of the world. This also offers an opportunity for business diversification for SHS providers.

Smart interconnection of SHSs in the manner described in this Chapter, offers SHS communities the benefits of a microgrid for the cost of the Energy Box technology and some interconnecting cables; making effective use of pre-existing ‘bought and paid for’ generation and storage assets (SHSs) to improve energy access rates without the significant cost of upgrading generation and storage capacity.

This technology could support bottom-up electrification in rural areas, which could be especially effective where governments cannot feasibly afford the costs of grid expansion and where SHS assets, already installed, can be used to provide microgrid service provision. While large-scale international policy solutions are constantly emerging, ensuring ‘no-one is left behind’ through a truly inclusive approach to energy access may lie at a local, interconnected community level.

In order to fully understand potential of the Energy Box it is required to provide further upgrades of the technology itself as well as perform studies on significantly bigger group of users who will be provided with appropriate business model and financing for new, high-power appliances. Aspects listing subjects for future investigation in the scope of providing interconnected SHSs networks are presented in Chapter 7. It also gives a summary of the key outcomes of this thesis and importance of the research while developing sustainable and scalable access to electricity across the Developing World.

7. Conclusion and Future Work

The key objective of the research presented in this thesis is to introduce a novel scalable and affordable approach within off-grid energy sector that can supply electricity for new range of electrical appliances amongst families currently relying on stand-alone SHSs.

The new concept of bottom-up electrification could be considered as an advancement to existing approach (via installation of individual SHSs) which currently gives chance to consume electricity for basic electrical appliances for millions of people. Interconnected SHS paradigm does not require users to cover high upfront costs for new generation and storage modules to adapt new fridge, TV or laptop. Instead, proposed microgrid utilises significant portion of electricity that currently goes to waste to boost new electric demand within the community.

Bottom-up electrification approach also offers a great scalability – network can expand step by step, and its development pace could be stimulated proportionally to growing electricity consumption. Such organic expansion of the microgrid may be a natural way of meeting future power requirements in the rural regions of the Developing World.

This thesis reveals numerous other benefits resulting from the introduction of bottom-up electrification across SSA. The main contributions to knowledge exposed in this document are summarized in Section 7.1. Although proposed concept enables a great range of benefits and opportunities introduced by more productive use of electricity within interconnected SHSs networks, some barriers and limitations have also been identified. Many of them require further investigation and analysis as well as deeper interaction with the policymakers. Other need additional technical work modelling to be performed on software and hardware side of the Energy Box controller. The most significant recommendations for future work are summarised in Section 7.2.

7.1. Contribution to Knowledge

Work presented in this thesis introduces a novel approach of a bottom-up electrification in the Developing World. The key contributions are listed below:

- Introduction of a Smart Power Management capable to operate on existing SHSs technology without interrupting internal control system of the SHS
- Development of the Energy Box prototype – system capable to provide interconnected SHSs networks in rural regions of the Developing World
- Analysis of the bottom-up transition potential in SSA, amongst users with basic access to electricity for lighting and phone charging
- Validation of the approach amongst SHSs users in Murambi village where first microgrid integrating SHSs in SSA has been designed

The core of this thesis is based on numerous studies considering SHS market in SSA where growth of such systems in the past years has been significantly high. These technologies deployed in SSA are significantly different to those installed in Bangladesh – where first interconnected SHSs microgrids were established by Solshare. As a result of outcomes presented in this thesis, local microgrid developers operating in SSA can now provide bottom-up transition within all types of SHS available on this market without necessarily reconfiguring the system.

The analysis of bottom-up transition in SSA starts with evaluation of off-grid market, primarily focusing on Rwanda. The results are generated with a support of data extracted from BBOXX remote monitoring system. The outcomes are valid for 50W SHSs which are currently limited to provide electricity primarily for lighting and phone charging. Such systems are not capable to power new appliances such as fridges or big TVs – the most desired devices amongst users currently relying on SHSs [138]. According to studies presented in this thesis, significant portion of electricity generated by off-grid SHSs currently goes to waste introducing opportunities to provide new range of electrical devices after introducing interconnections.

Field studies performed in the Northern Province of Rwanda give understanding of typical topologies of villages where SHSs are popular. The analysis also includes numerous interviews with SHSs users who could potentially gain benefits from installation of the interconnected SHSs network. Results gathered from interviews in Rwanda also presents strong willingness of SHSs users to participate in the local energy market. Benefits resulting from the introduction of interconnections are particularly important either for prosumers who wish to invest in new appliances, consumers who do not have access to electricity at all or others who are purely willing to export electricity to support electric demand of other users.

The novelty presenting optimal usage of electricity includes design of a new Smart Power Management (SPM) system. Such module provides appropriate power flows control within the microgrid network, enabling all assets interconnected in the system contribute to existing demand in the village microgrid. Simultaneously, all batteries in the microgrid tend to provide similar rate of power which helps to maintain their longer operational life cycle. As a result of introducing SPM each module connected to the network “understands” conditions of the microgrid. Energy Box has therefore capabilities to optimise power flows according to demand and supply at each section of the network; users with high SoC are prioritised in contributing to overall demand over those who typically experience high energy requirements. Such coordination results in maximising electricity consumption in the system. Simultaneously, all SPM functions are developed to minimise reliance on sophisticated communication technology and all control aspects are performed based on microgrid voltage analysis making it a cost-effective solution.

Finally, deployment of the first interconnected SHS microgrid with a SPM system has been accomplished in the Northern Province of Rwanda. The system connected 8 households with various demand, with or without SHSs. Feedback gathered from users testing first prototypes of the Energy Box presents future potential for such network expansion in rural Rwanda. It also gives suggestions of how new range of appliances could support existing businesses and how such transition could support introduction of new local enterprises.

7.2. Future Work

Although information included in this thesis present various techno-economic aspects of bottom-up electrification across the Global South, further research is required to be conducted to optimise the Energy Box as well as to develop further feasibility studies for the bottom-up electrification.

Introduction of Power Protection Features within Energy Box

The first Energy Box prototypes installed in Murambi are primarily designed to prove functionality of SPM in field. Results indicate that addition of new high-power appliances within a network of interconnected SHSs is possible without adding generation or storage modules in the system.

Further technical improvements of the Energy Box would consider installation of protection circuits. As such, each Energy Box would gain capabilities to disconnect system once reverse polarity on a DC circuit is detected, maintaining safe operation of the Energy Box.

Other potential enhancements are associated with a design of gate drives for the buck converter. Prototypes introduced in this thesis make use of DC/DC switching regulators to adjust Gate-Source voltage of the MOSFETs. Instead of using such regulators, 12V battery voltage can be used activate PWM of a magnitude of 12V between Gate and Source terminals. It can be accomplished by using bootstrap method maintaining appropriate voltage level to support MOSFET [142].

Further Optimisation of the Energy Box Software

Software currently installed for each of the Energy Boxes has a capability to monitor network parameters and gives indication of rate of energy imported and exported from the SHS. Further development is required to improve robustness of the communication system. For each Energy Box deployed in field remote monitoring system worked appropriately just for the first few hours and no sensible data from the microgrid was recorded. As such, this thesis does not present rates of energy each prosumer contributes to meet new electric demand in the village which would validate appropriate operation of the SPM. Future work on software development can also introduce micropayment scheme between prosumers. As such, each customer would have a chance to register to MTN Mobile Money platform to gain monetary benefits from either exported electricity. Such system would also automatically charge users for electricity consumption for new high-power appliances.

Capabilities to Exchange Electricity with the National Network

Although SPM developed to date presents capabilities to interconnect SHSs within off-grid environment, to provide next stage of the bottom-up electrification and capabilities to exchange electricity between SHSs and national power network, further system development is required. This would involve introduction of additional features to maintain stability between two network topologies (AC and DC) as well as smart power conversion to inject electricity from one system to another. As a result of such interaction, interconnected SHSs network could become useful solutions for public utility companies which would gain capabilities to utilise assets deployed in field (as form of SHSs) to maintain higher reliability of power supply in rural regions of SSA. As a result of utilising DC interconnected SHS microgrids equipped with highly efficient appliances, overall power consumption per household could be successfully reduced which would minimize overall requirements for power network expansion in the future, bringing significant economic benefits associated with the national grid expansion plans.

Business Model for the Introduced SHSs Microgrids

Successful deployment of interconnected SHSs microgrids needs to relay on appropriate business model which would provide growth and expansion of such systems. This requires clear understanding of mechanisms supporting growth of off-grid electrification projects across SSA. Evidence suggest that installation of microgrid systems strongly depend on rate of subsidies and grants available [143]. As such, it is expected that development of interconnected SHSs microgrids would require financial support from the public sector.

Further studies are required to be performed to indicate benefits that interconnected SHSs networks can introduce within off-grid environment, considering future grid expansion to rural regions. Interaction with public utility companies on these aspects as well as approval the proposed technology could introduce appropriate financing mechanism which could effectively improve quality of services provided by off-grid systems across many countries in SSA.

Further Field Tests and Understanding Impact on Local Societies

Appropriate business model for distribution of new, high-power appliances would require verification on significantly bigger sample group than in Murambi village in 2019 (eight households interconnected). Such research would also need to be conducted within various locations to understand how different types of consumers make use of the proposed system. As a result, long term effect of the introduced technology could be examined to fully estimate impact on the community provided by installation of the Energy Box.

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APPENDIX A

Bottom-up Electrification Questionnaire - Rwanda

Age: 15-25 ○ 25-35 ○ 35-45 ○ 45+ ○

SEX: M / F

How many people live in your household? …………

How much do you currently pay for electricity per month? ………..

When do you think your power consumption is the highest?

7am-10am ○ 10am-3pm ○ 3pm-5pm ○ 5pm-8pm ○ 8pm-10pm ○ 10pm-7am ○

How many hours a day do you use electricity for?

0 – 3 hours ○ 3 - 6 hours ○ 6-10 hours ○ 10-14 hours ○ 14-18 hours ○ more ○

Which of the following items do you possess?

Light Bulbs ○	Radio ○	Phone Charger ○
Small TV ○	Fan ○	Shaver ○
Large TV ○	Iron ○	Fridge ○

Which of the listed items do you desire the most? ………………………….

Is there any other device you are willing to use? …………………….

Do you know what is the energy consumption of your?

Light Bulbs? …….

Phone Charger? ………

Other equipment? ……..

Have you been BBOXX customer for more than 3 years?

YES ○ NO ○

Have you previously upgraded your system from small to biggest Solar Home System?

YES ○ NO ○

If YES:

Would you be interested in Upgrading the System in order to consume electricity for larger appliances?

YES ○ NO ○

What would that be (the cost applies for the first 3 years since the upgrade)?

22” TV – 13 450 RWF/month for 3 years, (6500 RWF/month after 3 years) ○

Fridge – 16 000 RWF/month for 3 years, (10 700 RWF/month after 3 years) ○

22” TV and Fridge – 24900 RWF/month for 3 years, (14 700 RWF /month after 3 years) ○

Fan – 5700 RWF/month for 3 years, (5000 RWF/month after 3 years) ○

DVD Player – 5400 RWF/month for 3 years, (500 RWF/ months after 3 years) ○

Sewing Machine – 11 860 RWF/month for 3 years (11 480 RWF/month after 3 years) ○

Anything else……….

If NO:

Would you be interested in selling electricity to your neighbours for 2$/month?

Yes ○ No ○

APPENDIX B

Bottom-Up Electrification: Community survey

Date: ____

Time: ____

Name of enumerator: ______________________________

Name of village: _________________________________

Introduction

Thank you for your time. We are a group of researchers from the University of Strathclyde in Glasgow, Scotland. We have designed a technology that joins together solar panels within villages to create a local mini-grid, which we hope can provide you with a more stable connection, improve capacity, avoid wasted energy, and connect neighbours who currently do not have their own solar panels. Through this mini-grid, you can sell excess energy to your neighbours, or buy energy from neighbours if you would like to run larger appliances but currently lack the capacity.

We would thus like to ask you a few questions about your current energy and living situation. This should only take around 15 minutes.

Household Profile

(1) Name of respondent:

(2) Sex of respondent:

(3) Age of respondent:

(4) What is your occupation?

----

(5) What is your education level?

----

(6) How many people live in the household?

----

(7) How many women live in the household?

----

(8) How many children live in the household?

----

(9) How many children go to school from the household?

(9a) Does anyone in the household attend college or university?

(9a) Does anyone in the household hope to attend college or university in future?

Household budget

(10) What is the main source of income in the household?

----

(11) Are there any other sources of income in the household? Please specify.

----

(12) In total, on average, how much income does the household get per month?

----

(13) How much approximately do you spend on utilities per month?

(14) How much approximately do you spend on food per month?

Electricity, utilities and activities

(15) Do you currently have access to electricity?

(15a) If so, how much do you spend on electricity per month?

(15b) Do you have a battery for storing electricity?

(16) On a scale of 1-10, how good is your electricity connection?

Very bad 0 – 1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – 9 – 10 *Very good*

(17) Which fuel does your family currently use for cooking (wood, biomass, charcoal)?

(18) Which of the following appliances do you currently have in your home:

○ Television
○ Phone/charger
○ Fan
○ Fridge
○ Shaver
○ Other (please specify)

(19) How many hours do your children spend studying per night?

(20) How often on average does your family eat together per week?

1 – Never
2 – Once per week
3 – Multiple times per week
4 – Every day
5 – Multiple times per day

(21) Do you and your family socialise in other ways, such as watching TV, playing games etc? If so, please specify:

(21a) How often do you engage in these other activities together?

1 – Never
2 – Once per month
3 – Once per week
4 – Multiple times per week
5 – Every day

APPENDIX C

Introduction

Thank you for your time and for participating in the Energy Box trial this summer. We would like to ask you a few quick questions about how the trial went for you and how you feel about the project going forward. This should only take 5 minutes.

1. On a scale of 1-10, how positive did you find your experience of the Energy Box overall?

Very negative 0 – 1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – 9 – 10 *Very positive*

2. During our field tests in August, would you say that your electricity connection was more or less reliable than usual? MORE LESS NO CHANGE

3. Based on your experience of the Energy Box, would you be willing to add more devices to your system in the future? YES / NO

    a. If yes, which appliances would you be interested to add?

4. Would you be willing to share your electricity with other people in the village for additional income every month? YES / NO

5. Would you be willing to share a refrigeration unit with your neighbours to reduce costs of ownership? If not, why not?

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6. How can new electrical appliances help to grow your business? What new appliances would you like to have in the village to improve your business?

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7. Do you think that sharing electricity in a local energy network, like with the Energy Box, can improve quality of life for you or people in your community? Please expand if you can.

8. Based on your experience with the Energy Box, how willing would you be to participate in a local energy network again in the future?

Not willing 0 – 1 – 2 – 3 – 4 – 5 – 6 – 7 – 8 – 9 – 10 *Very willing*

9. Would you recommend the Energy Box to your friends and family?