Review

A field trial of off-grid SHS Interconnection in Rwanda's Northern Province

Bartosz Soltowski a,⁎, Fraser Stewart b, Scott Strachan a, David Campos-Gaona a, Olimpo Anaya-Lara a, Stuart Galloway a

a Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XO, UK
b School of Government and Public Policy, University of Strathclyde, Glasgow G1 1XO, UK

Abstract

Article history:
Received 23 July 2021
Revised 10 November 2021
Accepted 12 November 2021
Available online xxxx

Solar Home Systems (SHSs) have become a popular means of electrification for millions of people living in rural regions of developing countries with no access to the national grid. As the electrical demand grows, however, there are economic and technical challenges that exist in scaling-up SHSs. At present, up to 70% of the energy generated by SHSs is surplus and effectively goes to waste, due to high solar resource peaks aligning with low demand periods and restricted storage capacity. Interconnecting existing SHSs to form ‘DC village’ microgrids, comprised of distributed photovoltaic generation and battery storage, enables communities to unlock this surplus energy for more productive uses. This may be to service small businesses with higher energy demand than can be provided by a typical SHS (e.g. to shops or barbers), or to allow domestic consumers to connect higher powered appliances. Meanwhile, people without their own SHS can also connect to the system introducing basic lighting and phone charging for lower capital costs than those with SHSs. This paper presents the results of a field trial conducted in Murambi Village, in the Northern Province of Rwanda, which involved the interconnection of seven households with their own SHS and one with no previous access to electricity. An innovative smart controller developed by the authors to facilitate SHS interconnection was deployed across this village. Using a mix of survey and focus group methods, the paper examines how people experienced the interconnected SHS system; the opportunities and benefits (social, economic) this presented; how the system enabled the use of new (higher power) appliances and new practices by trialing a novel shared refrigeration unit; and the potential of SHS interconnection in the broader context of the ‘bottom-up electrification’ paradigm.

© 2021 The Authors. Published by Elsevier Inc. on behalf of International Energy Initiative. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Keywords:
Bottom-up electrification
Interconnection
Solar Home Systems
Off-grid Microgrids
Local energy markets
SDG7

Contents

Introduction ................................................................. 70
Socioeconomic impact of interconnections. ................................. 71
- Increased capacity for larger appliances ................................. 71
- Economic stimulus ........................................................ 71
- Higher electrification rates ................................................. 71
Demand aspirations assessment ............................................. 71
Interconnection and the energy box ......................................... 72
Field trial: Murambi Village, Rwanda .................................... 72
Network design and consumption profiles of BBOXX customers in Murambi ............................................ 74
- Fridge share ............................................................... 75
Results. ........................................................................ 75
- Acceptance of technology .................................................. 75
- Reliability of supply ...................................................... 75
- Willingness to upgrade .................................................... 76
- Fridge share scheme ...................................................... 76
- Community expectations .................................................. 76
Summary of the field work ................................................... 77

⁎ Corresponding author.
E-mail address: bartosz.soltowski@strath.ac.uk (B. Soltowski).

https://doi.org/10.1016/j.esd.2021.11.004
0973-0826/© 2021 The Authors. Published by Elsevier Inc. on behalf of International Energy Initiative. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Introduction

Over 1 billion people around the world live without access to electricity, with the highest concentration residing in rural regions of developing countries; mainly in Sub-Saharan Africa (600 million) and Developing Asia (500 million) (Blimpo & Cosgrove-Davies, 2019; Rosenthal, 2009). In these areas, the majority of people still rely on “traditional” sources of energy such as kerosene for lighting or charcoal and wood for cooking – almost 3 billion people in the case of the latter. Lack of access to clean energy has significant negative impacts on health, wellbeing and socio-economic development more broadly. This lack of reliable, sustainable and affordable energy limits the educational prospects of children and young adults, stifles local economic activity, and has both direct and indirect impacts on the health and wellbeing of some of the world’s most vulnerable communities (Torero, 2016; Venkata Ramana et al., 2015). This problem is especially acute and difficult to resolve in developing countries where governments lack the financial and infrastructural capacity to extend the national grid to these harder-to-reach rural populations where the poorest and most vulnerable communities are often found.

Over the last decade or so, different types of off-grid technologies have been introduced to combat this problem. Of these technologies, Solar Home Systems (SHSs) – a small solar photovoltaic (PV) module and battery installed directly in people’s homes – have been considered to be the most effective means of providing more immediate energy access for off-grid communities with little or no prospect of future grid connection. SHSs typically provide Tier 1 energy access (Energy Sector Management Assistance Program (ESMAP), 2014), which consists of a few LED lights and a phone charger (Global off-grid solar market report semi-annual sales and impact data authors’ note, 2017; Hossain et al., 2019). The development of pay-as-you-go (PAYGO) business models also means that these systems require no up-front investment from individual users and carry substantially less political or technical effort than the more costly and coordinated approach required of national grid expansion. While perhaps not the most cost-effective means of providing off-grid energy access when first introduced, the falling costs of solar PV year-on-year (Gul et al., 2016) have made SHSs a more desirable and affordable electricity solution for people living below the poverty line in under-developed countries – albeit often deployed with some microfinance instrument being put in place by non-governmental organizations (NGOs) or private companies. The SHS market size in Sub-Saharan Africa is now estimated at 63 million households (Sanneh & Hu, 2009).

For this growing popularity, however, SHSs are by no means a perfected technology. First, there are problems with SHSs in their capac- ity for scaling-up. Evidence shows that some SHS users show great in- terest in improving their systems to handle larger appliances (Soltowski et al., 2019). One way of achieving this is to invest in new solar PV modules or battery storage, but this can be a very expensive solution and as such is not viable for most people in off-grid communities. Second, significant portion of electricity generated by SHSs currently goes to waste due to the inability of most households to fully utilize generation peaks (Fairley, 2018). Meanwhile, many people living in close proximity to those with their own SHS still cannot afford electricity at all. However, it is adjacency that offers an opportunity for greater inclu- sivity in energy provision.

In such instances, SHS owners (prosumers) can be interconnected to form village scale microgrids (Soltowski et al., 2019). These interconnected SHS microgrids can effectively unlock surplus generation for use by those who wish to increase demand for larger appliances, such as local businesses, and/or to connect low-income households unable to afford the up-front costs of their own SHS. With this setup being relatively simple, requiring only low-cost distribution cables and smart controllers to regulate power flows (costs of which are typically cheaper than the cheapest SHS PAYGO contract), interconnection could be hugely effective both for increasing demand and connecting people at the “bottom of the economic pyramid”.

To date, extensive research on bottom-up electrification has been conducted especially in Bangladesh – country with very high population density as well as successful programs supporting financing of SHSs (Fairley, 2018; Koepke & Groh, 2016; Sharif & Mithila, 2013). Other publications highlighting novel smart grids providing prosumers’ electricity exchange were based on research conducted in India and on the Philippines (Fowlie et al., 2018; Prevedello & Werth, 2021). Available studies emphasize opportunities as well as barriers faced while intro- ducing SHS interconnections in the context of developing Asia (Kirchoff & Strunz, 2019). While there has been significant success re- ported in this region, further research involving field trials should be conducted to explore transferability of this concept to other regions of the world where deployment of SHS has been successful in the past few years. One such place where interconnection may be an effective solution is East Africa, where there are many village communities with relatively high densities of SHSs and where a substantial proportion of surplus SHS generation exists. Data from one of Rwanda’s leading SHS providers, BBOXX, shows that an average of 60% of generated energy is unutilized (Soltowski et al., 2019).

This paper investigates the potential for the introduction of bottom- up electrification in rural Sub-Saharan Africa, through a field trial of novel SHS interconnection technology, informed and measured through survey research. The fundamental outcomes presented in the paper highlight results of fieldwork within off-grid regions (where interconnected SHS microgrids are feasible) and grid-connected areas to assess electric demand growth amongst villagers with a “strong” power supply. Both communities were of a similar socio-economic background with a majority of those surveyed living from farming and operating small local grocery stores.

Through a survey of people currently residing in grid-connected communities in rural Rwanda, it was first demonstrated that demand for larger electrical appliances (beyond LED lighting and phone charg- ing) in rural Sub-Saharan Africa exists and that a sizeable portion of this population has both the capability and willingness to pay for them. To meet this demand for new electrical appliances, a novel plug-and-play device, known as the “Energy Box”, was developed, providing the capability to interconnect SHSs to utilize electricity that nor- mally (in non-interconnected, stand-alone operation) is not utilized; supporting larger appliances and giving opportunity for more produc- tive uses of energy and improved social and economic development within the community. Results of a field trial of the first-of-its-kind inter- connected SHS microgrid deployed in East Africa are presented herein. The system interconnected eight households in Murambi Village in the Northern Province of Rwanda. This research takes an interdisci- plinary mixed-methods approach, using survey and focus group data along with remotely acquired technical data to give a well-rounded un- derstanding of the social, economic and technical impact of the project both for end-users and the wider community.
The remainder of this paper is organized as follows. First, the anticipated socioeconomic impacts of SHS interconnection is provided. Second, the “Energy Box” is presented as a simple and effective means of achieving SHS interconnection. Third, an overview of the Murambi Village field trial is presented, profiling the engagement and experiences of residents and SHS users there; outlining the socio-technical features of the microgrid. The paper achieves this using survey and focus group results. Finally, a discussion on the socioeconomic impacts of the trial is presented with specific recommendations on the wider implications of SHS interconnection technology for the future.

**Socioeconomic impact of interconnections**

SHSs in the form of a small solar PV module and battery, typically used to power some light bulbs and phone charging, have been hugely effective in bringing clean electricity to off-grid communities in the last decade (International Finance Corporation, 2018; Khan, 2004). In areas where grid connection is infeasible due to political and infrastructural limitations (Morrissey, 2017), SHSs have proved an effective means of delivering rural energy access for many and contributing to the achievement of United Nations Sustainable Development Goal 7 (SDG7). With SHSs, people without grid access can reap the well-cited social, economic and health benefits of electrification including better lung health, educational opportunities and local economic development (Samad & Zhang, 2016).

Yet, SHS technology is not without issue. As it stands, around 60% of electricity generated by SHSs goes completely to waste. This is due to SHSs typically being oversized and users being unable to fully utilize the generated energy during the daily solar peak. Meanwhile, people who wish to install larger appliances such as fridges or 22-in. TVs are unable to afford the required SHS capacity upgrade, while extremely low-income households in the same community are unable to afford a SHS at all.

To combat this, SHS interconnection to form local microgrids can create a shared electricity pool that effectively utilizes the surplus energy made available (Groh, 2016). This can also be scaled up from connecting individual SHSs to connecting full microgrids together, following a bottom-up electrification paradigm. While still in their relative infancy, technologies that connect SHSs together to unlock latent excess capacity for more productive uses have been developed for use in several locations in Bangladesh (IDCOL, 2016). Yet despite this development, little is known about the real-life impacts of interconnection on communities in Sub-Saharan Africa where village topologies, SHS technology and potential electrical demand levels may be significantly different to those in Bangladesh. Given the ability of bottom-up electrification model to efficiently unlock excess capacity, some immediate and common techno-socio-economic benefits are expected.

**Increased capacity for larger appliances**

The main goal of interconnection more broadly is to unlock latent excess generation for better use. One common finding from surveys of SHS users in off-grid, developing locations is their desire to install larger electrical appliances, such as fridges or big 22-in. TVs (i.e. in line with Tier 2 energy access), which many SHSs struggle to support. With this newly unlocked generation, an increase in the use of higher power appliances can be expected in places where interconnection takes place, particularly amongst local shops and cafes.

**Economic stimulus**

With this excess capacity unlocked for larger appliances, interconnection could provide a substantial economic boost for local off-grid communities. Again, while it is not certain exactly how all communities would utilize this new capacity, new business opportunities arise with the ability to install larger appliances. It would be reasonable to expect that this in turn could provide a significant economic boost to rural areas in developing countries in the form of higher revenue for existing businesses who install larger appliances, and by creating new business opportunities based around these larger appliances.

**Higher electrification rates**

Interconnected SHS microgrids consist of consumers as well as prosumers (i.e. SHS owning households), therefore opening up energy access to lower income households and increasing village (and ultimately rural) electrification rates. This can increase quality of life more widely and lay the foundation for a more inclusive electrification effort that ensures “nobody is left behind” (Stuart et al., 2016).

Other indirect benefits are also feasible – knowing that electrification and increased economic activity can improve living conditions, health, happiness, gender equalities and social inclusion (Scott et al., 2014), these fundamental social and economic benefits have huge potential to have a much wider impact beyond these immediate outcomes. However, these are far less testable hypotheses and deductions without time-series information across several installations: this paper will thus focus on understanding the immediate local impacts and outcomes.

**Demand aspirations assessment**

Before installation of the interconnected SHS microgrid in Murambi, an assessment of the community’s aspirations to connect the new range of appliances within was conducted. It was performed by a team of University of Strathclyde researchers and was undertaken in Northern and Western Province of Rwanda amongst electricity consumers who were connected to the main power network no more than seven years before the research took place. To quantify and verify the potential for bottom-up energy access, appropriate assessment and evaluation of 66 households within several community centers (rural villages with high population densities and wide range of businesses) has been conducted. The first set of results highlights a variety of electrical appliances currently used by the group of interviewed users. The population of different grid-connected devices utilized within the community are listed in Fig. 1.

In addition to appliances listed in Fig. 1, wide range of other devices has been adapted by the interviewed families. These include hair dryers, printers, cameras, irons, kettles, speakers and blenders. According to Fig. 1, high number of appliances used within rural grid-connected communities is not currently offered within a standard SHS which includes LED lighting and phone charging. This indicates that relatively high quantities of SHS users residing in rural areas have willingness and financial capacity to purchase new range of electrical appliances beyond currently offered within a standard SHS set. This can be achieved by providing low-cost fridges, laptops and TVs of minimum power and energy requirements. As such, the principal constraint

![Fig. 1. Demand specification amongst grid-connected users in rural Rwanda.](image-url)
limiting SHS users from adapting new appliances is generation and storage capacity within their solar installations.

Furthermore, all devices purchased by the interviewed families in grid-connected rural Rwanda were bought without access to financing. Buyers had to cover full upfront cost for these appliances, without having access to PAYGO. Therefore, it is a reasonable assumption that an appropriate financing scheme would most likely boost existing demand even further. The survey outcomes highlighting price distribution of selected appliances (TVs, radios and fridges) amongst interviewed households are presented in Fig. 2. intersection between grey fields underlines median for each appliance category. Light grey field presents third quartile price range whereas dark grey indicates second quartile within each group.

According to Fig. 2, some residents in rural Rwanda have the income capacity to purchase refrigeration systems for up to $US350. Furthermore, the research outcomes indicate that monthly running costs of a local shop with such a 200 l fridge might reach up to $US15 (at cost of electricity of approximately 0.18$/kWh (ESMAP, 2019; Mercandalli & Losch, 2017)). Fridges are primarily used by local businesses supporting small butchers with cold storage for meat, and so there is an expected return on the investment for such productive uses of energy. Other fridges provide smaller cooling space for grocery shops and running cost is estimated at $US6 - $US7/month. For households equipped with TVs, typical purchase price of these appliances ranges between $US80 and $US160 which is equivalent to approximately 15% - 20% of gross annual income of households analyzed. Monthly electricity bills for households with TVs are at $US45 - $US65. Similarly to fridges, financing for TVs is also not available for grid connected customers.

Demand assessment performed in rural grid-connected Rwanda shows that people still have the capability to purchase appliances of high power and energy requirements (e.g. fridges, TVs) and meet their full capital cost. This transition is achieved with no support of PAYGO contracts distributing costs of appliances over time.

The assessment conducted within grid-connected villages in Rwanda proves that some demand for new, high-power appliances in rural regions of the country exists and with the support of an appropriate technologies, financing scheme, fulfilling this demand could serve to enhance social and economic development within the community. However, where no grid exists but where basic energy access in terms of lighting and phone charging is available through stand-alone SHSs, there remains the challenge of providing sufficient generation capacity to meet this new, additional demand. This can be achieved by interconnecting SHSs, using the Energy Box connectors/controllers, which enable utilization of electricity which is currently unutilized. As a result, new range of appliances can be supported even by a small network of pre-existing interconnected SHSs, without the need to install additional generation and storage capacity. Evaluation of pilot project outcomes for the development of such an interconnected SHS microgrid in Rwanda is presented in this paper.

### Interconnection and the energy box

With all potential benefits resulting from introduction of new electric appliances in rural communities in mind, interconnection technologies have been developed to various stages in recent months and years. One such interconnection technology is the Energy Box; a ‘smart’ power management controller designed by an interdisciplinary team of researchers from across electrical engineering, political science and computer science at the University of Strathclyde in Glasgow, UK. The Energy Box connects SHSs together to form local microgrids, where users can easily import and export energy for income generation, to supply higher-powered devices or to connect lower-income households unable to afford the upfront costs of a SHS.

To create the initial microgrid, users with SHSs are given an Energy Box – a unit which easily connects to their SHS module. These boxes are connected together between households using low-cost distribution system at 48 V DC. The controller can then step down voltage to supply new high-power devices operating at 12 V DC. Electricity is traded across this microgrid via remotely monitored microtransactions. Prices for this electricity are automatically allocated based on the demand/supply ratio present in the system and indicated by one of 4 LEDs installed within each Energy Box. When this ratio is high, the cost of importing electricity increases, but will reduce as more surplus energy is introduced to the pool and the ratio increases. If a consumer does not want to import energy from the microgrid, perhaps because the present cost is too high, they can simply disconnect their own appliances. Similarly, SHS owning households can decide when to import or export depending on their own energy demand and financial needs.

For those without their own SHS, the Energy Box allows for base-level electrification (Tier 1) at an affordable rate. These users also receive and Energy Box and connect to the local interconnected SHS microgrid, from which they can receive affordable electricity from the excesses generated in their neighbors’ systems. This might be a cost-effective simple alternative to SHS installation for basic electricity services, which optimizes the utilization of assets already installed on the-ground. At present, even the most basic SHS packages begin on PAYGO contracts at $5–$10 per month, which is still out of the range of many of the poorest people in these developing areas. People without their own SHSs can instead obtain reliable and consistent Tier 1 energy access without need to purchase PV systems and energy storage modules – the most expensive elements of the SHS. Meanwhile, it is estimated that the production cost of each Energy Box as well as cable used to connect to the microgrid network is approximately $US32/household (based on our field studies introduced in the following part of the paper) which is significantly lower than capital cost of a new SHS (IRENA, 2016). As a result, the Energy Box has the potential to unlock this latent excess SHS capacity, especially in highly populated off-grid regions, and reap those key socioeconomic benefits of interconnection.

### Field trial: Murambi Village, Rwanda

To test these expectations and observe how the Energy Box would work in practice, a pilot project was established in Murambi Village in the Northern Province of Rwanda. Rwanda was chosen specifically as a country with a high rate of SHSs, with many village locations where there is a relatively high density of these systems in operation. Baseline surveys were conducted across three different villages to establish the social, economic and demographic makeup of villagers and to establish topographical suitability. Murambi village was chosen as a small community with a good mix of residential and business buildings. This afforded the project the opportunity to test how the system suits and benefits people in their homes as well as local businesses and the local economy more broadly.

In addition to this demographic variance, topologies of the villages would also have a substantial impact on the effectiveness of interconnection and power distribution. Villages with large distances...
between prosumers may require higher initial investment costs for interconnections. In addition, depending on the distribution of SHSs and demand across an interconnected SHS microgrid, there may be additional power losses and voltage drops to contend with, even at a distribution level of 48 V DC. Therefore, during the initial site surveys, several villages with a relatively high-density of SHSs were considered (i.e. where distances between houses ranged from 5 to 60 m), before selecting the village of Murambi. Focus groups were conducted in conjunction with local representatives and workshops were held to raise 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 household members was 5. Five of the six households owned a standard SHS from providers BBOXX, consisting of a 50 W PV module and 12 V 17 Ah battery, equipped with two or three LEDs and phone charger, while one used a larger capacity Mobisol system (with an 80 W PV module and 12 V 120 Ah 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 8-in. 12 V 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 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. 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 (Fig. 3).

As with a majority of people across off-grid areas in developing countries (IDCOL, 2016), most Murambi residents rely on farming as their primary source of income. Significantly fewer villagers make their living from other jobs. 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 effectively extend their business opening hours.

Households relying on SHSs typically consume electricity for lighting and phone charging. Some also have a small TV or radio, although these are not commonplace due to cost and SHS capacity limitations and restrictions. In addition to the monthly payments for the SHS, households spend a significant portion of their income on other sources of energy (e.g. wood or charcoal), mainly for cooking. 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 households have thus had to switch from wood to more expensive sources for cooking like charcoal. The average proportional monthly expenditure of Murambi residents (based on the survey results) are illustrated in Fig. 4.

A significant portion (25–30%) of monthly expenditure is spent on energy, with 15–25% of their monthly income on basic access to electricity. Expenditure as a proportion of household income is shown in Fig. 4. The most common financial model for SHS ownership is a 3-year PAYGO model, with costs ranging anywhere from $5 to $150 per month (Brief, 2011; Rolffs et al., 2014) depending on SHS generation and storage capabilities as well as appliances supplied.

In some instances, where households have upgraded their SHS to accommodate higher power devices such as TVs, they will spend more than 30% of their household income on SHS services. All customers are also 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, once these PAYGO contracts end, total expenditure on a SHS after the first 3 years reduces by approximately 30%, which may encourage households to consider upgrading to accommodate higher power appliances. Furthermore, analysis performed by the University of Strathclyde researchers indicates that approximately 30% of users interviewed in rural Rwanda with access to electricity via BBOXX SHSs increased their income by opening small businesses. As such, this user group represents one that may be considered likely candidates for upscaling demand by a set of new electric appliances.

These findings have a few immediate implications for the viability of SHS interconnection. First, the costs of energy in these areas are substantial for those with their own SHSS and restrictive to those on the...
lowest incomes. Interconnecting these SHSs offers an alternative means of electrification that is inclusive of people in those lowest income brackets. Furthermore, in utilizing a proportion of this surplus energy pool to provide an entry level of Tier 1 energy access for the poorest households, it offers an opportunity for SHS owning households to generate income in the process, and also progress to Tier 2 of the ‘energy ladder’. This is consistent not just in Murambi, but across all villages surveyed.

**Network design and consumption profiles of BBOXX customers in Murambi**

With these factors in mind, a total of eight households were subsequently interconnected in Murambi village. The interconnected SHS microgrid consisted of 220 m of 2.5 mm² distribution cable, with typical distances between connected buildings ranging from 5 to 20 m. The topology of the Murambi interconnected SHS microgrid is presented in Fig. 5.

In total in Murambi, there were 13 installed BBOXX systems and 1 Mobisol system. At the time of this field trial, some customers had already paid off their 3-year PAYGO contract and were left only paying a monthly maintenance fee, which allowed the microgrid to interconnect ‘customers’ with 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 analyzed. This allowed the overall energy surplus within the network to be estimated and, by extension, the 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 (prior to deployment of the microgrid) is illustrated in Fig. 6. Customer 1 represented the business owner, used the BBOXX SHS to power three LEDs, a phone charger and an 12 V TV. All other users analyzed were generating electricity to supply LEDs, phone chargers and occasionally radios (data on the average rate of energy consumption was exported from BBOXX's Smart Solar remote monitoring system, which is installed in each SHS).
From Fig. 6, we can see that the typical energy consumption per BBOXX customer in Murambi is between 50 and 60 Wh/day. Yet, it is estimated that a 50 W panel at the optimal inclination angle can generate average of around 200 Wh/day in the month of August (when field work was undertaken). Therefore, it is proven that over 60% of generated energy 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 (80 W solar panel modules as oppose to 50 W installed with each BBOXX SHS).

**Fridge share**

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 high-power appliance to test on the newly formed microgrid. Results from initial field surveys showed that a fridge was the most desired appliance on offer. Of course, 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 neighbors, 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. 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. The 95 l fridge used in the trial never exceeded 20 W, and the maximum daily energy consumption was 230 Wh/day in cases when system was starting from warm and had been opened several times throughout the day. The cost of such device is $US300.

A local shop owner, with a completed PAYGO contract and subsequent desire to expand his business through the provision of communal refrigeration facility, was furnished with this refrigeration unit. The central village position of this shop made it a convenient location for shared/communal refrigeration. Refrigeration space was also used to chill drinks for sale in the local business.

**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 once 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. Results are presented as follows.

**Acceptance of technology**

The first question was designed to understand overall impressions amongst users towards the new technology in Murambi Village once 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 Fig. 7. Overall, users expressed a positive experience of interconnecting SHSs in Murambi village and the advantages of this, with an average score of 8.25 out of 10 and no negative responses to report. This positive response substantiated by the outcomes of the focus group discussions, where non-users expressed a positive opinion about the trial based on their passive observations of the effects it had on their neighbors - 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 later enquired about how they too could join the microgrid in future.

**Reliability of supply**

The next set of questions related to the overall quality of the power supply within the village during the Energy Box field tests. 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 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 the installation of the microgrid. This might be a result of the high reliability of power supply from BBOXX systems, which are intentionally oversized for the average customer to allow unlock this spare capacity.
for future upgrade. 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.

Willingness to 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. Users 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 amongst 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 (Fig. 8). 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. 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 (Fig. 9) 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 skeptical of being able to afford their own TV unit). Despite individual concerns of affordability for some appliances, however, all users declared willingness to 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.

Fridge share scheme

Beyond the benefits for storing food and drinks, 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 in turn provided additional income to those exporting their excess to the microgrid). Initial indications from survey and focus group responses suggests that the range of new businesses that can arise from SHS interconnection is varied. Some villagers expressed an interest in opening a TV viewing shop in order to attract new customers, for example, while others wanted to open a new barber or grocery shop – interconnection was seen as a possible enabler for these aspirations.

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 direct sale (export) of 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 amongst children 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 8, 9 or 10.

Summary of the field work

The field trial outcomes closely aligned with key initial expectations, 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. As anticipated, 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 neighboring 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 actually 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 neighbors 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 paper presents the findings of 4-weeks long field trial conducted across a limited population size, it does offer some interesting and encouraging insights into user behaviors 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 near future.

One of the most notable limitations of the study was the almost exclusive focus it had on Energy Box users. While non-users were present in focus groups and surveyed in the first instance, quantitative data was only gathered over a limited period of time on the Energy Box users (and some neighbors), and so the study lacks systematic comparison between those with the treatment and those without. In addition, it is also limited in its geographic focus to rural Rwanda. Future studies would benefit from a more experimental research design, especially from a Randomized Control Trial (RCT) where the treatment is allocated to communities randomly across various settings and users both with and without the interconnection are more systematically monitored and compared over time.

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 study 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.

Conclusion and future work

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 interests 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 sustainable development goal 7 (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’ for affordable costs, 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 pertinent for SDG7 and development efforts, the ability of SHS interconnection to offer electricity at a lower cost than that of a distributed SHSs in places with high population densities, which presents a viable avenue for inclusive electrification in some of most hard-to-reach areas of the world.

The biggest barrier identified while introducing Murambi microgrid is the cost of high-power devices. At the time of writing, a highly efficient DC fridge consuming 18 W of power and approximately 200-220 Wh of energy per day costs approximately $US300. Although such high costs impose significant barriers for many domestic users and local businesses, it is evident that the overall price of efficient DC solar technologies are falling enabling greater number of users to purchase such devices. As such, further market trends can boost development of the bottom-up electrification approach supporting productive use of electricity in the future (AGSOL, 2020; Aid, 2019).

A bottom-up electrification approach can also offer an opportunity for business diversification for SHS providers who can introduce new contracts for appliances currently not supported by a single SHS As such, SHSs distributors and operators could maintain their customers beyond the initial period of the PAYGO contract. This would require development of novel business models for small entrepreneurs who wish to share profits resulting from services and productive use of energy (PUE) such as cooling, milling, etc. Further investments in PUE may also require appropriate policies as well as subsidies which develop new and strengthen existing supply chains to further enable sustainable development in rural regions in Sub-Saharan Africa.

Although the interconnected SHS microgrid deployed in Murambi could effectively support new appliances enabling the development of new businesses, further remote monitoring improvements within the Energy Box controller are recommended to monitor and analyze the overall rates of electricity exchange between prosumers. It was noted that the communication interface between each controller and server was not reliable enough to provide full range of telemetry data for such detailed analysis. Despite this fact, anecdotal evidence pointed to the villagers experiencing no problems with the reliability of the power supply for the whole duration of the pilot project. Further research is required to develop appropriate tariffs for electricity in order to incentivize the use of electricity when the largest surplus is experienced to manage the reliance on batteries for night use. This will also require the consideration of an appropriate peer-to-peer platform for money exchanged across the interconnected SHSs networks (Tushar et al., 2021). Smart interconnection of SHSs in the manner described in this paper, offers SHS communities
the benefits of a micro or minigrid 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 or minigrid 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has been supported through the EPSRC Center for Doctoral Training in Wind & Marine Energy Systems & Structures (EP/L016680/1).

References

AGSOL (2020). Solar milling: exploring market requirements to close the commercial viability gap January 2020 efficiency for access coalitions. January, 1–33. UK Aid, “the State of the Off-Grid Appliance Market October 2019 Efficiency for Access Coalition,” no. October, 2019.

Blimo, M. P., & Cosgrove-Davies, M. (2019). Electricity access in Sub-Saharan Africa: Uptake. Reliability, and Complementary Factors for Economic Impact, 12. Brief, L. (2011). Issue brief stimulating pay-as-you-go energy access in Kenya and Tanzania: the role of development finance.

Energy Sector Management Assistance Program (ESMAP) (2014). A new multi-tier approach to measuring energy access agenda. World Bank.

Lifting the burden of electricity subsidies, while expanding access: the challenge growing affordable grid and off grid access while slimming subsidies. ESMAP (2019). 2019 no. January.

Faiyrel, P. (2018). ‘Swarm electrification’ powers villages [resources-startups]. IEEE Spectrum, 55, no. 4, 21 IEEE.

Fowlie, M., Khaitan, Y., Wolfram, C., & Wolfson, D. (2018). Solar microgrids and remote energy access : How weak incentives can undermine smart technology. "Global off-grid solar market report semi-annual sales and impact data authors’ note,", December, pp. 1–88, 2017.

Groh, S. (2016). Approaching energy poverty through innovation. Dhaka, 55(4), 21.

Gulf, M., Kottak, Y., & Munere, T. (2016). Review on recent trend of solar photovoltaic technology 34(4).

Hossain, C. A., Chowdhury, N., Longo, M., & Yaïci, W. (2019). System and cost analysis of the Low Energy Access: How weak incentives can undermine smart technology.

Prevedello, G., & Werth, A. (2021). The benefits of sharing in off-grid microgrids: A case study in the Philippines. Applied Energy, 300, no. August, Article 117605. https://doi.org/10.1016/j.apenergy.2021.117605.

Rolf, P., Byrne, R., & Ockwell, D. (2014). Financing sustainable energy for all: Pay-as-you-go vs. traditional solar finance approaches in Kenya.

Rosenthal, G. (2009). Economic and Social Council. Oxford Handb. United Nations, 00293 (March), 1–20. https://doi.org/10.1093/oxfordhb/9780195606103.003.0007.

Sadan, H., & Zhang, F. (2016). Benefits of electrification and the role of reliability: Evidence from India 1 Hussain Sustainable Samad and Fan Zhang abstract I. Introduction. Open Access E-Journal, 1(2).

Sanneh, E. S., & Hu, A. H. (2009). Lighting Rural and Peri-Urban H easing of the Gambia using Solar Photovoltaics (PV). The Open Energy Journal, 2(1), 99–110. https://doi.org/10.2174/187637109902100109.

Saito, A., Oski, E., Lemma, A., & Rud, J. (2014). Businesses in low and middle income July. Sharif, L., & Mitlash, M. (2013). Rural electrification using PV: the success story of Bangladesh. Energy Procedia, 33, 343–345. https://doi.org/10.1016/j.egypro.2013.05.075.

Soltowski, B., Campos-Gaona, D., Strachan, S., & Anaya-Lara, D. (2019). Bottom-up electrification: introducing renewable solar and wind grids and microgrid technologies. Energy Access for Rural Africa in motion.

Stuart, E. (2016). Leaving no one behind: a critical path for the first 1000 days of the Sustainable Development Goals. Dev. Prog. Philp. (July), 1–62. Torero, M. (2016). The impact of rural electrification: challenges and ways forward. Review of Economics Development, 23, no. HS, 49–75. https://doi.org/10.3917/edd.l.030.0049.

Tushar, V., et al. (2021). Peer-to-peer energy systems for connected communities: a review of recent advances emerging in Energy Access and the 21st Century Energy Access Agenda. 22, no. PA, Article 116131. https://doi.org/10.1016/j.apenergy.2020.116131.

Venkata Ramana, P., Michael, T., Sumi, M., & Kammila, S. (2015). The state of the global clean and improved cooking sector: ESMAP GAC (pp. 1–179) doi: 007/15.

Bartosz Soltowski received his MEng and PhD degree from the University of Strathclyde in 2015 and 2021 respectively. Between 2015 and 2019 EPSRC-funded PhD student involved in pioneering the concept of Rural Bottom-Up Electrification across the Sub-Saharan Africa. Participated in renewable energy-based projects in the UK, Poland, France and Rwanda. Currently Senior Research Associate at the Institute for Energy and Environment conducting studies in the field of Energy Access in Sub-Saharan Africa. He is primarily involved in identifying novel low-cost technical solutions improving access to electricity across rural communities in the Developing World.

Fraser Stewart received his BA Hons in Political Science in 2017 and MSc in Political Science Research in 2018. He is currently ESRC-funded PhD student, using mixed methods to study inequality and justice in local energy systems around the world. With this research he has participated in local energy initiatives in the U.K., Sweden, The Gambia, Rwanda and the US amongst others. He is also part of the U.K. government backed EnergyREV consortium; a group of 112 leading energy researchers tasked with studying and informing the design of smart local energy systems and policy for the future.

Scott M. Strachan received his BEng-hons and Ph.D. degrees from the University of Strathclyde in 1995 and 2005 respectively. Since his research appointment within the Institute of Energy and Environment (Inst EE) in 1997, he has conducted and led research projects with leading UK energy companies, mainly focusing on the areas of plant condition monitoring, asset management and intelligent systems applications for power systems. He has been active in energy for development research since 2006, and is a founder of the Electronic and Electrical Engineering (EEE) Department’s outreach project introducing new Smart Grids concepts and conference proceedings.

Scott Strachan received his BEng-hons and Ph.D. degrees from the University of Strathclyde in 1995 and 2005 respectively. Since his research appointment within the Institute of Energy and Environment (Inst EE) in 1997, he has conducted and led research projects with leading UK energy companies, mainly focusing on the areas of plant condition monitoring, asset management and intelligent systems applications for power systems. He has been active in energy for development research since 2006, and is a founder of the Electronic and Electrical Engineering (EEE) Department’s outreach project introducing new Smart Grids concepts and conference proceedings.

David Campos-Gaona (MT2-5M’19) received the B.E. degree in electronic engineering, and the M.Sc. and Ph.D. degrees in electrical engineering, all from Instituto Tecnológico de Morelia, Morelia, Mexico, in 2004, 2007, and 2012, respectively. From 2014 to 2016, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada. Since August 2016, he has with the University of Strathclyde, Glasgow, UK, first as a research fellow, and now as Lecturer. His research interests include wind farm power integration, HVdc transmission systems, and real-time digital control of power-electronic-based devices.

Olimpo Anaya-Lara (SM’20), is a Professor in the Institute for Energy and Environment at the University of Strathclyde, UK. Over the course of his career, he has successfully undertaken research on power electronic equipment, control systems design, and stability and control of power systems with increased wind energy penetration. Dr. Anaya-Lara is a key participant to the Wind Integration Sub-Programme of the European Energy Research Alliance (EERA) Joint Programme Wind (JP Wind), leading Strathclyde’s involvement and contribution to this Sub-Programme. He was appointed to the post of Visiting Professor in Wind Energy at NTNU, Trondheim, Norway funded by Det Norske Veritas (2010-2013). He has also been involved in pioneering the concept of Rural Bottom-Up Electrification for Rural Africa in motion.

Rural Bottom-Up Electrification for Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.

Rural Africa in motion.