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Assessing Whether Connection of Solar Home Systems Can Improve Electricity Access in Off-Grid Areas

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Abstract

In Sub-Saharan Africa, millions of people live without access to electricity. In rural areas, connection to national grids is not always feasible. A growing clean energy response has been implementation of solar home systems. These are composed of solar panels, batteries, and essential electrical appliances. With a limited capacity, the battery is unable to handle large variations in electricity demand. A potential solution to this may be connecting separate solar home systems using electric cables. This could allow for variations in electricity demand between separate households to be evened out through electricity exchanges.

This study examines the potential benefits of electricity exchange between off-grid solar home systems. To assess the effects of the exchanges, the solar home systems were simulated using a Python code. Konza, a village located in Kenya, is home to multiple owners of solar home systems and was therefore chosen as the case village for the study. Based on previous studies of load profiles for electric appliances in similar areas, probability-based demand was predicted for each appliance. Using the web-based software PVGIS, solar generation data was estimated. The electricity demand and solar generation were used as inputs to the Python code. The simulation calculated hourly battery charges over one year for independent and connected households. The effects of the exchange were assessed by comparing results before and after connection.

The study examines three separate cases. Case 1 included three households that owned varying sets of electric appliances. Improvements to electricity access were observed including a 17% reduction in amount of demand left unserved. Case 2 added adjustments to electric appliances for one household. Unserved demand was reduced by 4.5% after connection, which suggested that some of the results from Case 1 were attributable to differences in electricity demand between separate households. In Case 3, the number of households was increased to six and unserved demand was reduced by 33% after connection. This indicated that a higher number of connected households will increase the benefits of connection. For all three cases, the improvements to electricity access were limited because seasonal variations in generation outweighed day-to-day variations in demand. The results suggest that the connection of separate solar home systems can to some degree improve electricity access for homeowners in off-grid areas, particularly where higher numbers of households are close to each other.

Sammendrag

I Afrika, sør for Sahara, lever millionvis av mennesker uten tilgang til strøm. I distrikter er det ofte ikke mulig å koble seg til nasjonale strømnett. En voksende ren-energi respons har vært implementering av frittstående solenergisystemer (solar home systems). Disse er sammensatt av solcellepaneler, batterier og elektriske apparater. Med begrenset kapasitet er batteriet ikke i stand til å håndtere store variasjoner i elektrisitetsforbruk. En mulig løsning på denne utfordringen kan være å koble sammen separate systemer ved hjelp av elektriske kabler. Dette kan legge til rette for at variasjoner i strømforbruk mellom ulike husholdninger utjevnes gjennom strømutveksling.

Denne studien undersøker de potensielle fordelene av strømutveksling mellom solenergisystemer utenfor strømnettet. For å vurdere effekten av utvekslingene, ble systemene simulert ved hjelp av en Python kode. Konza, en landsby i Kenya, er hjemsted for flere eiere av solenergisystemer og ble derfor valgt som caselandsby for studien. Basert på tidligere studier på lastprofiler for elektriske apparater i lignende områder, ble sannsynlighetsbasert etterspørsel predikert for hvert apparat. Ved hjelp av den nettbaserte programvaren PVGIS ble data for strømgenerasjon estimert. Elektrisitetsbehovet og strømgenerasjonen ble brukt som input til Python koden. Simuleringen beregnet timevis batteriladning over ett år for uavhengige og sammenkoblede husholdninger. Effekten av utvekslingene ble vurdert ved å sammenligne resultater før og etter sammenkobling.

Studien undersøker tre ulike case. Case 1 inkluderte tre husstander som eide forskjellige sett med elektriske apparater. Forbedringer i elektrisitetstilgangen ble observert, med blandt annet en 17 % reduksjon i mengden strømbehov som ikke ble oppfylt. Case 2 la til justeringer av elektriske apparater for én husholdning. Mengden uoppfylt strømbehov ble redusert med 4,5 % etter sammenkobling, noe som tydet på at noen av resultatene fra case 1 kan tilskrives forskjeller i strømbehov mellom ulike husholdninger. I case 3 ble antallet husstander økt til seks og mengden uoppfyllt strømbehov ble redusert med 33 % etter tilknytning. Dette indikerte at et høyere antall sammenkoblede husholdninger vil øke fordelene ved tilknytning. For alle tre tilfellene var forbedringer i elektrisitetstilgangen begrenset fordi sesongvariasjoner i strømgenerasjon oppveide daglige variasjoner i etterspørsel. Resultatene tyder på at sammenkobling av frittstående solenergisystemer til en viss grad kan forbedre elektrisitetstilgangen for huseiere i områder utenfor nettet, spesielt der flere husholdninger er nære hverandre.

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

Close to 600 million people are still without access to electricity in sub-Saharan Africa (IEA, 2020). Millions are therefore dependent on kerosene lamps or candles for lighting while wood and coal are used to cook meals and water. This is polluting and harmful to people's health (WHO, 2021). Increased access to electric lights can improve education possibilities as well as improving health conditions. Powering and recharging of phones and computers can improve communication and connectivity while acquisition of televisions and radios and connection to the internet can improve access to information (ARE). Access to electricity is an essential factor in the improvement of life quality for millions of people across sub-Saharan Africa.

In many rural areas of Africa, where distances between villages are large, access to a national electricity grid is not feasible economically. Therefore, off grid solutions may provide the cost-effective route to electrification. One off-grid solution that has become widespread in such areas is the solar home system (Zeyringer et al., 2015). This system consists of a solar panel, a battery and one or more electric appliances. A solar panel generates electricity during the day, but homeowners use most electricity during the evening. The battery must account for this. Seasonal variations in weather mean that the battery must also have sufficient capacity to last through periods with less sunlight. Due to high costs the capacity of the battery is limited, so the amount of electricity that can be stored at one time is restricted to some given amount. Therefore, homeowners may not always be able to access electricity when they would have liked to.

A partial solution to this problem could be connection of separate solar home systems via electric cables. With an intervention like this, households could share electricity with each other, evening out variations in consumption. If some homeowners would prefer to use more electricity at a given time while others are satisfied with less use, an electricity exchange could be made. This may allow for improved electricity access for solar home system owners.

1.2 Problem statement

This study aims to determine whether the proposed connection of separate solar home systems can provide system owners with improved electricity access. To assess the effects of the intervention, the solar home systems are simulated using a Python-based code that is written for this study. The simulation takes hourly solar electricity generation and hourly electricity consumption as inputs. From this, hourly battery charge is calculated for each household over a one-year period. Konza, located in Kenya, is chosen as the case village for the study. Here, multiple solar home systems have been distributed by the company Sunami Solar. The company provides specifications for solar panels, batteries and electric appliances owned in the village. Hourly solar generation for the specified solar panels is estimated using the web-based software PVGIS. Hourly probabilities of electric appliance usage are predicted based on studies from comparable areas. These probabilities are assumed to be constant for each day throughout the simulated year. The results from simulations of independent and connected households are compared to each other. From the comparison it is determined to which degree the proposed intervention improves electricity access.

To evaluate the results, some key points are compared for the independent and connected solar home systems. For electricity access to improve, batteries with low charges must receive electricity from batteries with high charges. Simultaneously, the charge of the delivering battery should not sink too low. To determine if the exchanges have the predicted effect, hourly battery charges pre- and post-connection are compared. Another important point of comparison is unserved demand. This occurs when homeowners would like to use electric appliances but are not able to due to insufficient electricity storage. Therefore, an objective for improved electricity access is a reduction in amount of unserved electricity demand encountered by the involved households.

The described method is used to analyse three separate cases. For Case 1, three solar home systems are simulated. Of these, two households own the same composition of electric appliances, named the TV package. The third household owns a composition of appliances named the basic package. In the second case, three households owning TV packages are simulated. This is done to reveal how different compositions of electric appliances affect the results. Finally, a third case including six households is explored. The results from Case 3 reveal whether the number of connected households affects results.

2 State of the art

To give a general view of which similar research has been conducted, summaries of relevant studies are presented in the following paragraphs. The goal of this chapter will be to demonstrate what has been found previously on the topic and how this thesis goes beyond this to contribute with something new.

Studies have examined the benefits of solar home systems as a substitute for grid-extensions in Rural areas of Kenya. Zeyringer et al. attempt to determine the cost effective way forward to electrifying the country by estimating electricity demand for households near electric infrastructure (Zeyringer et al., 2015). This is used to predict household electricity demand for all households in Kenya without electricity. The study concludes that off-grid PV is cheaper than grid-connection for areas where consumption is low and connection costs are high. This is the case for most rural areas with low population density. Ondraczek comes to a similar conclusion using the same method of reasoning (Ondraczek, 2014). It is found that the per kWh costs are lower for stand-alone PV systems than conventional power plants currently powering much of Kenya. In another study, it is reasoned that since grid extensions have advanced more slowly in Kenya than in other major regions, the benefits of stand-alone systems should be mapped (Rabah, 2005). This study finds that use of PV systems would result in improved quality of life through illumination, improved air quality, improved access to information and more for rural areas in Kenya. The findings of these studies indicate that solar home systems are likely to continue to function as a substitute for grid-extensions in many rural areas in Kenya.

Other studies have investigated microgrids, with centralized solar panels and storage, as potential substitutes to grid-extensions in rural areas. Longe et al. use Homer software to simulate a microgrid in a South African municipality and found it had a standalone breakeven distance limit of 34 km less than the required 150km for grid extension (Longe et al., 2014). That means that in villages more than 116 km from national grids microgrids are a cheaper alternative than grid connection is. The same method is used in another study for Ntabankulu local municipality, also in South Africa, where it is also suggested that microgrids are a cheaper solution than grid-extension (Longe et al., 2017). Microgrids, as well as stand-alone systems, are often put forward as alternatives to grid extensions in rural unelectrified areas.

Many studies have made use of simulations to assess the operation of potential stand-alone systems and microgrids. Cho et al. make use of Matlab software to simulate a solar-wind-hybrid system in Pyin Kha Yaing Village, Burma (Cho & Mon, 2018). The simulations allow researchers to assess the performance of the system before building it. Hassan et al. also use Matlab software to simulate a stand-alone PV system in Bambul, Gambia (Sakiliba et al., 2015).The aforementioned studies by Longe et al. make use of Homer Pro in their studies. The simulations allow for assessments to be made without building the systems, while still taking weather data and electric consumption into account.

In a master's thesis about off-grid solar PV in rural Kenya, interviews were conducted in Kenyan villages. These are used to determine which factors affect consumer decisions on the type of off-grid solar PV system chosen in villages where both solar home systems and microgrids were available (Hansen, 2018). Interviews from a village close to Isolo, where solar home systems and mini grids could be found, revealed that some solar home system owners had opted into a microgrid connection to allow for a higher level of electricity use. This despite the fact that the microgrid connection gave an increase in costs for the homeowners. Conversely, many solar home system owners had chosen the opposite and not opted for connection. Among reasons given for this were reliability, costs of the intervention and having sufficient electricity already. The findings of this report show that microgrids and solar home systems can often be found in the same villages. Some households chose to connect to the microgrid while others chose not to. Electricity needs and costs play large parts in the making of these decisions (Hansen, 2018).

The state of the art of the present study lies in the connection of existing solar home systems. The suggested system can be regarded as an intermediate of the solar home system and the microgrid. Households are connected in a larger system as they would be in a microgrid but there is no shared storage and production as each household has its own battery and solar panel. The literature summary demonstrates how both solar home systems and microgrids have been examined as ways to electrify rural off-grid areas. These often use simulation-based approaches to assess the performance of suggested systems. Since simulations are common in similar research, the tool is utilised in this study too. However, this study investigates a different electronic system than what previous research on off-grid electrification has done. All households have their own production and storage but can share electricity with each other in an interconnected system.

3 Theory

3.1 Composition of the solar home system

A solar home system is an off-grid electricity system. These are typically low power, less than 100 W. This makes them suitable for home appliances such as light bulbs, computers, or water pumps. They tend to be designed to supply either DC or AC and DC appliances (Salas, 2017). The solar home systems examined in this study run on DC power only. The DC solar home system consists of a solar panel, charge controller, a battery, and one or more electric loads. Figure 1 shows a schematic representation of the system composition.

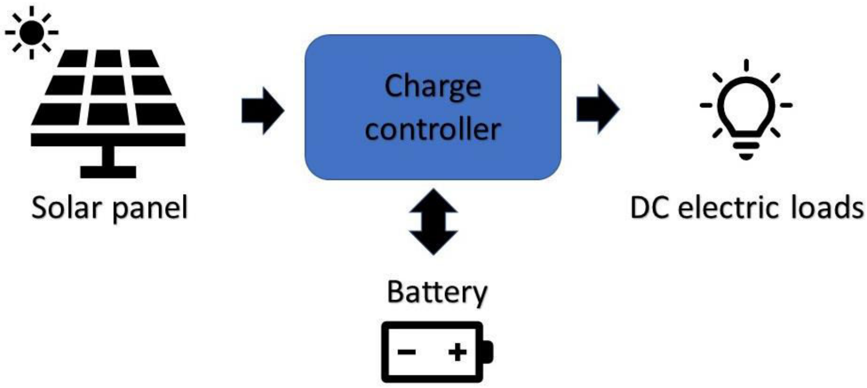

Figure 1. Schematic representation of the composition of a solar home system.

3.1.1 The solar panel

The solar panel is the component that generates electricity for the system. It consists of a collection of photovoltaic cells that absorb the sun's rays and convert them to electric energy through a process called photovoltaic effect. In a solar home system, the panel is typically placed on the roof of a household. They are generally positioned in a way that optimises solar generation, although other factors such as roof inclination can affect the choice of positioning. There are different types of PV cells, with varying prices and conversion efficiencies.

Photovoltaic effect is the process where incident sunlight on the photovoltaic cells generates an electric current. The photovoltaic cells that build up a solar panel are composed of two types of semiconductors: p-type and n-type. These are joined together to create an p-n-junction. When the p-n-junction is formed an electric field is created. The p-side of the junction is positively charged, and the n-side is negatively charged. Electrons move across the junction to the positively charged p-type semiconductor, leaving behind a positive charge. Holes move the opposite way to the n-type semiconductor, leaving behind a negative charge. The process creates a depletion zone in the middle of the p-n-junction where there can be no more movement of charge carriers. This electric field provides a voltage that can drive the current through an external circuit. When sunlight is incident on the semiconductors, photon energy from the sun's rays is transferred to an electron. This causes it to jump to a higher energy state called the conduction band. In the conduction band the electrons are free to move through the material, creating an electric current (Afework et al.). The process is illustrated in Figure 2.

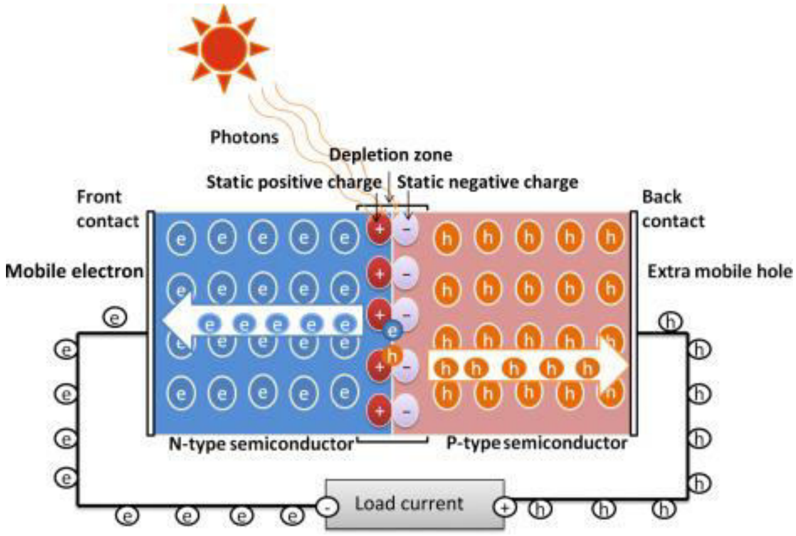

Figure 2. Schematic representation of a photovoltaic cell. The figure helps demonstrate the process of photovoltaic effect. The n-type semiconductor and p-type semiconductors make up the cell. The movement of electrons (e) and holes (h) creates a depletion zone between the two semiconductors. Free electrons move through the material in the illustrated circuit. From: (Simya et al., 2018).

A collection of photovoltaic cells makes up a solar module and a solar panel consists of one or more of these modules. The individual cells, where the process of photovoltaic effect takes place, are connected in series and/or parallel circuits so that they can produce higher voltages, currents, and powers. The connected cells are then mounted in a support structure or frame referred to as a solar module. This is illustrated in Figure 3. The module supplies electricity at a specific voltage, typically around 12 V. A solar panel consists of one or more modules, assembled in a field installable unit (Osanyinpeju, 2019). Since the solar home system typically runs on low power, a solar panel consisting of a single module is common for this type of system.

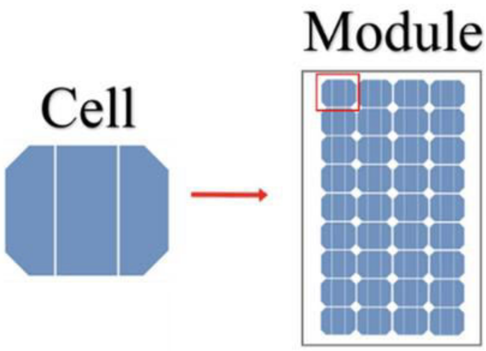

Figure 3. Solar cell and solar module. *A solar module is made up of a collection of solar cells. The solar panels typically used in solar home systems consist of one of these modules. Modified from: (Roderick, 2021).*

There are four major types of solar panel available in the modern market: monocrystalline, polycrystalline, PERC and thin-film panels. Monocrystalline panels consist of a single pure silicon crystal that is cut into wafers. These are the longest lasting and most area efficient of all the solar panel types. Monocrystalline panels are also among the most expensive due to high production costs. Polycrystalline solar panels are made up from parts of multiple silicon crystals that are moulded together. This method uses less material making them cheaper than monocrystalline panels. However, their lower silicon purity makes them less efficient in terms of area and energy conversion (McBride, 2021). The silicon based monocrystalline and polycrystalline technologies are by far the most widespread, and had a combined global market share of 96% as of 2015 (Xu et al., 2017). PERC-panels are a modern improvement on the monocrystalline cell. A passivation surface is added to the rear layer of the cell, enhancing efficiency. These panels are more efficient but also more expensive than traditional panels. The fourth type are named thin-film panels. These are built up of fine layers that are thin enough to be flexible. These are low cost and easier to install due to their flexibility. Despite this, thin film panels have a lower energy conversion efficiency than the other panel types (McBride, 2021).

To optimise electricity generation the solar panel must be positioned properly relative to the position of the sun. When sunlight reaches the earth's atmosphere, some of the light is refracted, some travels to the earth's surface in a straight line, and some is absorbed by the atmosphere. The refracted part is referred to as diffuse radiation while the part that reaches the surface in a straight line is referred to as direct sunlight. Due to the diffuse radiation, solar panels can generate electricity even in cloudy conditions. However, direct sunlight is much more intense. Therefore, a solar panel is optimally positioned perpendicular to direct sunlight (Kochmarev et al., 2020).

The angling of the solar panel relative to the sun can be described using the two angles azimuth and slope. Azimuth is the angle formed between the solar panel and the direction due south. To face the sun directly, panels should face towards the south when installed in the northern hemisphere and towards the north when installed in the southern hemisphere. If installed close to the equator panels should face directly upwards. The slope is the angle formed between the panel and the horizontal. A 90° slope corresponds to a vertical placement and a 0° slope corresponds to a horizontal placement. Generally, a slope set equal to the latitude maximizes electricity generation over a year (Kochmarev et al., 2020) (European Commision, 2020). Figure 4 shows the two angles relative to coordinate axes. Azimuth and slope are represented by γ and β respectively.

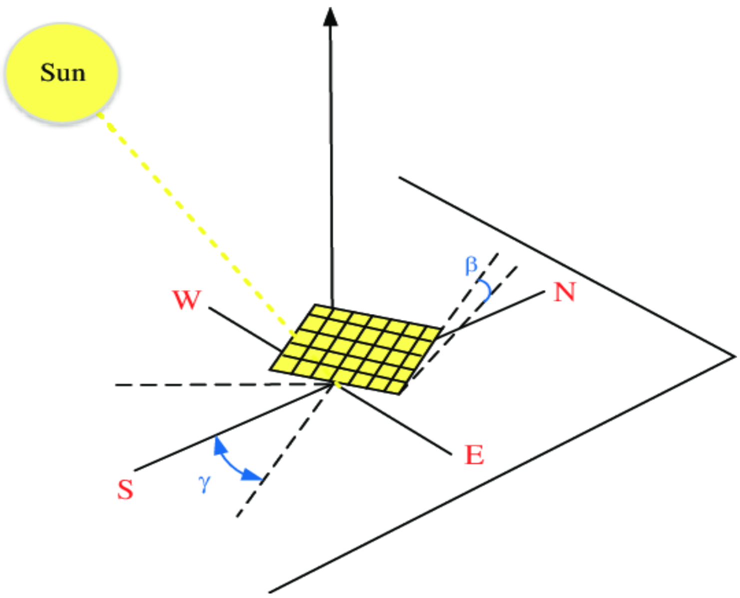

Figure 4. Azimuth and slope angle relative to coordinate axes. The figure shows azimuth (*γ) and slope (β) for a solar panel relative to the coordinates North, East, South, and West.* From: *(Khosravi et al., 2020).*

There are also other factors that may influence the positioning of the solar panel. Even though a given mounting position maximizes solar generation over a year it may be advantageous to place the panel differently with the goal of meeting electricity demand more accurately. If demand is higher at certain times of day, the solar panel could be placed in a way which optimises generation at these times. For solar panels placed on rooftops it can be more economical to install them in positions that follow the slope of the roof even though the angling is less optimal with regards to electricity generation.

3.1.2 The battery

For a solar home system, a lead acid battery is typically used (Achaibou et al., 2012). The battery's main function is storing electric energy that is produced during times of sun so that it can be utilised when the sun is either down or blocked, for example by clouds. Typically, the battery is charged during the day and discharged during the evening and night. The battery is also used to compensate for instabilities in the power delivered by the panel so that a stable voltage is provided to the loads.

It is important that the charging of the battery is properly regulated. If too much electricity is delivered to the battery, it will be overcharged. This may cause the battery life to be shortened. The battery may also be over-discharged if too much electricity is drawn from it. Over-discharging can lead to the battery losing effectiveness over time. For a lead-acid battery, repeated discharges below 50% may decrease battery life expectancy. For discharges below 20% permanent damage will occur. For this reason, battery manufacturers often recommend limiting the depth of discharge to protect the battery from damage. Battery systems are commonly sized so that the discharge is limited to an average of 30% of total capacity (Garche & Brandt, 2019) (EcoCoch, 2020).

There is a power loss associated with the charging and discharging of the battery. A significant source of power loss for most batteries is heat generation. Heat generation loss refers to energy that is lost through conversion to heat during the process. Lead acid batteries also lose power though gassing. Gassing is the decomposition of water into hydrogen and oxygen and increases for higher voltages during the charging phase. Heat generation and gassing combined in the lead acid battery cause approximately 20% of the added energy to be lost before it can be utilised, giving a round trip efficiency of approximately 80% (Battery Test Centre).

3.1.3 The charge controller

The charge controller is used to protect the battery from overcharging or over-discharging by regulating the voltage and current during power exchanges between the solar module, the battery, and the loads. It may also prevent complete discharge of the battery. The regulation of current protects the electric appliances from being damaged (Satpathy & Pamuru, 2021).

3.2 Seasonal variations in weather

The electricity generated in solar panels is affected by weather conditions. These conditions vary on a seasonal basis. In most of Kenya, weather is split into wet and dry seasons. The wet seasons last roughly from March to May and October to December. The remaining months define the dry seasons (Onogma, 2019). During the wet seasons heavy rainfall dominates the weather. During the dry seasons the weather is defined by hot sunny days (Zijlma, 2020). A closer look at weather expectations for the case village can be made using weather atlas. Statistics from this database show that March, April, May, October, November, and December are the months where most days of rainfall are expected in Konza. Data showing the average amount of hours of sunshine per day reveals that fewer sunshine hours are expected during the months with most rain. The months with the highest amount of average sunshine days are July, August, and September, in the dry season (Weather Atlas).

These seasonal variations in weather mean that seasonal variations in generated electricity should be expected. During the rainy seasons, higher levels of cloud cover mean that less sunlight is prevalent. Electricity generation will likely be lower. During the dry seasons, more hours of sunlight are expected which should lead to higher electricity generation. As mentioned above, most days of sunshine are expected in July, August and September meaning these months should give particularly high electricity generation.

In most of the world, there are more hours of daylight during the summer than there are during the winter. The further away from the equator, the larger the difference in hours of daylight from summer to winter. The village of Konza lies close to the equator and therefore sees little change in number of daylight hours throughout the year. In the city of Nairobi, which is close to Konza, the sun rises at around 06.30 and sets at around 18.40 with little variation through the year (WorldData). This means that electricity generation should take place approximately between these times.

3.3 Variations in electricity load and solar generation

This subchapter has the goal of explaining how connected solar home systems could benefit from electricity exchange.

Figure 5 shows the shape of a typical solar generation curve and a typical load curve for a household over one day. The curves are not based on data but demonstrate the distinctive shapes taken by solar generation and load curves in rural areas (Pandyaswargo et al., 2020) (Namaganda-Kiyimba et al., 2021). Typically, electric consumption is at its highest during the morning and evening. These are the times when most people are home and using electric appliances. Often a peak appears around noon, though much smaller than the ones that appear in the morning and evening. The solar generation curve is affected by the position of the sun and peaks around midday (IEA, 2019).

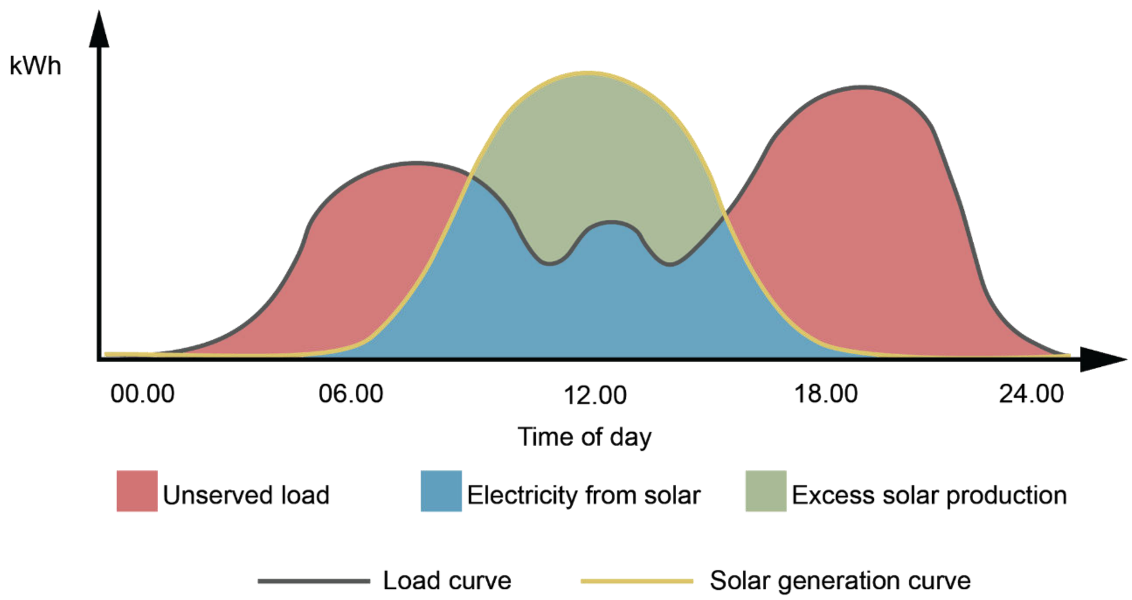

Figure 5. Typical load curve and typical solar generation curve. *The yellow curve represents solar generation, and the grey curve represents electricity load. The y-axis shows quantity of electricity, measured in kWh while the x-axis shows time of day. The blue area represents electricity load that is provided by the solar panel while the red area shows electric load that cannot be provided by the solar panel, named unserved load. The green area shows excess solar production, which is generated electricity that is not consumed by the homeowner. (Bekkestad, 2021).*

In the evening and morning, the energy required by the loads is greater than the energy provided by the solar panel. During daytime the solar generation supersedes the load. With no electricity storage, only the load that is utilised in this period can be met as it is directly powered by the solar panel. The green area represents excess solar production. This area shows surplus electricity that is generated by the solar panel but cannot be utilised. To provide electricity at the same time as consumers demand it, the battery is introduced. The role of the battery is to store excess electricity so that it can be utilised later when the load exceeds solar generation. In this way the solar panel and battery work together so that electric load can be met at the desired time.

The amount of generated electricity that can be utilised is determined by the capacity of the battery. To optimise costs the battery must be as cheap as possible while still offering substantial capacity to cover electricity demand. Therefore, the battery should be dimensioned so that it can cover the minimum necessary load. Due to variations in weather the amount of electricity generated varies from day to day. Hence the battery should have substantial capacity to store more than one day's worth of electricity in case of some cloudy days with low generation.

Seasonal variation in weather also plays a role in determining necessary battery capacity. Close to the equator more hours of sunlight are experienced during the dry season than during the wet season. In the rest of the world there are more hours of sunlight during the summer than during the winter. Assuming that electricity demand stays constant throughout the year, average battery charge should vary with the seasons. This is demonstrated by Figure 6 which shows the monthly average battery state of charge for a simulated PV-system in Gaza, Palestine. The system is rated at 3.2 kW and has a battery storage capacity of 19.2 kWh. The system is dimensioned for a residential house with a daily energy load of 10 kWh (Omar & Mahmoud, 2019). In Palestine, winter lasts from December to March while summer lasts from June to September. A clear seasonal effect can be observed on the battery charge, which is on average lower during the winter months.

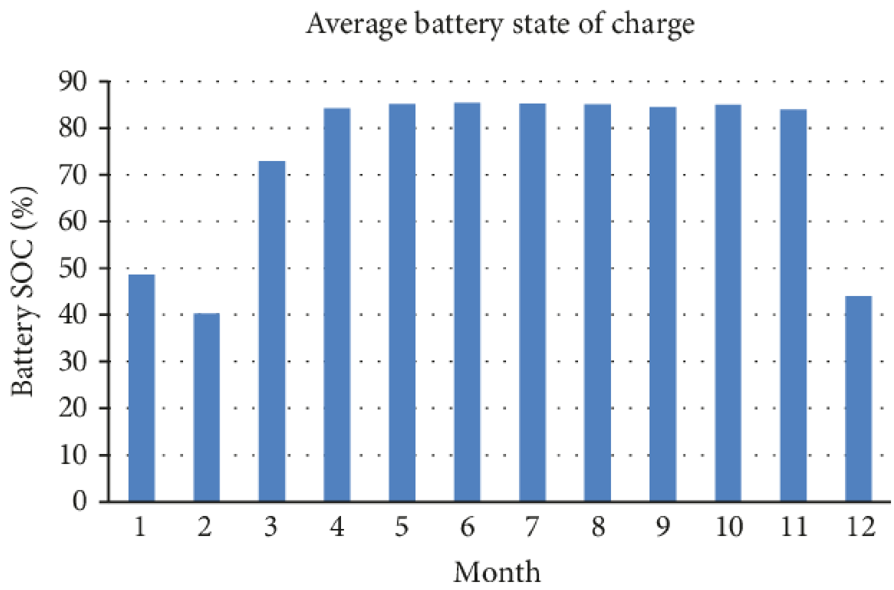

Figure 6. Average battery state of charge. *Average battery state of charge (y-axis) for each month of the year from simulation of PV system in Gaza, Palestine. Months 1 – 12 are shown on the x-axis and denote January to December respectively. From: (Omar & Mahmoud, 2019).*

Daily, seasonal, and random variations in weather will affect households in the same village in similar fashion. Similar states of charge for the batteries should therefore be expected. This means that one can distinguish between two situations where storage in a village of connected households could be optimised. In the first situation batteries on average encounter charges so high that generated electricity cannot be stored. In the second, batteries encounter charges so low that appliances cannot be powered. During both scenarios variations in how much electricity is used in the individual households could be evened out through electricity sharing. Consider the first situation and assume that one household's battery reaches a 100% state of charge while a neighbour uses more electricity that day and only reaches 90%. Excess electricity may be stored in the neighbour's battery. Less electricity is wasted meaning total demand can potentially increase. Consider the second situation and assume one households’ battery reaches its discharge limit while a neighbour has used less electricity than usual that day. Electricity could be transferred from one household to the other so that essential appliances can still be powered.

3.4 Power loss in electricity transmission

When transmitting electricity over large distances some power loss is associated with the transmission. The size of the loss depends on a range of factors such as the length of the cable, the size of the electric current and the cross-sectional area of the wire. For a DC current the power loss in a wire, P_{loss}, can be calculated using Equation 1.

$$P_{loss} = I^2 R \qquad \textit{Equation 1}$$

$$R = \rho \frac{L}{A} \qquad \textit{Equation 2}$$

Here, *I* represents the current (A) through the wire and *R* represents the wire resistance (Ω). The resistance can be broken down using Equation 2, where *ρ* is the resistivity (Ωm), *L* represents the length of the wire (m), and *A* the cross-sectional area (m^2) (Tipler, 2008). To determine the power loss as a percentage of total power transmitted the equation may be divided by the total power. The percentage of power lost, $P_{loss\,(\%)}$, is expressed by Equation 3.

$$P_{loss\,(\%)} = \frac{I^2 \rho L}{AP} \qquad \textit{Equation 3}$$

Where *P* (W) is the total power transmitted. In a solar home system with a standard voltage the current will vary for different power transmissions. To account for this the percentage power loss can be expressed with respect to a voltage rather than a current. Equation 4 shows the percentage of power lost with respect to power transmitted and system voltage, *V* (V).

$$P_{loss\,(\%)} = \frac{P \rho L}{V^2 A} \qquad \textit{Equation 4}$$

4 Methodology

4.1 Case village

Chosen to use as case for the study is the village of Konza, in Kajiado County, Kenya. The position of the village is shown in Figure 7. Konza lies close to the capital of Nairobi, slightly south of the equator. The village is home to nine owners of solar home systems distributed by the company Sunami Solar. The choice was made at the recommendation of Sunami because of the number of solar home systems distributed there. Konza will be used to determine solar irradiation data, geographical assumptions and specifications for system components used in the simulation.

Figure 7. Location of the case village Konza. *(Google maps, 2021a)*

Two separate solar home system packages have been distributed by Sunami in the village. Three of the Sunami customers own a package consisting of a minimum of six light bulbs. The specific number of bulbs is assumed to be eight in this study. The remaining six customers own a package that includes a 32-inch TV, six light bulbs and two charging outlets for smartphones. These two separate packages are referred to as the basic package and the TV package. All households are equipped with a 120 W solar panel and a 100 Ah battery. The systems operate at 12 V, giving 1.2 kWh of electricity storage. Tables 1 and 2 give an overview of all components and their power ratings for the two packages.

Table 1. Overview of power ratings and number of units for each appliance in the TV package

Appliance	Power rating (W)	Number of
32-inch TV	70	1
Phone charger	4	2
Light bulb	5	6

Table 2. Overview of power ratings and number of units for each appliance in the basic package

Appliance	Power rating (W)	Number of
Light bulb	5	8

The power ratings of the lightbulbs are confirmed to be 5 W by the company. Power ratings for the specific chargers and the 32-inch TV are unknown and are therefore estimated based on relevant literature. A cell phone typically draws 2-6 W while charging and is therefore assigned a 4 W power rating for this study (Heikkinen & Nurminen, 2012) (Bekaroo & Seeam, 2016). The power rating for the TV is more uncertain as the type of TV is unknown, and different TV technologies can draw significantly different wattages. For this study it is assumed that customers use an LCD TV as this is the most widely produced and sold television display type worldwide. The LCD is also cheaper than competing technologies such as LED and OLED, making it a more realistic choice of television for off-grid solutions in Kenya. LCD televisions have power ratings of approximately 70 W (Bowyer et al., 2019).

Due to insufficient information the geographical positions of each specific household cannot be used for this study. The specific households that own solar home systems, and which of the two packages each household owns is also unknown. This means that the distances between relevant households in Konza cannot be accurately mapped. Therefore, distances between houses observed using satellite imaging of the village are used to give an idea of typical distances between clusters of houses. Figure 8 shows a satellite image from the village. A cluster of three buildings have distances drawn between them.

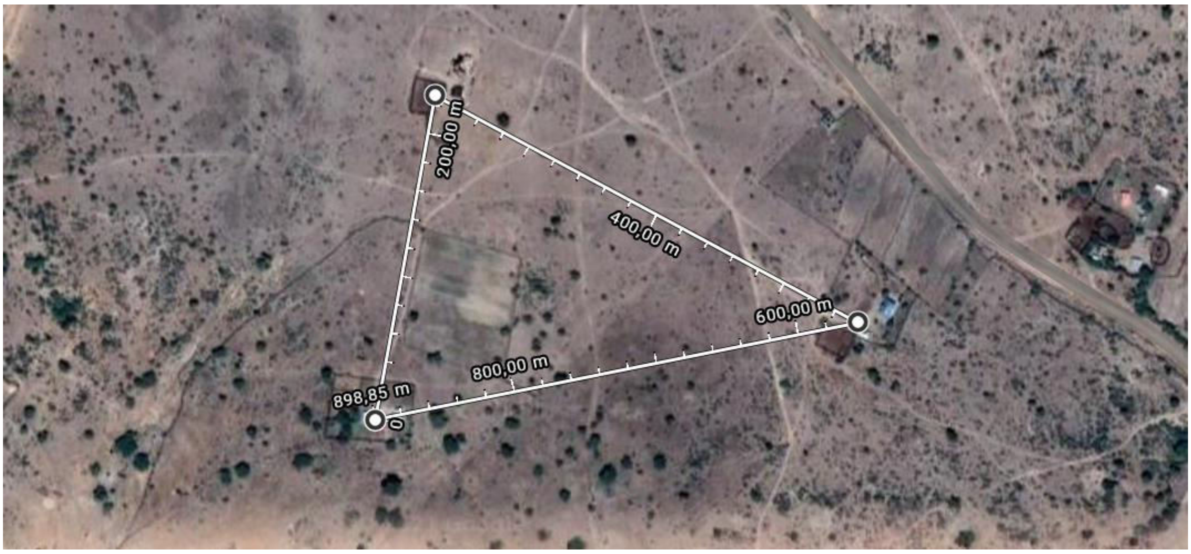

Figure 8. Satellite image of a cluster of three buildings in Konza, with distances. *(Google maps, 2021b)*

For the cluster of three buildings the total length of cable that would be needed to connect them amounts to 899 metres. This averages out to approximately 300 metres between each household.

4.2 Prices and specifications for cables

After a market analysis the following products were found to be the cheapest available: Solar Cable 4mm and Solar Cable 6mm. The cables are produced by Chinese company Henan Central Plain Cables and Wires. They are designed for use in solar systems and are particularly suitable for outdoor use (ZW-Cable). The cables can be purchased at coherent lengths up to 1000 meters. Therefore, purchasing cables at an average length of 300 meters is realistic. The 4mm cable is sold at a price of 0.45 USD/meter while the 6mm cable is sold at a price of 0.66 USD/meter (T. Wang, personal communication, 22.09.21). This amounts to 135 USD and 198 USD for 300-meter rolls of each cable respectively.

The 6mm cable is more expensive but has a larger cross-sectional area than the 4 mm cable. Therefore, it has a lower resistance. This means that less power is lost in the transmission, as explained in Chapter 3.4. Equation 4 shows that the transmission loss is also dependent on the transmitted power. Table 3 compares the two cables for share of power lost for different power transmissions. The results will help determine which cable is optimal for the desired use. The cable length L was assumed to be 300 m. The resistivity of copper is $\rho = 1.68 \times 10^{-8}$ (Tipler, 2008).

Table 3: Power losses for 4 mm cable

Transmitted power (W)	Power loss (%)
10	8.88
50	43.8
100	87.5

Table 4. Power losses for 6 mm cable

Transmitted power (W)	Power loss (%)
10	5.83
50	29.2
100	58.3

Given that the difference in price is not large, the 6 mm cable seems a more attractive choice. As power increases, the difference in power loss between the two cables becomes larger. At a 100 W transmission almost all power is lost for the 4mm cable. Considering that the 300-meter length is an average the losses could become even higher if length increases. Therefore the 6 mm cable is chosen for the study so that losses in transmission of electricity are minimized as much as possible.

As mentioned at the beginning of this subchapter, the products from Henan Central Plain Cables and Wires were the cheapest of this type found on the market. To demonstrate the disparity in prices they are compared to similar products from Norwegian company Nexans. Nexans sell the 4mm and 6mm cable at prices of approximately 15 NOK per meter and 19 NOK per meter respectively (J. K. Gulbrandsen, personal communication, 02.11.21). At the exchange rate per November 2021 this gives 1.74 USD and 2.21 USD. (Bloomberg, 2021). This is approximately four times more expensive than the 0.45 USD per meter and 0.66 USD per meter prices offered by Henan Central Plain Cables and Wires. The large disparity in market prices for products from different companies shows that there is some uncertainty related to cable costs.

4.3 Collecting data for solar generation and electricity demand

4.3.1 Solar generation data

To estimate how much electricity the 120 W solar panels generate, the photovoltaic geographical information system (PVGIS) was used. PVGIS is a web-based software that provides information about solar radiation and PV performance. It was developed by the European Commission Joint Research Centre as a means to assess solar resources and study performance of PV panels (European Comission, 2019). The tool takes geographical position, PV technology, rated PV power and information about panel mounting as inputs. It makes use of satellite based solar radiation to estimate generated power for a PV panel in the chosen location (European Comission, 2020).

Relevant data was entered to the PVGIS tool so that hourly electricity generation data could be estimated. The geographical position of Konza was entered using the latitude and longitude of -1.688 and 37.044. Satellite data from 2015 was used for the calculation since this was the latest data available in the PVGIS database. The rated panel wattage of 120 W was entered, and system losses were assumed to be 14%, the default value given by PVGIS. The solar panel is assumed to be crystalline silicon as this was found to be the most common type in Chapter 3.1.1. The specifics around positioning and mounting of the solar panels on rooftops in the area are unknown. Therefore, it was assumed that the solar panels are positioned in a way that maximizes solar generation of the course of the year. Azimuth and slope angle were optimised by the tool. PVGIS takes geographical position and terrain data into account to predict the azimuth and slope that optimize production over the year, for one fixed position.

From the input data, an hourly time series of PV system power was produced, giving momentary generated power for one point in each hour. These values are assumed constant over each corresponding hour, so that an estimated value for total generated electricity each hour can be calculated. This data is used to represent solar generation for each simulated household in the study. Figure 9 shows a screenshot of the website with the outlined input data typed in.

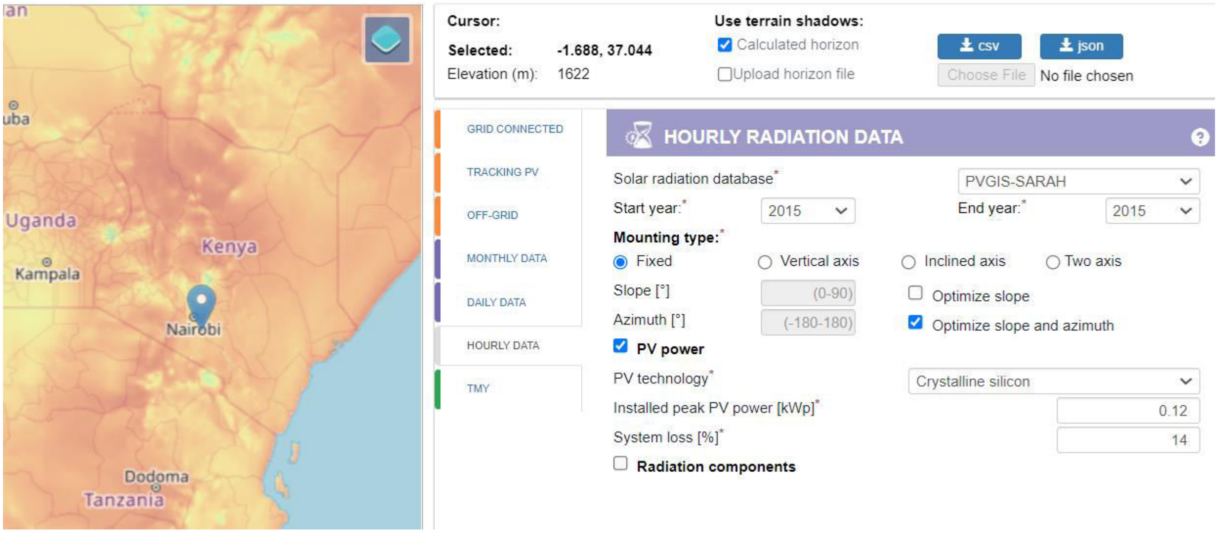

Figure 9. Screenshot of PVGIS website with relevant input data. *(European Comission, 2021)*

4.3.2 Electricity demand data

Electricity use for each household is estimated based on the applications that are owned. Relevant literature on load profiles for lights, phone chargers and televisions in comparable areas will be examined. This will give some indications of likely times of use for different applications.

Some studies have researched likely patterns of use for light bulbs, phone chargers and televisions in off-grid homes. In a report from Business Innovation Facility, surveys are conducted in Malawi with the goal of mapping off-grid household habits for phone charging and lighting (BIF, 2016). Questionnaires were answered by a sample of 513 respondents covering seven districts in the country. They found that most phones were charged between one and three times a week when it took 15 minutes to reach the nearest charging station. If charging is possible in a person's own home, more frequent charges might be expected. Solar lights were found to be used for an average of seven hours a day. This is enough time for them to be used both in the morning and the evening.

An article from *Molecular Diversity Preservation international* (MDPI) estimates daily load patterns for off-grid villages in Myanmar, Indonesia and Laos (Pandyaswargo et al., 2020). The estimated load curve for lighting had two main peaks in all the investigated villages. One in the morning and one in the evening. The largest peak was observed during the evening. This suggests that more lights are likely to be used during the evening than the during morning while use during the daytime and night-time is rare. Use of the television peaked during the evening with some small likelihood of use during the morning and around noon. The load curve for cell phone charging was also similar for each case with the results suggesting charging is most common during the evening, specifically between 17.00 and 19.00 for all three villages. Estimated hours of use per day for the relevant appliances based on the findings from the literature are presented in Table 5. The results from the demand generation for this study will be compared to the values in the table to ensure their reliability.

Table 5. Expected daily hours of use for electric appliances

Appliance	Estimated hours of use
Light bulb	7-8
32-inch TV	2
Phone charging point	1

In order to generate electricity demand data, probability functions are used. Each electrical appliance is assigned a probability of use for each hour of the day. To match the electricity generation data, demand data is built up in hourly steps. Each electrical appliance is therefore assumed to be turned either on or off for the full hour. If the appliance is turned on for any given hour it is assumed to draw the rated power over the full hour. All applications are assigned low probabilities of use during the night. Lightbulbs are assigned high probabilities during morning and evening where the literature review suggests use is high. The probabilities of use in the evening are higher than those in the morning. The TV is assigned the highest probabilities during the evening with some likelihood of use around morning and noon. Chargers are assigned the highest likelihood of use between 17.00 and 19.00. Probabilities are assigned for 24 hours, giving day-to-day variation. This means that other variations such as weekly, monthly, or seasonal are not considered. The reason for this is that only day-to-day variations are presented in the reviewed literature. Table 6 presents the hourly probabilities of use for each application, which are used for the simulation.

Table 6. Predicted hourly probabilities of use for electric appliances

Time of day	Probabilities light bulb (%)	Probabilities TV (%)	Probabilities chargers (%)
01.00	0.03	0.001	0.001
02.00	0.03	0.001	0.001
03.00	0.03	0.001	0.001
04.00	0.03	0.001	0.001
05.00	0.03	0.001	0.001
06.00	0.3	0.005	0.001
07.00	0.2	0.2	0.03
08.00	0.001	0.01	0.01
09.00	0.001	0.01	0.01
10.00	0.001	0.01	0.01
11.00	0.001	0.01	0.01
12.00	0.02	0.03	0.1
13.00	0.02	0.03	0.01
14.00	0.001	0.01	0.01

15.00	0.001	0.01	0.01
16.00	0.001	0.01	0.01
17.00	0.2	0.01	0.01
18.00	0.3	0.03	0.01
19.00	0.5	0.1	0.3
20.00	0.6	0.25	0.3
21.00	0.5	0.25	0.1
22.00	0.3	0.1	0.05
23.00	0.05	0.05	0.01
24.00	0.03	0.001	0.01

The TV, which draws a much higher power than the other appliances, causes large fluctuations to the demand curve when assumed to draw power for a full hour. It is also reasonable to assume that this appliance would be used for shorter periods than an hour if turned on during breakfast or lunch. Therefore, the TV is assigned two possible power ratings: 35 W and 70 W. The 35 W power rating represents an hour where the TV is only used for 30 minutes. Uses during morning and evening are restricted to the half hour use while uses in the evening, where the TV is expected to be used more often, are assigned a full hour.

4.4 Rules and assumptions for the simulation

In order to simulate the solar home systems, a code has been written for this study (see Appendix). The code is written for Python and utilises a for-loop. For every hour through the relevant year the battery charge is checked and updated appropriately with regards to generated electricity and electricity demand. For each hour the applications are assumed to be powered directly by the PV panel if generation in the same hour is sufficient. If generation of electricity supersedes demand the battery charge is increased by the difference. If demand is greater than production the battery charge is reduced by the difference. The flowchart in Figure 10 gives a simplified illustration of how the simulation functions.

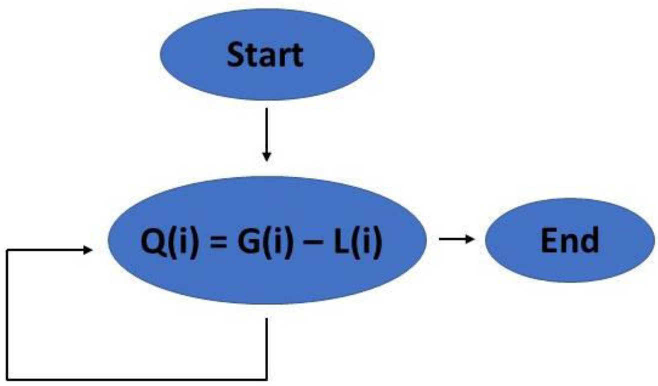

Figure 10. Flow chart for Python simulation. *The figure shows a simplified flowchart of the solar home system simulation. The for-loop runs through each hour of the year and updates the battery charge accordingly. After the 8760 hours in one year, the loop ends. Q represents the battery charge, G is generated electricity, and L is electricity demand. i represents hour of the year.*

The battery has specifications that have been considered. In Chapter 3.1.2 a lead acid battery is found to have a round trip efficiency of 80%. In the simulation this is conceptualised as a 10% power loss during charge and a 10% power loss during discharge. Also, a discharge limit at 30% of the battery's capacity is recommended. Therefore, the battery capacity is limited to 30% of the maximum charge. This gives a lower limit at 0.36 kWh of the available 1.2 kWh battery capacity. Any electricity demand that would draw the battery charge below this level is not served. This demand is instead logged and labelled as unserved demand. Any electricity generation that would bring the battery charge above its maximum limit is not stored, and instead labelled as excess electricity.

To simulate the connected system some rules must be set with regards to exchange of electricity. There are two instances where exchange of electricity is called for. The first is when excess electricity cannot be stored due to the battery capacity being full. In these cases, the excess should be transferred to a neighbour. These transfers will be referred to as excess electricity transfers. Excess electricity transfers are evenly distributed between the other households given that their batteries have available capacity.

The second instance where exchange is called for is when one or more households have little capacity left in their batteries while another or more households have sufficient capacity. These transfers will be referred to as low charge transfers. The precise rules for how such an exchange should happen are not obvious. The recipient's capacity should be low enough for the exchange to be necessary as there are electricity losses associated with the transmission and the charging and discharging of batteries whenever an exchange is made. Too much exchange could risk reducing the total electricity available in the system through battery losses and transmission losses, rendering the concept redundant. Also, households should not deliver electricity when battery charges are not sufficiently high to power their own needs. For this simulation 0.6 kWh is set as an upper limit for receiving electricity while 0.8 kWh is set as a lower limit for delivering electricity. This corresponds to 29% of available capacity to 64% of available capacity. If any household encounters a charge of 0.8 kWh or above, all generation of electricity is evenly distributed between other households given that their charges stand at 0.6 kWh or less.

For the simulation of connected solar home systems, the power loss caused by cable resistance under transmission must be included. This was found to be dependent on the transmitted power and is expressed by Equation 4 in Chapter 3.4. The equation is implemented into the code so that the transmission losses vary with transmission size as described.

5 Results and discussion

5.1 Solar generation and electricity demand

5.1.1 Solar generation

Figure 11 shows the results for estimated solar generation from PVGIS, over one full year. Clear seasonal variations can be observed and are almost as expected based on the theory presented in Chapter 3.2. March to May and September to December were predicted to host lower electricity generation due to wet seasons with high cloud cover and fewer sunshine hours. However, both seasons appear to have been shifted forward by two months. The periods January to March and September to October have the lowest average generation. A possible explanation for this is that the weather in 2015, the year from which weather data was used, may have differed from what is typical. Another possible explanation is that the wet and dry seasons did not affect solar generation in the same way as was expected.

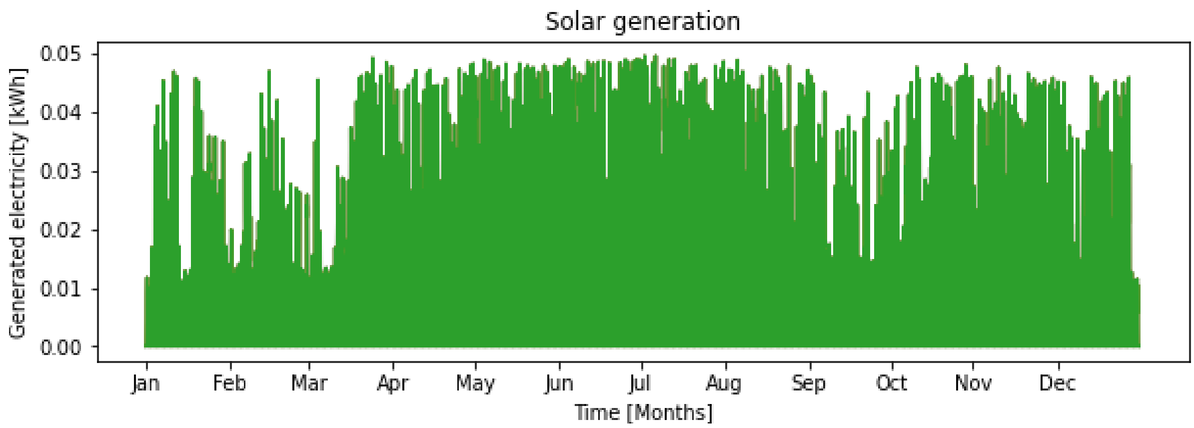

Figure 11. Solar generation. *The figure presents estimated hourly generation of electricity over one full year. The y-axis shows generated electricity measured in kWh. The x-axis shows months of the year.*

Hourly electricity generation for three days in mid-April are presented in Figure 12. The values for each data point represent electricity generated over the following hour. The figure shows that solar generation begins early in the morning, before 06.00. Peak production happens around noon and generation ends in the afternoon before 18.00. The generation curves are consistent with the theory from Chapter 3.2, although electricity generation appears to start slightly earlier than sunrise and end earlier than sundown. This might be caused by horizons from mountains, trees, or buildings in the area, that PVGIS calculations have considered.

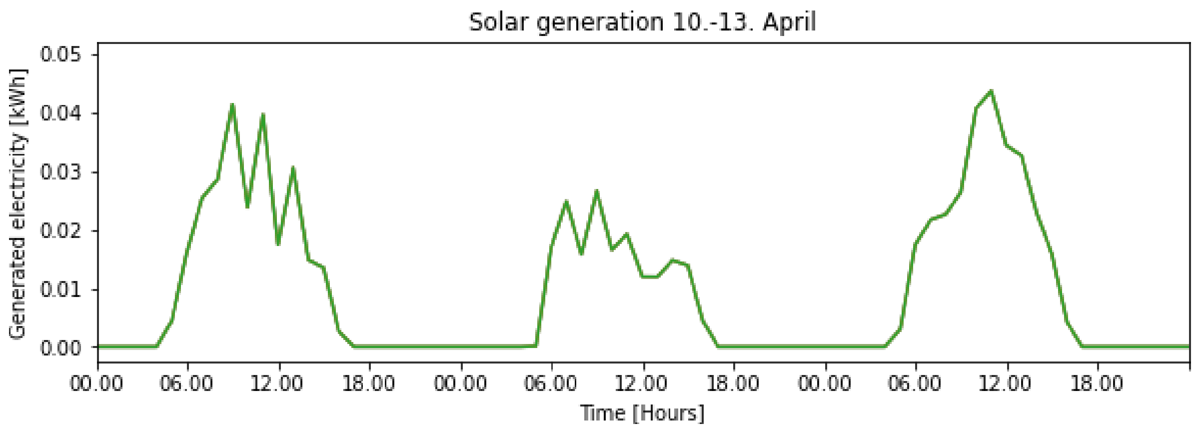

Figure 12: Solar generation 10. - 13. April. *The figure shows generated electricity from the 10. -13. April. Generated electricity is shown on the y-axis (kWh) while time of day is shown on the x-axis.*

5.1.2 Household electricity demand

Figures 13 and 14 show three days of simulated electricity demand for a TV package and a basic package, based on the probabilities from Chapter 4.2. For both packages the light bulbs are consistently used during the morning and the evening. The evening uses last longer and peak at higher energy consumptions. This means that lights are turned on for longer periods in the evenings and that a higher number of lightbulbs are used at one time. The light bulb curves for the basic package peak at higher levels than for the TV package, which is expected given that the basic package includes eight bulbs rather than six. Three uses of the TV are registered: two in the evening and one just after 12.00 on the second day. The two first uses peak at 0.035 kWh per hour, which correspond to half-hour uses of the appliance. The last use peaks at 0.07 kWh which corresponds to use for a full hour. There are four occurrences of phone charger use, all appearing at around 19.00. The last charger usage curve peaks at a higher energy consumption suggesting both chargers are used simultaneously.

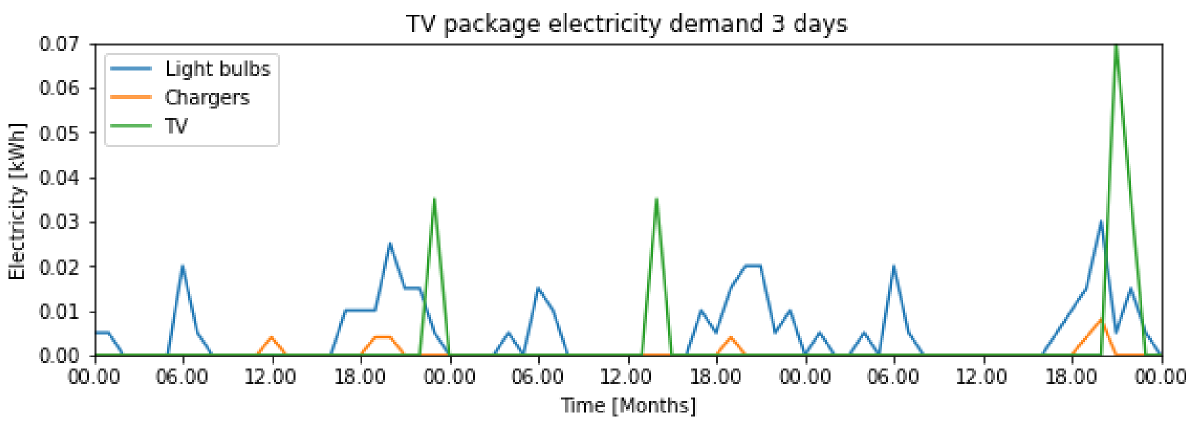

Figure 13: Three-day electricity demand for TV package. *The figure shows three days of simulated electricity demand for each appliance in the TV package. Light bulbs, chargers and TV are represented by blue, orange, and green respectively. The y-axis shows demanded electricity for the respective hour (kWh) and the x-axis shows time of day.*

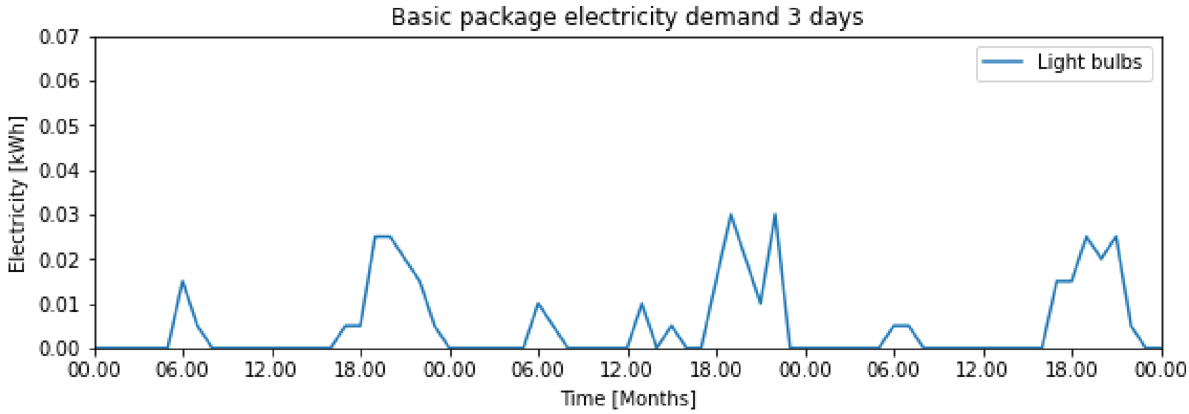

Figure 14: Three-day electricity demand for basic package. *The figure shows three days of simulated electricity demand for the basic package, which contains light bulbs only. The y-axis shows demanded electricity for the respective hour (kWh) and the x-axis shows time of day.*

The demand curves are consistent with the findings from the literature. Light bulbs are used most frequently during the evening and morning, with highest usage during the evening. Uses appear to last around two hours in the morning and seven hours in the evening. This gives around nine hours of use per day, slightly more than the seven hours suggested in the report from Business Innovation Facility (BIF, 2016). Uses of the TV occur twice in the evening and once around lunchtime. This is also consistent with the literature which suggested high uses in the evening with small probabilities of use around morning and lunchtime. It is important to note that the demand data is probability based, meaning that new curves will be generated each time the demand data is refreshed. Over multiple days, the curves take the same average shape.

5.1.3 Solar generation and electricity demand

Figure 15 shows the total electricity use for the three-day TV package demand displayed in Figure 14. This is plotted next to solar generation, from Figure 12. These are plotted together to show how solar generation and electricity demand vary compared to each other. Interesting to note is how the peaks in demand during the morning tend to be covered by the solar generation curve. This indicates that the sun rises early enough for the system to power appliances used in the morning. The peaks in demand registered during the evening are not covered by solar generation, meaning that the sun goes down too early to power these usages directly. Appliances used in this period must be powered by the battery.

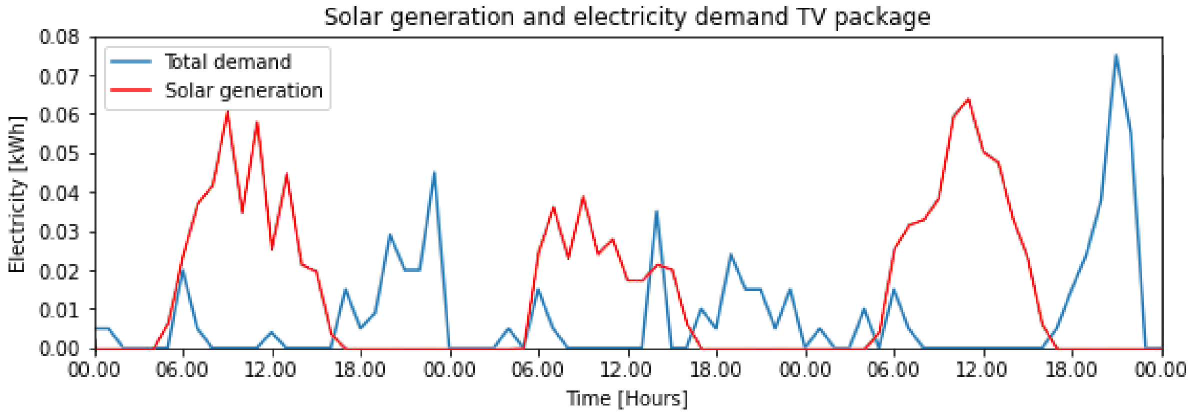

Figure 15. Solar generation and electricity demand. *The figure shows solar generation for three days in April (blue) and electricity demand for three random days (red). The demand curve belongs to the TV package. The data is plotted in hourly steps, with the x-axis showing time of day. The y-axis shows generated/demanded kWh of electricity for each corresponding hour.*

5.2 Case 1. Before connection

For Case 1, three households are simulated before and after connection. Two of the households own the TV package while the third owns the basic package. This is the same ratio of TV package to basic package ownership as in Konza at the time of the study.

5.2.1 Electricity demand

The electricity demand used for the simulation is presented in Figure 16. The two households with TV packages and household with the basic package are referred to as TV 1, TV 2 and Basic respectively. Basic has a stepwise demand with eight clear horizontal lines above zero. This is because each of the eight lightbulbs are turned either on or off for any given hour. They draw 5 W when turned on and 0 W when turned off. For higher electricity demand the lines become fainter. This is because it is less likely that higher numbers of bulbs are used simultaneously. For TV 1 and TV 2, the same stepwise pattern can be observed. Again, this is because appliances are turned either on or off. The electricity usages peak at higher values for the TV packages because the larger number of appliances gives higher possible momentary electricity use. The TV was assumed to draw either 0.035 kWh for half an hour of use or 0.07 kWh for a full hour of use. The gap found between 0.06 kWh and 0.09 kWh shows the difference between instances where the TV is turned on for half an hour and a full hour. The deviations from the steps of 0.005 kWh are caused by the chargers which draw 5 W when turned on, corresponding to 0.004 kWh per hour. This prevents the demand from only moving up in steps of five. Since the generation of electricity demand is probability based, a new generation would give slightly different results. Over the course of a year, however, the variations even out and the data would take a similar shape.

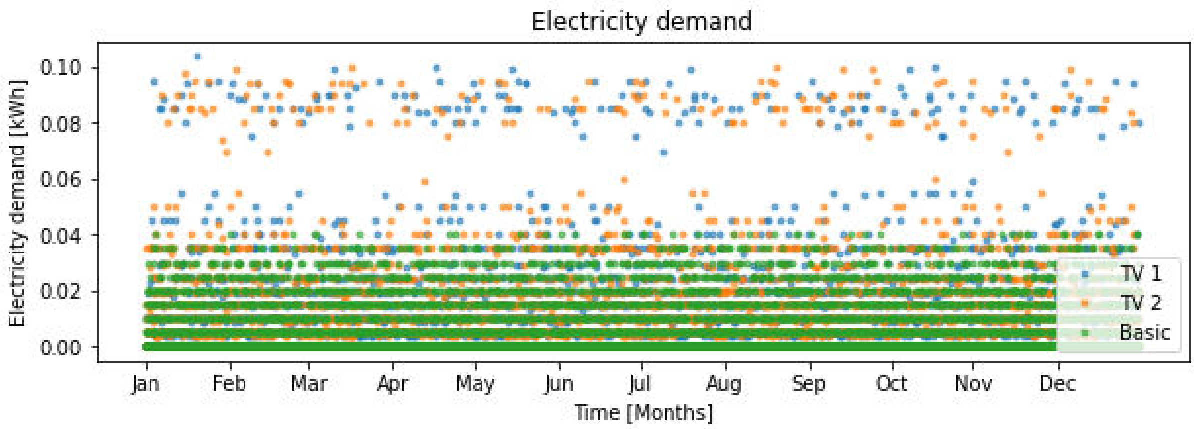

Figure 16: Electricity demand. *The figure shows electricity demand used for the simulation. Each data point represents the electricity use for one household in a specific hour. Blue, orange, and green denote TV1, TV 2 and Basic respectively. The y-axis shows electricity demand measured in kWh and the x-axis shows time measured in months.*

5.2.2 Battery charge

Figure 17 shows simulated battery charges for the three households. Basic has a higher average charge than the TV package households do. Since solar generation is identical for each household this means that TV 1 and TV 2 must have higher average demand than Basic. This is admissible because the TV package includes more appliances than the basic package does. TV 1 and TV 2 have similar charges throughout the year, with some degree of variation. This variation is explained by the probability-based generation of demand data.

For the first quarter of the year, from January to March, battery charge falls gradually for all households. Charges rise and stay high through the summer months but fall to lower levels again from September through to late October. After this they rise again. The large variations in battery charge appear to happen on a seasonal level and must be caused by similar variations in solar generation, electricity demand, or a combination of both. As shown by Figure 16, the electricity demand for all households varies on an hourly and daily basis, but there is no observable seasonal variation. In Figure 11, which shows solar generation, clear seasonal variations were observed. Comparison of solar generation and battery charge confirms that there is a clear causational effect. The rapidly falling battery charges during January, February, and March match the low average solar generation in this period. From April to August all battery charges stay high. There is a dip in average generation in September, which affects charges for TV 1 and TV 2 strongly. Generation is more consistent for the last quarter of the year, where battery charges are high.

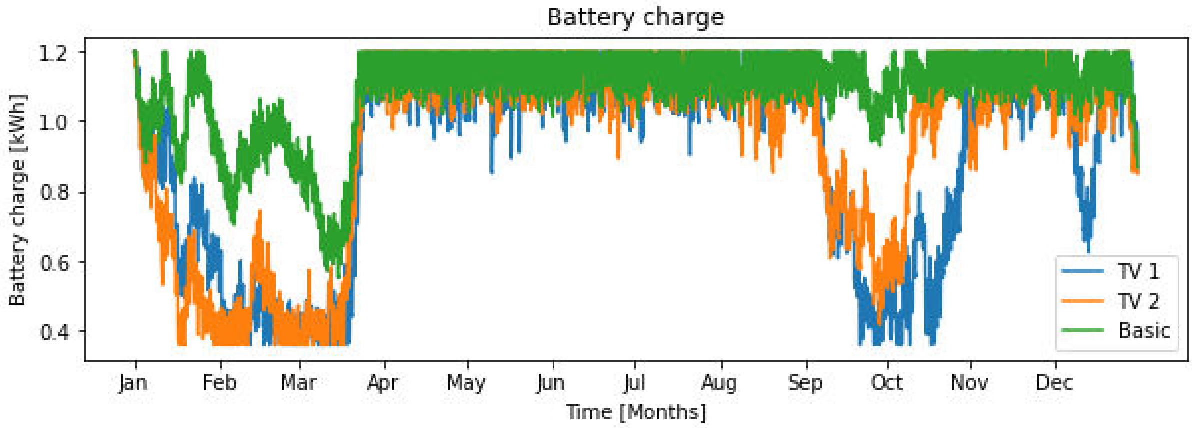

***Figure 17: Battery charge**. Shows battery charges for three independent households over the course of the simulated year. The colours blue, orange and green denote TV 1, TV2 and Basic respectively. The y-axis shows battery charge measured in kWh. Minimum charge is 0.36 kWh and maximum charge is 1.2 kWh. Each month of the year is shown along the x-axis.*

5.2.3 Unserved demand

Figure 18 shows unserved demand. This is the amount of electricity households would have liked to utilise that was not available at the time. The figure shows that Basic is never exposed to unserved demand. The households with TV packages both encounter unserved demand during January, February, and March where solar generation is low and battery charges hover around the discharge limit. In late September TV 1 encounters some instances of unserved demand, also consistent with the level of battery charge at this time of the year. During January, February, and March the data points take a similar shape to those in Figure 16, showing electricity demand. This indicates that very little of the two households' electricity demand during this period is provided, as most of it is registered as unserved.

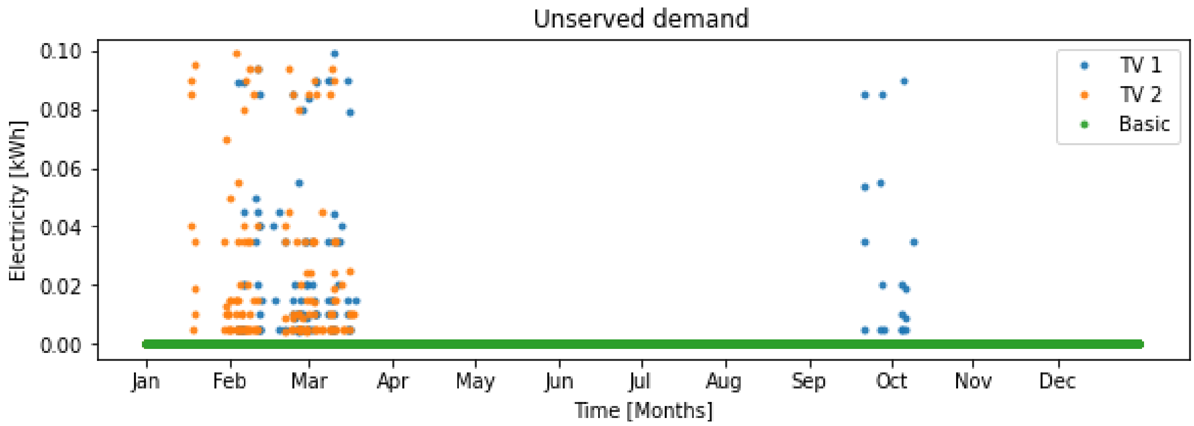

***Figure 18. Unserved demand.** The figure shows unserved demand for the three independent households. Each data point denotes a quantity of electricity for one of the three households in a specific hour of the year. Quantity of electricity is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange and green represent TV 1, TV 2, and Basic respectively.*

5.2.4 Excess electricity generation

Figure 19 shows generated electricity that cannot be stored due to the limited battery capacity. This figure is dominated by green data points, indicating that the Basic generates excess electricity more frequently than the other households do. During both periods where electricity generation and battery charges are low almost no excess is generated. This is intuitive as the batteries do not reach full capacity, so all generation is either stored or used in these periods. Excess electricity generation is interesting to examine because the connected system will distribute excesses between households with available battery capacity. The figure displays a huge potential for increased electricity access if the excess electricity can be stored and utilised.

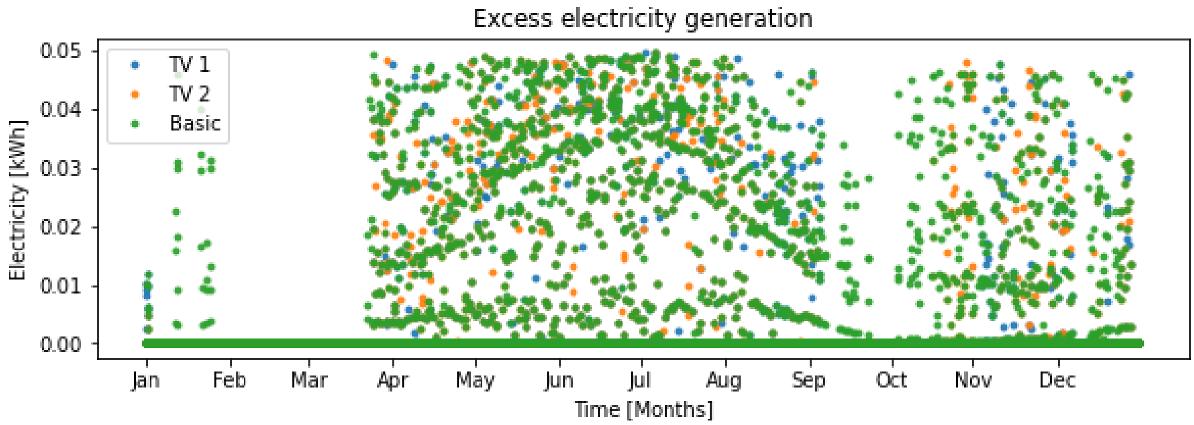

***Figure 19. Excess electricity generation**. The figure displays generated electricity that cannot be stored due to the limited battery capacity. Each data point represents a quantity of electricity for one of the three households in a specific hour of the year. Quantity of unserved demand is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange and green represent TV 1, TV 2 and Basic respectively.*

5.2.5 Key values

Table 7 gives some key values that help demonstrate potential effects of the system connection. The total electricity generation over the full year is notably higher than the total electricity demand. This shows that there is more than enough electricity generated throughout a year for total demand to be covered. Only 6.5 kWh of electricity demand is left unserved throughout the year while there is an excess generation of 81.5 kWh. This electricity has the potential of being stored given that there is available capacity. In other words, there are large amounts of unutilised electricity in the system and small quantities of demand left unserved. If the system is successful in evening out demand variations, reductions in unserved demand should be expected.

Table 7: Overview of key values for each household and system as a whole.

	Generated electricity (kWh)	Demanded electricity (kWh)	Unserved demand (kWh)	Excess electricity (kWh)
TV 1	86.8	58.4	3.1	23.4
TV 2	86.8	57.1	3.4	25.4
Basic	86.8	49.4	0	32.7
System total	260	165	6.5	81.5

5.3 Case 1. After connection

5.3.1 Battery charge

Figures 20 and 21 show battery charge before and after the system connection. Figure 20 is the same as Figure 17, presented in the previous section. Looking at the charge of Basic in both figures, some clear differences can be observed. Between January and April, the curve retains the same shape but descends faster after connection. This can be explained by electricity deliveries being made to the other households. In March, Basic hits the discharge limit after connection. This happens despite the fact that no electricity deliveries are made after its own charge has fallen below 0.8 kWh, as laid out in Chapter 4.4. In late September Basic also undergoes a larger dip in charge when connected, showing that deliveries occur here too. The battery charges for the TV package households appear to be almost unchanged for most of the year. A clear difference can be observed in late September where the charges are lifted after connection. TV 1 hits the discharge limit in September before connection, but not after. This is explained by the reception of electricity, likely from Basic.

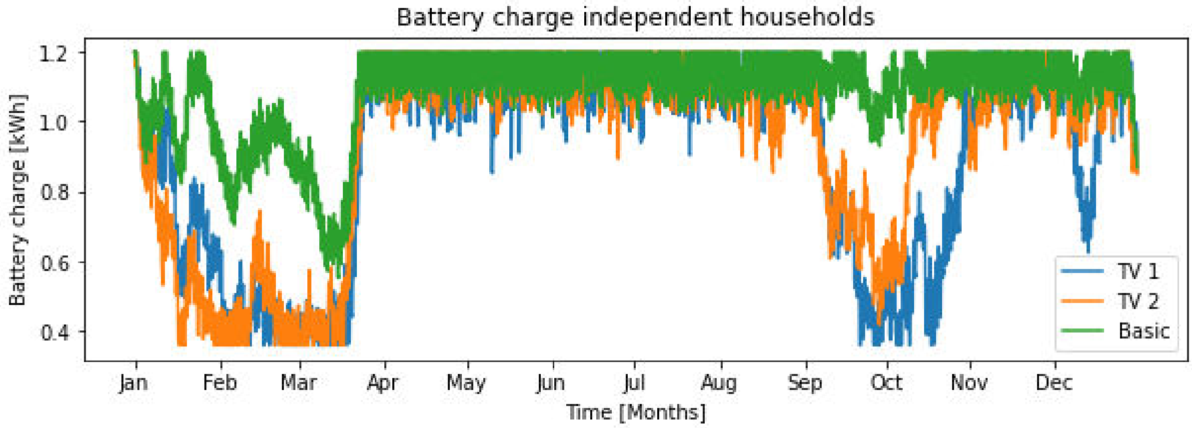

Figure 20. Battery charge independent households. *Shows battery charges for three independent households over the course of the simulated year. The colours blue, orange, and green represent TV 1, TV2, and Basic respectively. The y-axis shows battery charge measured in kWh. Minimum charge is 0.36 kWh and maximum charge is 1.2 kWh. Time is found along the x-axis, measured in months.*

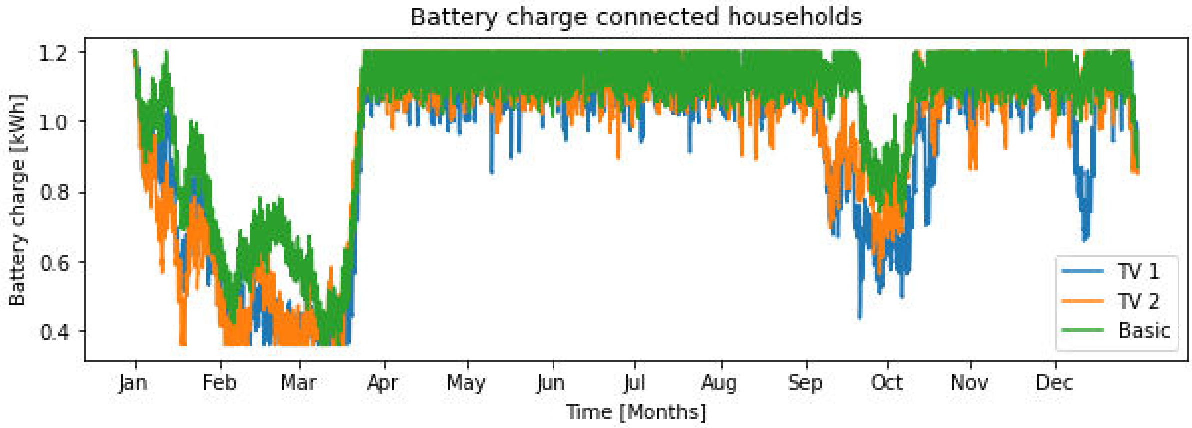

Figure 21. Battery charge connected households. *Shows battery charges for three connected households over the course of the simulated year. The colours blue, orange, and green denote TV 1, TV2, and Basic respectively. The y-axis shows battery charge measured in kWh. Minimum charge is 0.36 kWh and maximum charge is 1.2 kWh. Time is found along the x-axis, measured in months.*

Table 8 contains average battery charges pre- and post-connection for the whole year. Both TV 1 and TV 2 obtain higher average charges after connection. Basic has a somewhat lower average charge. This shows that the exchange system works as expected, as the two low charge batteries are boosted by the high charge battery. Looking at the average charge for all three batteries in the system, a slight decline is calculated. The decline in average charge may be caused by power losses in transmission between the households.

Table 8: Average battery charges for independent and connected households

	TV 1	**TV 2**	**Basic**	**Total**
Independent (kWh)	0.91	0.94	1.1	0.98
Connected (kWh)	0.95	0.97	1.0	0.97

5.3.2 Unserved demand

Figures 22 and 23 compare unserved demand before and after connection. Figure 22 is the same one as presented in Chapter 5.2.3. At the beginning of the year, slightly fewer data points can be found showing high values of unserved demand after connection. This can be explained by the delivery of electricity from the Basic to the TV package households. Notably, Basic begins to encounter some low values of unserved demand in March after connection, corresponding to the point where its battery charge hits the discharge limit. TV 1 encounters some instances of unserved demand in late September before connection, but not after.

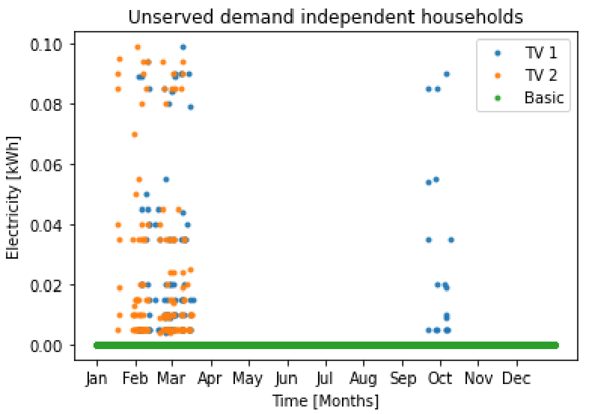

Figure 22. Unserved demand independent households. *Each data point denotes a quantity of electricity for one household in a specific hour of the year. Quantity of unserved demand is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, and green represent TV 1, TV 2, and Basic respectively.*

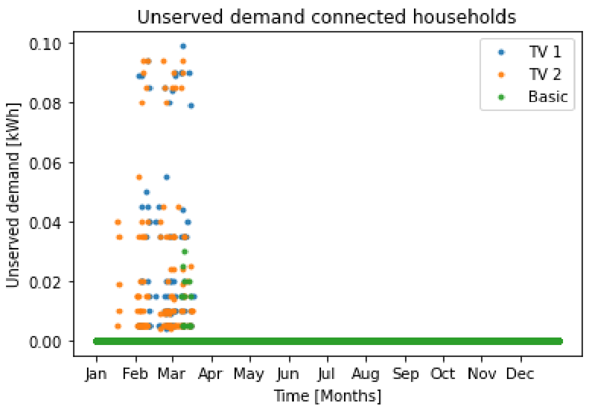

Figure 23. Unserved demand connected households. *Each data point denotes a quantity of electricity for one household in a specific hour of the year. Quantity of unserved demand is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, and green represent TV 1, TV 2, and Basic respectively.*

Table 9 compares total quantity of unserved demand throughout the year for independent and connected households. Both TV package households are subjected to less unserved demand after connection, while the basic package household experiences more. This is an interesting result, as the connection benefits two households but disadvantages the third. For the system as a whole, the total unserved demand is reduced from 6.6 kWh to 5.5 kWh. This is a 17% reduction.

Table 9: Unserved demand for independent and connected households. *The table presents the total amount of unserved demand for each of the three households, independent and connected, over one year. The final column gives the sum of unserved demand for all households, independent and connected.*

	TV 1	TV 2	Basic	Total
Independent (kWh)	3.1	3.4	0	6.6
Connected (kWh)	2.6	2.7	0.16	5.5

5.3.3 Deliveries and reception

Figures 24 and 25 give an overview of delivered and received electricity for each household. The data points take a similar shape to those in Figure 19, showing excess electricity generation. This indicates that most of the electricity transfers that take place are caused by excess electricity being distributed to other households. To locate transfers that happen due to low charge states, data points at 0.01 kWh of delivered electricity must be found as this is the defined quantity for low charge transfers. These transfers take place when charge states fall below 0.6 kWh. This happens in the periods January to April and September to October. Looking at Figure 24, clear green data points can be observed at these locations. These data points stand out slightly compared to the rest because they group together. A look at the same areas in Figure 25 shows that TV 1 receives most of the low charge transfers in the first period while TV 2 receives most of them in the second period.

The existence of expected power losses in transmission can be confirmed by examining the two figures. Values for delivered electricity peak at around 0.05 kWh while values for received electricity peak at around 0.04 kWh. Some amount of electricity must be lost in transmission because the maximum delivery value is higher than the maximum reception value. Power loss can also be detected when looking at the identified low charge transfers. The received values are slightly lower than the 0.01 kWh deliveries. This difference also includes a 10% battery discharge loss as the electricity from low charge transfers is provided from the battery of the delivering household.

The overall spread of the data points takes slightly different forms in the two figures. In Figure 25 data points group together at around 0.04 kWh and 0.02 kWh. This can be explained by the distribution of transferred electricity. The electricity is either received by one household or distributed between two. The grouping of data points around 0.04 kWh may show instances where one recipient collects the sum of the transfer from the other two households. The grouping around 0.02 kWh may show instances where the transfer is shared between two households.

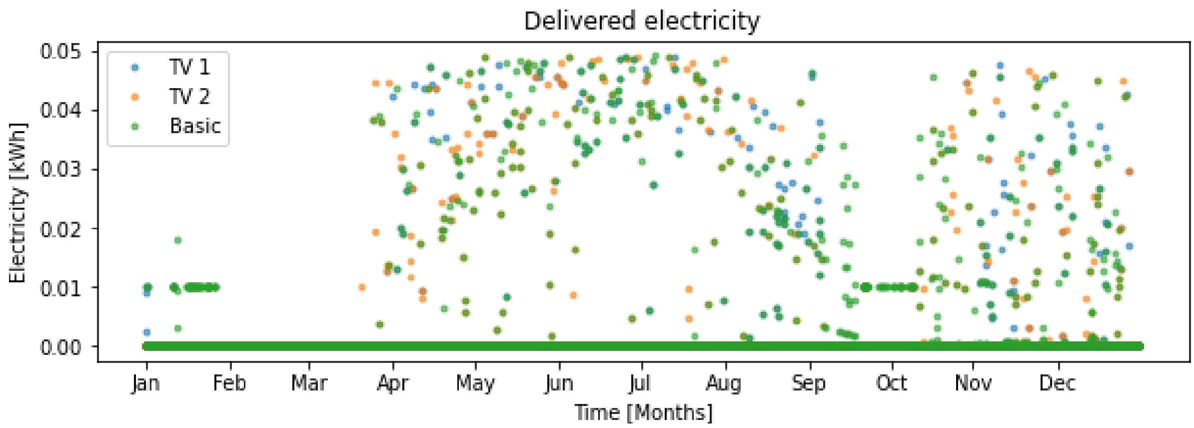

Figure 24. Delivered electricity. *The figure gives an overview of delivered electricity. Each data point corresponds to a quantity of electricity and a specific hour of the year. Quantity of electricity is shown on the y-axis, measured in kWh. Time is shown on the x-axis and is measured in hours. The colours blue, orange, and green represent TV 1, TV 2, and Basic respectively.*

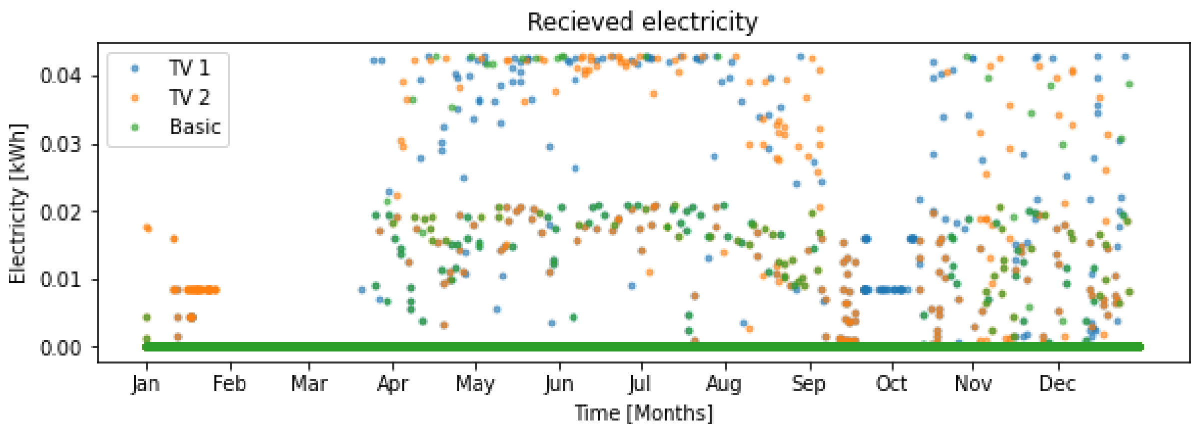

Figure 25. Received electricity. *The figure gives an overview of received electricity. Each data point corresponds to a quantity of electricity and a specific hour of the year. Quantity of electricity is shown on the y-axis, measured in kWh. Time is shown on the x-axis and measured in hours. Blue, orange, and green represent TV 1, TV 2, and Basic respectively.*

The total amount of delivered and received electricity for each household is presented in Table 10. It is interesting to note that only TV 1 receives more electricity than it delivers. In sum, much more electricity is delivered than is received for the whole system. The reason for this is that much of the delivered electricity is lost during the transmission.

Table 10: Overview of electricity exchanges

	TV 1	**TV 2**	**Basic**	**Total**
Total delivered (kWh)	5.1	5.9	9.0	20
Total received (kWh)	6.2	5.6	2.6	14.6
Net exchange (kWh)	1.1	-0.3	-6.2	-5.5

5.3.4 Transmission losses

Figure 26 displays transmission loss for every electricity exchange that is made. Notably the data takes a similar shape to that of figures 24 and 25 showing delivered and received electricity. This indicates that higher power transmissions correlate with high power losses, as Equation 4 suggests. The highest power transmissions are found from Figure 24 to be around 0.05 kWh per hour. This gives an average power of 50 W for the relevant hour. Figure 26 shows that these transfers incur losses of almost 60% of transmitted power. Since these transfers are made for excess electricity the size of the transmission loss is not necessarily an issue. This is electricity that otherwise would not have been utilised, so any transfer can be considered a net positive. The low charge transfers which were identified in figures 24 and 25 can be found in the same locations for Figure 26. These only incur transmission losses of around 5%. For low charge transfers it is beneficial that the transmission loss is low because this electricity does have an alternative value to the delivering household.

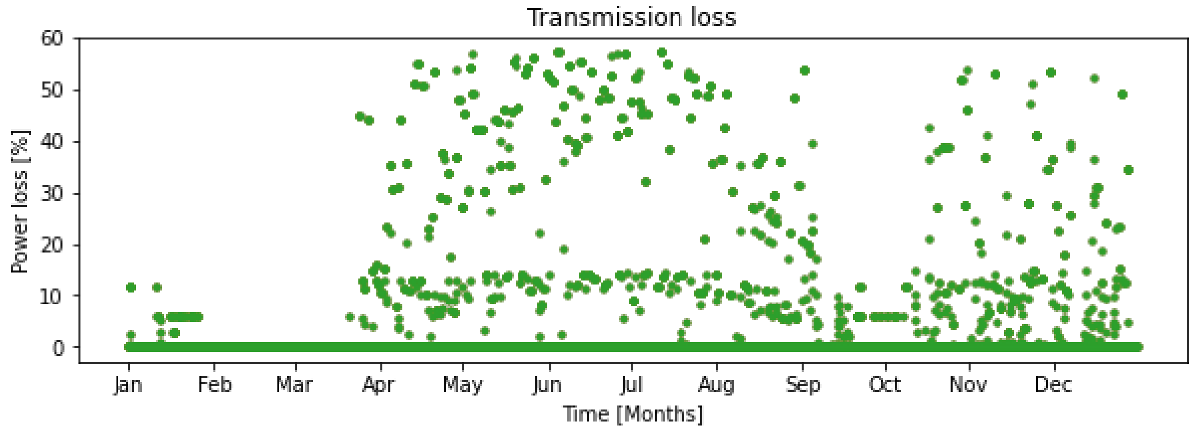

Figure 26. Transmission loss. *The figure shows percentage of transmitted power that is lost for each electricity transfer over the simulated year. Each data point corresponds to a proportion of power loss (y-axis), and a specific hour of the year (x-axis).*

5.3.5 Utility of electricity exchanges

To analyse the benefits of the intervention two types of electricity exchange are given a closer look: excess electricity transfers and low charge transfers.

5.3.5.1 Excess electricity transfers

One of the premises for electricity exchange is that excess electricity should be delivered to households with available capacity. The utility of these exchanges is uncertain because the battery charges proved to be more strongly affected by variation in electricity generation than by variation in electricity demand. When one household has a high battery charge the other households are likely to encounter high charges too. Therefore, the benefits of distributing the excess electricity are limited. To illustrate this a three-day period where battery charges and generated electricity are particularly high is examined.

Figures 27 and 28 show the battery charge for a three-day period in April, before and after connection. Noon is marked for each day. This is approximately where the charge states peak as production is high during mid-day. Moving into the evening, production falls and consumption rises. Charge sinks accordingly before beginning to rise again in the morning. On the first day in Figure 27, TV 2 does not reach a full battery charge whereas the other two households do. After the households are connected, in Figure 28, TV 2 does reach full charge. This is due to TV 2 receiving excess electricity from the other two households.

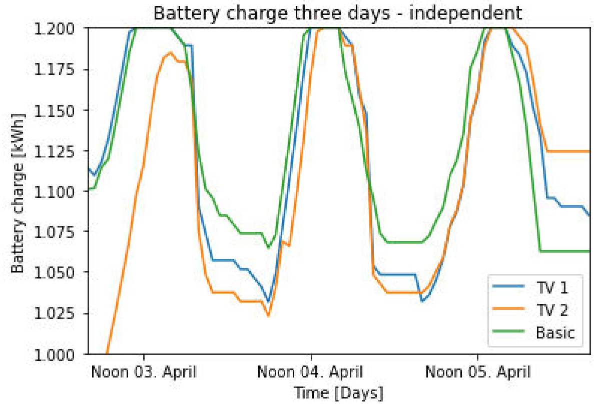

Figure 27. Battery charge three days - independent. *Shows battery charge (y-axis) from 03. - 05. April (x-axis). Blue, orange, and green represent TV1, TV 2, and Basic respectively.*

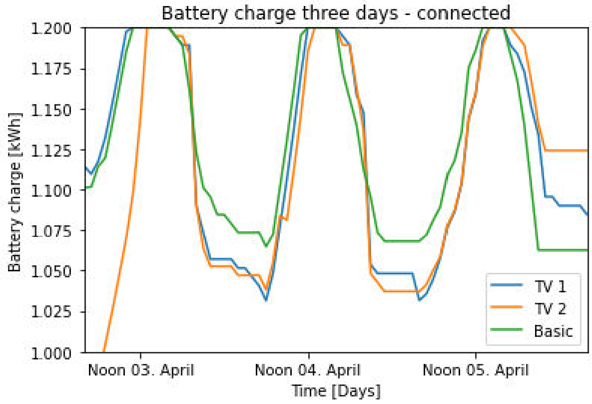

Figure 28. Battery charge three days – connected. *Shows battery charge (y-axis) from 03 - 05. April. (x-axis). Blue, orange, and green represent TV1, TV 2, and Basic respectively.*

The expectation would be that the reception of excess electricity benefits TV 2 as the household has access to more electricity than it did without the exchange. Following the TV 2 curve through the next few days however, it reaches peak capacity both days independently. In fact, on the fourth and fifth of April all three households encounter full batteries and excess electricity. This renders the electricity reception on the third of April unnecessary. Unless the household specifically increases consumption on the third of April so much that the battery capacity does not hit full charge the next day, there will have been no extra benefit provided by the transfer.

This is a recurring circumstance throughout the simulated year. At times where any given household generates excess electricity the other households are likely to have high battery charges too. This means that the advantages of excess electricity transfers are not as clear as first anticipated.

5.3.5.2 Low charge transfers

The second type of electricity exchange in the simulation is the low charge transfer. This is evoked when any household's battery charge falls below a 0.6 kWh charge at the same time as any other household's battery has a charge above 0.8 kWh. Two periods of the year were identified as periods where these transfers were common. January to March and September to October.

In the first period, there were few benefits provided by the exchanges. Changes in battery charge were small for the two TV package households after connection was made. There were only small reductions in occurrences of unserved demand. Simultaneously, a clear fall in average charge was observed for the basic package household. This household did not encounter any unserved demand independently but did after connection.

Again, the results can be attributed to the fact that seasonal variation in electricity generation is more influential than random variation in demand. When electricity generation is low this affects all households. Given that one household's battery has a low charge it is likely that the other households are also experiencing low charges. In the examined case, the basic package household had to deliver to both TV package households at the same time. Rather than keeping all batteries at a sufficient charge, the low charge batteries dragged the high charge battery down to their level of charge.

The second period where low charge transfers were particularly common lasted from September to October. During this period the electricity exchanges gave clearer benefits. The average charge states for the TV package households were lifted after connection was made. The unserved demand encountered by TV 1 was eliminated. The battery charge for the Basic fell to around 0.8 kWh while electricity was delivered to its neighbours but increased rapidly afterwards. After exchanges, all households were left with the potential of increasing electricity consumption without emptying their batteries.

The reason the second period had a more successful outcome was that electricity generation was higher than in the first period. Prior to connection battery charges for TV 1 and TV 2 only barely fall to low levels while the charge for Basic stayed high. The recipient households did not need as much electricity and the delivering household had much to share. During the first period all battery charges were low prior to connection. This indicates that the low charge transfer is only successful until a certain level of electricity scarcity is reached. When scarcity in generation is very high, all households are likely to be affected similarly and the exchange has little positive effect. In fact, due to transmission losses and battery charge losses, the total electricity in the system is reduced when exchanges are made. Intuitively this will not improve the electricity access when all battery charges and solar generation levels are already low.

It is important to note that the basic package household has a much lower electricity consumption than the TV package households. From Table 7, the total electricity demand for Basic is 49.5 kWh. TV 1 and TV 2 have demands of 58.4 kWh and 57.1 kWh. This difference is clearly reflected in the charge states prior to connection. The fact that one household includes fewer applications and a lower demand than the other two makes connection more likely to give benefits. As shown in Table 10, Basic almost exclusively delivers electricity to the other two households, receiving little in return. This does not appear to be a good deal for the owner of the basic package, who might be unlikely to accept an arrangement like this. Moreover, the results do not necessarily only demonstrate an evening out of demand variation. They also show an evening out of average demand differences. If all three households in the connected system included a TV package, the results may look different.

5.4 Case 2. Connection of three households with TV packages

To reveal how much differences in electricity consumption between different package types affected the results, the simulation has been run including only TV package households. TV 1 and TV 2 have the same demand data as used in Case 1. TV 3 is introduced.

5.4.1 Battery charge

Figure 29 shows the battery charges prior to connection. TV 3 appears to have a higher average charge than the other two households in January and late September. Therefore, TV 3 should deliver electricity to TV 1 and TV 2 in these periods. Examination of Figure 30, which shows the charges after connection, confirms that this is the case. The charge for TV 3 falls faster in January and dips to a lower level in late September. TV 1 and TV 2 encounter small increases in charge in September and October. As in Case 1, the second period of low average charges appears to host more improvement than the first. Electricity generation is higher in the second period, so initial charges are not as low. In this case, TV 3 has a higher initial charge and can compensate the other two households.

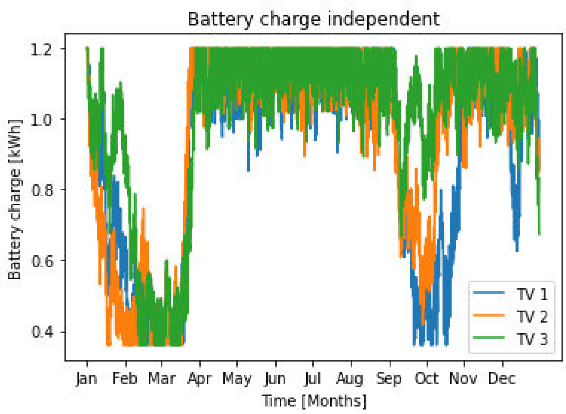

Figure 29. Battery charge independent. *Shows battery charge for three independent households with TV packages. The x-axis shows charge (kWh) and the y-axis shows time (months). Bule, orange, and green denote TV1, TV 2, and TV 3 respectively.*

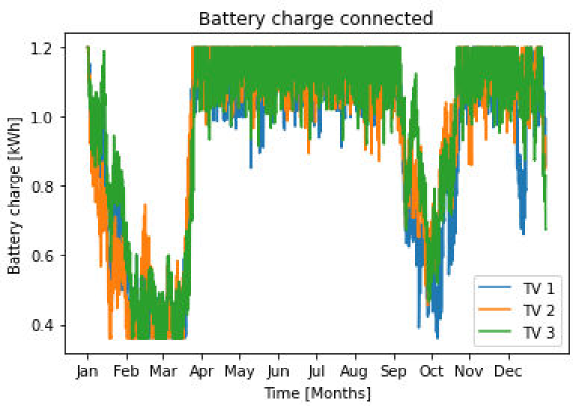

Figure 30. Battery charge connected. *Shows battery charge for three connected households with TV packages. The x-axis shows charge (kWh) and the y-axis shows time (months). Bule, orange, and green denote TV1, TV 2, and TV 3 respectively.*

5.4.2 Unserved demand

Figures 31 and 32 show unserved demand before and after connection. All three households encounter many instances in both situations. Changes are almost non-existent for the first period of low charges. For the second period the unserved demand for TV 2 is substantially reduced, although four occurrences still appear.

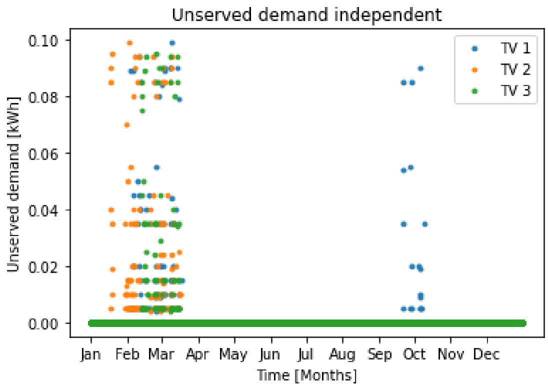

Figure 31. Unserved demand independent. *Shows unserved demand for three independent households with TV packages. Each data point represents a quantity of electricity for one household in a specific hour of the year. Quantity of unserved demand is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, and green represent TV 1, TV 2, and TV 3 respectively.*

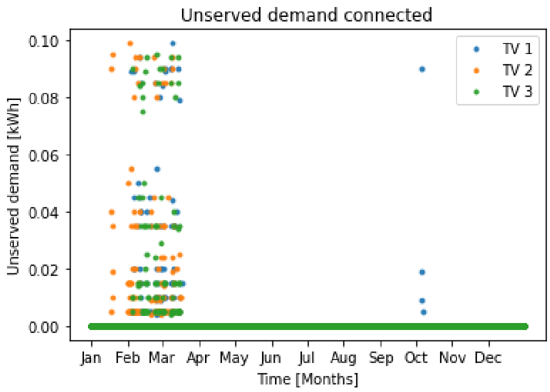

Figure 32. Unserved demand connected. *Shows unserved demand for three connected households with TV packages. Each data point denotes a quantity of electricity for one household in a specific hour of the year. Quantity of unserved demand is found on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, and green represent TV 1, TV 2, and basic respectively.*

Table 11 gives an overview of total unserved demand for each household over course of the simulated year. TV 1 and TV 2 undergo reductions while TV 3 sees an increase. This means that the deliveries made by TV 3 lead to the household encountering more unserved demand than it did prior to connection. For the system as a whole, unserved demand is reduced by 4.5%.

Table 11. Unserved demand for three TV package households before and after connection. *The table presents the total quantity of unserved demand for each of the three households, independent and connected, over one year. The final column gives total unserved demand for all households.*

	TV 1	**TV 2**	**TV 3**	**Total**
Independent (kWh)	3.1	3.4	2.3	8.8
Connected (kWh)	2.7	3.1	2.6	8.4

5.4.3 Summary

Analysed data for the connection of three TV package households confirms that the electricity exchange is less beneficial with this composition. Expected changes in battery charge are observed, but there was not sufficient electricity in the system to substantially lift low charges. Unserved demand is reduced by 4.5%, more than three times less than the 17% reduction made in Case 1. For connection of three TV package households, electricity exchange brings less improvement to electricity access. This indicates that some of the improvements made in Case 1 can be attributed to average differences in electricity demand for the different appliance compositions.

5.5 Case 3. Connection of six households.

To determine whether a higher number of households included in the system will affect the results, a new simulation is run where twice the number of households are included. The six-household simulation is not adapted to the conditions of the case village and continues to assume a 300-meter distance for every transfer made. So that the results are comparable to those in Case 1, the ratio between TV package households and basic package households is kept the same. That gives four TV package households and two basic package households.

5.5.1 Battery charge

Figures 33 and 34 present the six households' battery charges over the course of the simulated year, before and after connection. As independent systems, the two households with basic packages have higher average charges than those with TV packages. The households with TV packages all encounter low charges in February and March. In September and October charges are also low, although TV 3's charge stays at a moderate level.

The connection of the systems has a clear effect on the battery charges. The charges appear to be drawn closer to each other for the first part of the year as the basic packages deliver electricity to the TV packages. Battery charges appear to spend less time at the discharge limit after connection is made. In September and October, the charges for the TV package batteries are clearly lifted and no households run out of electricity.

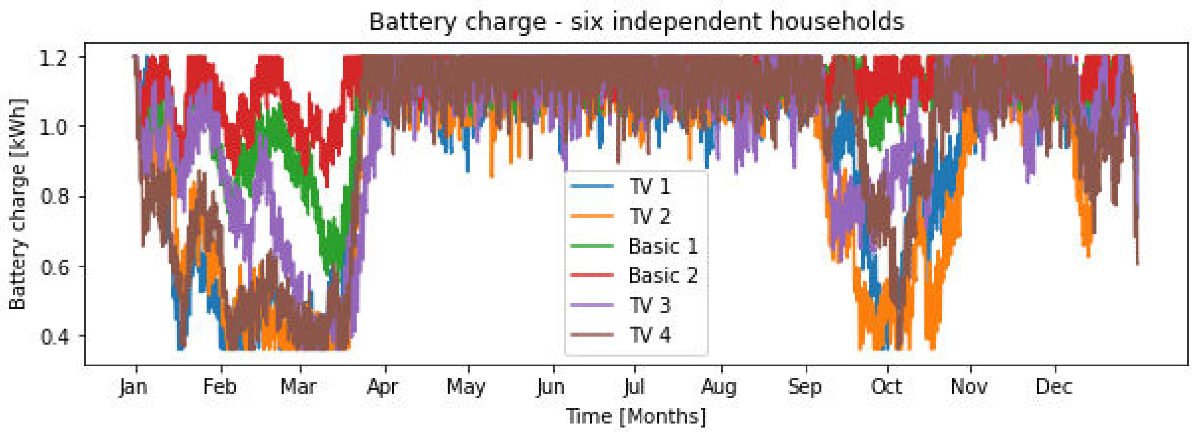

Figure 33. Battery charge - six independent households. *The figure shows battery charges for six independent households over the course of the simulated year. The colours blue, orange, green, red, purple, and brown denote TV 1, TV 2, Basic 1, Basic 2, TV 3, and TV 4 respectively. The y-axis shows battery charge measured in kWh. Minimum charge is 0.36 kWh and maximum charge is 1.2 kWh. Time is shown along the x-axis, measured in months.*

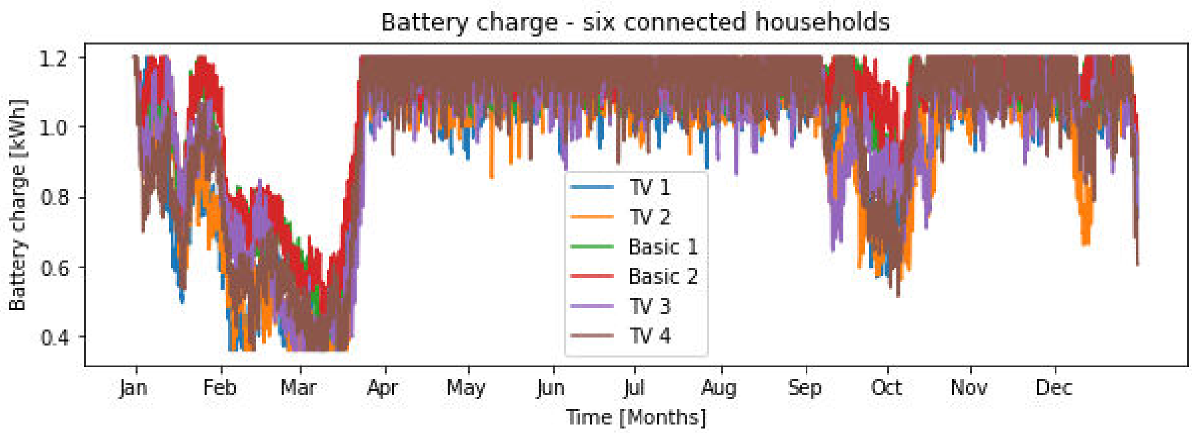

Figure 34. Battery charge - six connected households. *The figure shows battery charges for six connected households over the course of the simulated year. The colours blue, orange, green, red, purple, and brown denote TV 1, TV2, Basic 1, Basic 2, TV 3, and TV 4 respectively. The y-axis shows battery charge measured in kWh. Minimum charge is 0.36 kWh and maximum charge is 1.2 kWh. Time is shown along the x-axis, measured in months.*

Table 12 presents average battery charges for all households in the system. As expected, average charges for the TV package households all rise while average charges for the basic package households fall. Interestingly, the average battery charge across the whole system rises by 0.02 kWh with connection. This is the opposite of what happened in Case 1, where the average charge for all batteries fell by 0.01 kWh after connection was made. However, this difference is small. Given that the results are generated from probability-based data, more simulations would be necessary to ensure that the size of this difference is significant.

Table 12: Average battery charges for six households before and after connection

	TV 1	TV 2	Basic 1	Basic 2	TV 3	TV 4	Total
Independent (kWh)	0.94	0.91	1.08	1.11	0.97	0.95	0.99
Connected (kWh)	0.98	0.97	1.04	1.06	0.99	0.99	1.01

5.5.2 Unserved demand

Unserved demand pre- and post-connection is presented in figures 35 and 36. During the first period where unserved demand is encountered, changes can be observed. After connection there are no occurrences of unserved demand in January, indicating that charges are held above the discharge limit for a longer period than they were with independent households. There are also fewer occurrences of unserved demand in the February to March period. Close inspection reveals that Basic 1 is subjected to some instances of unserved demand after connection is made, despite this not happening pre-connection. For the second period all occurrences of unserved demand disappear when households are connected.

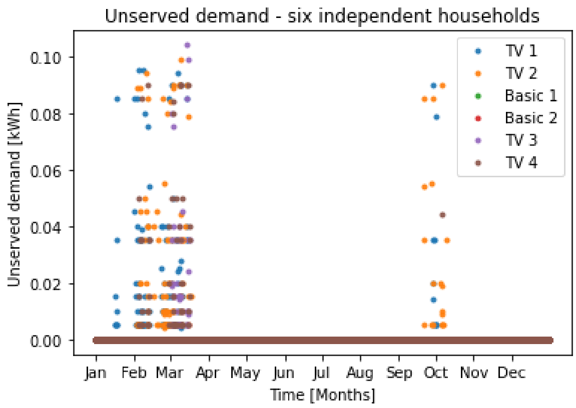

Figure 35. Unserved demand – six independent households. *Each data point represents a quantity of unserved demand for one household in a specific hour of the year. Quantity of electricity is shown on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, green, red, purple, and brown represent TV 1, TV 2, Basic 1, Basic 2, TV 3, and TV 4 respectively.*

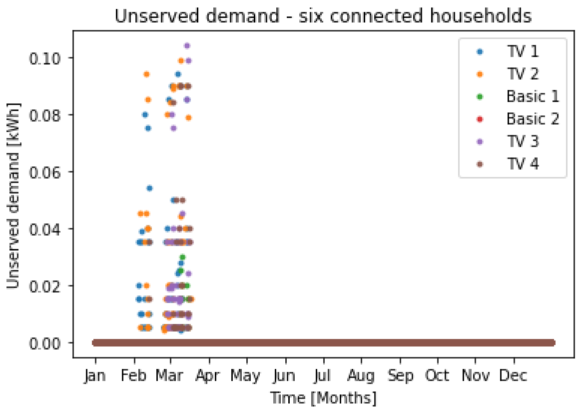

Figure 36. Unserved demand - six connected households. *Each data point represents a quantity of unserved demand for one household in a specific hour of the year. Quantity of electricity is shown on the y-axis, measured in kWh. Hours of the year are found along the x-axis, measured in months. The colours blue, orange, green, red, purple, and brown represent TV 1, TV 2, Basic 1, Basic 2, TV 3, and TV 4 respectively.*

To give a better overview of changes in unserved demand, the total quantity encountered by each household throughout the year is presented in Table 13. For TV 1, TV 2, and TV 4 the quantity of unserved demand is significantly reduced. Basic 1 sees a slight increase, as was observed in Figure 36. TV 3 also sees a slight increase while Basic 2 sees no change. The total unserved demand for the system is lowered from 8.9 kWh to 6.0 kWh. This is a 33% reduction in unserved demand, almost twice as high as the 17% reduction measured for the three-household system in Case 1. These results indicate that the inclusion of more households increase the benefits of the intervention.

Table 13. Unserved demand for six households independent and connected. *The table presents the total amount of unserved demand for each of the six households over one year, independent and connected. The final column shows total unserved demand for all households.*

	TV 1	**TV 2**	**Basic 1**	**Basic 2**	**TV 3**	**TV 4**	**Total**
Independent (kWh)	3.1	3.1	0	0	1.1	1.6	8.9
Connected (kWh)	1.9	1.9	0.16	0	1.2	0.8	6.0

5.5.3 Utility in increasing number of connected households

When the number of households in the system is increased from three to six, results are improved. Amount of electricity demand left unserved is reduced by a larger proportion when six houses are connected than when three houses are connected. Average charge state for all households also increases slightly for connection of six households, although more simulations would be needed to determine if this is a significant change. The results make sense intuitively as more households in the system give more varying demand curves. Given that one battery has a low charge, the probability that another battery has sufficient charge to deliver electricity is higher at any given time. In other words, more variations in demand give more opportunities to even the variations out through exchange.

All but one household encountered unserved demand during the January to March period where electricity generation is low. This highlights the fact that seasonal variation in generation still impacts the battery charges more than demand variation does. During this period of the year all households must lower their demand to cope with the low generation. Doubling the number of households in the system does increase the benefits of exchange, but seasonal variations still far outweigh demand variations. This shows that the advantages of the intervention are limited even with a higher number of households.

6 Study strengths and limitations

6.1 Error in PVGIS slope optimisation

The angles for placement of the solar panels were optimised by PVGIS to give the highest possible electricity generation over a full year. The azimuth and slope estimated by the tool were -180° and 90° respectively. After results had been analysed it was found that the slope angle was not in accordance with the theory from Chapter 3.1.1. Here, it was found that an optimal slope angle for highest year-round generation is roughly equal to the latitude of the solar panel placement. Konza lies just south of the equator with a latitude of approximately -1.7°. In other words, the theory suggests an almost horizontal panel placement while PVGIS generated data using a vertical panel placement. Solar generation data was estimated again with the angles suggested by the theory placed in manually. The results gave a much higher year-round solar generation, confirming that an error has occurred in the PVGIS estimation of optimal slope angle.

The simulation is run with lower electricity generation than the 120 W solar panel can produce when optimally positioned in the case village. This means that the households should have access to more electricity than has been accounted for. Consequently, the households should be expected to have higher average battery charges and fewer instances of unserved demand prior to connection. However, given that the goal of the study is to determine whether connection of separate solar home systems can lead to improved electricity access, the results from the simulation are relevant, regardless of the uncertainty in electricity generation levels. The results do provide information about how electricity access differs for independent and connected households and can therefore be used to draw conclusions. These conclusions may be relevant for households placed in different areas that generate less electricity, or households where demand is higher than what is predicted for the case village of this study.

6.2 Uncertainty regarding time zone of PVGIS data

In Chapter 5.1.1, it is noted that solar generation appears to begin and end earlier than expected with respect to sunrise and sundown in Konza. Reasons discussed for this were possible horizons which PVGIS may have considered. After results had been analysed it was found that the mismatch might be caused by the use of UTC time rather than local time in the solar generation dataset. For this study it was assumed that output data was given in local time, which has an offset of UTC + 3 hours. If the data was given in UTC time, generation would match expected sunrise and sundown more accurately.

The PVGIS website does not clarify which time zone output data is given in. If it is the case that UTC time was used, results are affected by this. Solar generation would begin later in the morning than the simulation accounts for, so that early consumption would need to be powered by the battery. Generation would end later in the evening, so the panel could provide power for later consumption than has been accounted for. These changes would affect the results to some degree. However, the possible shift in generation would affect all households identically, before and after connection. Given that the study aims to determine the effects of electricity exchanges, results can, regardless of this uncertainty, be used to draw conclusions concerning the problem statement.

6.3 Possible improvements for demand data

Although the demand data is based on literature from areas with similar electricity needs, it does not account for systematic variations other than those within the one-day range. This is because the size of day-to-day variations in electricity use were not mapped in any of the reviewed literature. Habits of homeowners could potentially vary on a basis of days or weeks or months. For example, if homeowners do not go out to work or have different routines on a Sunday the demand curve would take a different shape every seventh day. Seasonal variations in weather could also affect consumption. Darker and more cloudy days could require more use of lights. The TV could be used more frequently on rainy days when homeowners prefer to stay inside. Seasonal variations in electricity generation could also affect demand as homeowners respond to the absence, or abundance, of available battery capacity. When generation is scarce homeowners may be sparing in their usage and prefer to save electricity. When sunlight is abundant homeowners may increase their use accordingly. Electricity demand may vary systematically in ways that are not accounted for in this study. To determine how such variations would affect results, electricity consumption could be measured directly in future studies.

6.4 Inaccuracy in the simulation

A fault in the Python code led to inaccurate data for electricity deliveries. When excess electricity transfers are made, the excess is calculated as electricity demand subtracted from electricity generation. This calculation is done for any hour where the battery charge is at its maximum level. The electricity surplus is then averaged out across the households that generate excess and logged as delivered electricity. This means that the electricity transfers registered in the figures showing deliveries do not display accurate results. The registered delivery is the average of all deliveries rather than the specific value for each household. Despite this inaccuracy, the effects on the results are small. The calculated excess is dependent on generated and demanded electricity. The generation is identical for each household, meaning that only variations in demand are averaged out. Moreover, this inaccuracy does not affect the battery charges for the delivering households or the receptions data. The error only causes inaccuracy to the data showing deliveries of electricity.

6.5 Length of transmission cables and connection shapes

In Chapter 4.1, a 300-meter length is estimated as the average length between clustered households in Konza. This is assumed to be the transmission length for each power exchange. For the three-house cases this assumption holds. However, if a different connection shape was to be implemented the new distances would need to be included in the simulation to produce accurate results. After the addition of more households to the interconnected system in Case 3, the 300-meter length is still assumed for each transmission. In Konza, distances between many households would be larger, causing higher power losses in the exchange of electricity than is accounted for. In the following paragraphs some different connection types and their potential transmission losses are discussed.

In Case 1, the households are assumed to be connected by three cables in a triangular shape, where each of the three households have a connection point to each other. Another option would have been connecting the households using only two cables. This could reduce the costs per household substantially as approximately 600 meters of cable would be necessary, rather than 900 meters. With the described connection type, electricity exchanges between the two end households would be at 600 meters. Equation 4 from Chapter 3.4 shows that a doubling of the length leads to a doubling of the share of power lost. A look at Figure 26, which presents transmission losses, reveals that many transfers already incur losses of up to 60%. A doubling of the power loss would make many of the transfers ineffective. Therefore, the triangular shape where all three households have a connection point to each other appears to be an optimal solution for connection. To test the effectiveness of different connection types, future research could use a simulation that takes varying transmission distances for different households into account.

The relationship between power loss and transmission distance makes connection of more than three households unrealistic for the case village. Figure 37 shows a potential connection shape for seven buildings, including the three buildings from the satellite image in Chapter 4.1.

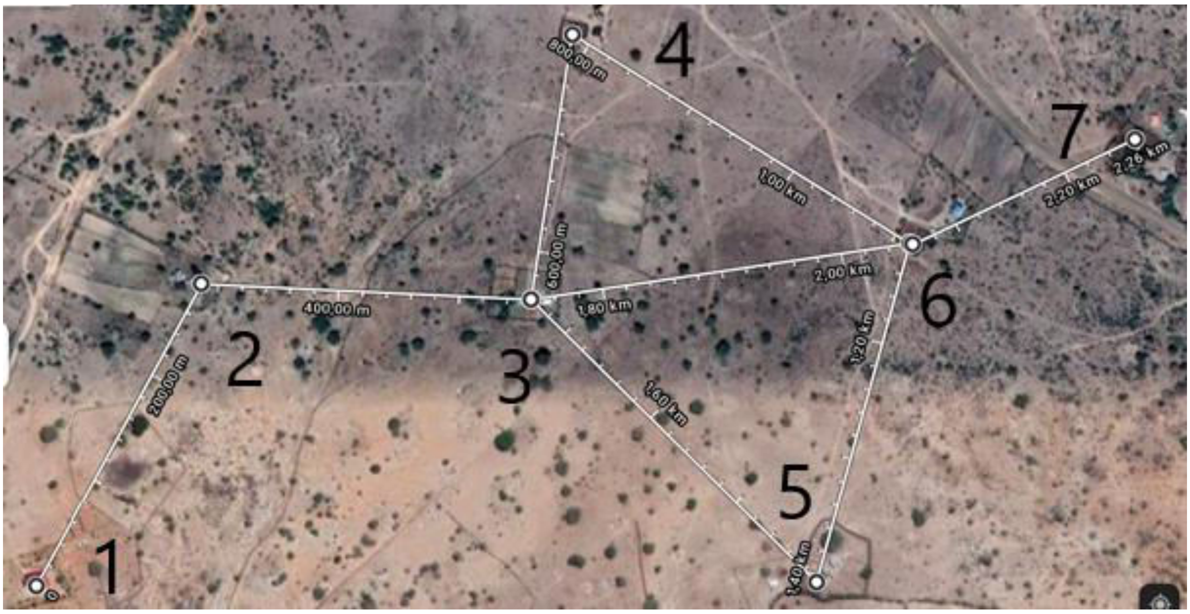

Figure 37. Satellite image of a seven-building cluster in Konza. The image shows a cluster of seven buildings in Konza. A potential connection shape, with distances, is illustrated. The buildings are numbered one to seven. (Google maps, 2021b)

To give some perspective, the distance from household one to household three is approximately 530 meters. The shortest possible transmission distance from household one to household seven is around 850 meters. Electricity exchanges would entail virtually all transmitted power being lost for certain exchanges. A potential solution to this could be a more intelligent exchange system which takes distances into account. For example, household one might be limited to only exchanging electricity with household two. Household two might only exchange electricity with household one and three. Household three has many more connection points and might exchange with four, five and six. Such a system could allow electricity to move along the system of households with modest transmission losses. To test whether such an exchange system would be successful, a simulation which takes different distances between separate households into account could be utilised in future research.

6.6 Feasibility of cable implementation

There are unaddressed challenges related to installation of the cables. The cables connecting the households must be laid, hung, or dug down over large distances. Geography is an important consideration here. Rural villages are often dominated by farmland, as can be observed in the satellite image in Figure 37. Cables stretched along the ground between households could get in the way of crops. They could also be at risk of being damaged by work in the field. Other hindrances such as roads create further difficulties. Moreover, cables laying unprotected on the ground could be disturbed by accidents or other unforeseen events.

To keep the cables out of the way, they could be either suspended in the air or dug down. Digging the cables down could be challenging as it would require interventions to the areas they cover. Crops, for example, may be disturbed by the process. A way around this could involve digging trenches for the cables so they can lay underground. If a road blocks the way however, digging a trench would not be a feasible solution. In this case hanging cables from pillars might be a more realistic solution. Both the burying and the hanging of cables could incur large costs. Costs of labour, transport and materials needed to implement these solutions would need to be considered.

6.7 Comparison of prices

To give some perspective on the costs of the intervention, the prices of the cables will be compared to the costs of the packages currently owned by Sunami customers in Konza. This should give some idea of whether the material costs are within a realistic price range for system owners. For the 300 m average distance used in Case 1 and 2, the cost of the cables from Henan Central Plain Cables and Wires amounts to 504 USD. That gives an average price of 168 USD per household.

Owners of the Sunami basic package pay a deposit of 27 USD and a daily lease of 0.90 USD for 1200 days. Owners of the TV package pay a deposit of 63 USD and a daily lease of 1.17 USD for 1200 days (Sunami Solar). With the inflation rate in Kenya for 2021 of 6%, this amounts to net present values of 919 USD and 1222 USD (Central Bank of Kenya, 2021).

The net present values of the package prices are presented with the per-household cost of cable material in Table 14. The price comparison demonstrates that an average price of 168 USD for cable materials is within a realistic price range for solar home system owners. However, there is some uncertainty associated with the prices of the cables. As mentioned in Chapter 4.2, cables sold by Nexans are around four times more expensive than the chosen cables. The large variation in market price means that the cost of cables at any time is uncertain.

Table 14. Net present values of costs for Sunami packages and electric cables.

Product	**Net present value of total costs (USD)**
Basic package	918
TV package	1222
300 m cable	168

Other expenses could also increase the total costs of the intervention. Technicalities around the connection of cables to the charge controllers have not been considered. Neither have potential modifications to or replacements of the charge controller in order to manage the electricity flows. Moreover, extra equipment could be necessary for the measurement of charge states in batteries. Subsequently, the cost of cable installation must also be accounted for. This includes wages and transportation for engineers who would install the equipment. The total price of the solar home system connection is uncertain.

6.8 Individual incentives for connection

As demonstrated in Case 2, some of the improvements to electricity access could be attributed to the average difference in demand between TV package and basic package owners. The results from Case 1 and Case 3 showed that owners of the basic packages did not benefit individually from the connection, despite the overall improvements for the whole system. For example, basic package owners are subjected to more unserved demand after connection than they were before. This means that homeowners with lower electricity demand might need incentives to participate in connection of solar home systems. A possible solution to this may be payment for electricity exchanges. Further investigation into how asymmetries in electricity deliveries and receptions may be compensated for could be made in future research.

7 Conclusion

The goal of the study was to examine whether connected solar home systems could provide homeowners in off-grid areas with improved electricity access. Previous studies have suggested that cost-effective improvements to electricity access in many rural areas of Africa are dependent on off-grid solutions. Solar home systems and microgrids are two solutions that have been implemented in many of these areas. For this study it was hypothesised that an intermediate of these solutions could be an effective addition in villages where solar home systems are already implemented. The intermediate involved using cables to connect the existing solar home systems so that variations in electricity consumption could be evened out through exchanges.

In Case 1 connection of three households was simulated and improvements to electricity access were observed. Battery charges were lifted for households going through periods of electricity shortages. This at the expense of households with high battery charges in the same periods. The amount of unserved demand, electricity that was unavailable at times when homeowners wished to consume, was reduced by 17%. One factor could explain why the reduction was limited to 17%. Seasonal variations in electricity generation were larger than variations in electricity demand. The seasonal variations also affected each household uniformly. This meant that a period of low electricity generation did not only have a larger impact on the battery charges than electricity demand did. It also affected all battery charges at the same time. With all households experiencing electricity shortage, transfers were unhelpful. Likewise, a long period of high electricity generation would lift all battery charges to the limit of the battery capacity. With all households encountering full battery capacities simultaneously, exchanges of excess electricity had limited effects.

The household with the basic package used less electricity than the households with TV packages. This suggested that some of the positive effects of connection could be attributed to overall differences in electricity demand, rather than variations. To investigate this, the simulation was run again for three TV package households in Case 2. As predicted, the unserved demand was reduced by a lower proportion, 4.5%, when all households were equipped with TV packages. This suggested that some of the benefits observed in Case 1 could be attributed to the differences in electricity demand between separate packages rather than the evening out of demand variations. This raises questions regarding incentives to participate in the system for individual homeowners. A homeowner with a lower electricity demand may not see any reason to participate if it is his or her neighbours who reap all the benefits. A potential solution to this may be introduction of payment for electricity exchanges.

In Case 3, the simulation was run for a system of six connected households. This was expected to improve the benefits of exchange as there are more opportunities to even out demand variations with a larger number of households. Results from the simulation showed that electricity access was improved. Battery charges were clearly affected by the exchanges and the amount of electricity demand left unserved was reduced by 33%. This is almost double the reduction from Case 1. These results indicate that for increasing numbers of households the benefits of connecting solar home systems grow.

Several uncertainties influence the reliability of the results. The electricity generation used for the simulation was estimated using a slope angle for the solar panel which was not optimal with regards to year-round electricity generation. With an optimised slope angle, higher electricity generation would be expected. Furthermore, the time zone that PVGIS generation data was presented in was not determined. If it is the case that UTC time was used, the results are influenced. Moreover, electricity demand data exclusively took day-to-day variations into account. Even though assumed demand was based on relevant literature, it could potentially vary in ways not considered for this study. Some errors in the simulation were also identified. This led to inaccurate data when deliveries of electricity were displayed. In addition, there is much uncertainty linked to the estimation of costs. This is due to unanswered questions regarding how cables should be optimally placed between houses without disturbing crops, roads, or other hindrances. Costs of transport, labour and material were also uncertain.

Several suggestions for future research on this topic are warranted. The reason electricity transfers could not produce higher improvements to electricity access was that seasonal variations in generation outweighed day-to-day variations in demand. To test this further, future researchers could experiment with households that have larger demand variation or areas that have smaller seasonal variation. This could reveal how much these variations affected results. In Case 3 the simulation was less accurate with regards to transmission geography. 300-meter distances were assumed constant, even though transmission distances would be larger for six households in the case village. Each household was also assumed to have a connection point to every other household, which is not realistic in the case village. To further test the utility of increasing numbers of connected households, a more sophisticated simulation could be utilised in future studies, that takes transmission distances and connection points into account. Also, further investigation of incentives for individual homeowners should be made. A form of compensation for deliveries of electricity may be necessary for the intervention to benefit homeowners on the individual level.

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Appendix

Code for simulation of independent solar home systems

```
#Import hourly electricity generation:
data = pd.read_excel (file1)
G = pd.DataFrame(data, columns= ['E'])

#Import hourly demand (kwh):
data = pd.read_excel (file2)
L1 = pd.DataFrame(data, columns= ['Total'])

data = pd.read_excel (file3)
L2 = pd.DataFrame(data, columns= ['Total'])

data = pd.read_excel (file4)
L3 = pd.DataFrame(data, columns= ['Total'])

def sim(G,L1,L2,L3, Qmax = 1.2, Qmin = 0.36): #Qmax and Qmin are batteries
                                              #max and min capacity
    nt=len(G)
    t = np.linspace(1,nt,nt)
    n = 3                                     #Defines number of batteries
    G = np.dstack([G.P.values/1000]*n).squeeze() #Generated electricity, G.
    L = np.dstack((L1,L2,L3)).squeeze()          #Electricity demand, L.

    Qi = np.zeros((nt,n))          #Battery charge
    Qi[0,:]= Qmax                  #Charges begin at Qmax
    unserved = np.zeros_like(Qi)   #Unserved demand
    excess = np.zeros_like(Qi)     #Excess electricity
    charge_loss = 0.1              #Battery charge and discharge loss

    #For each hour of the year, battery charge is updated accordingly:
    for h in range(1,len(t)):
        dE = G[h,:]- L[h,:]
        Qi[h,:] = Qi[h-1,:] + dE*(dE>=0) *(1-charge_loss) + dE*(dE<0) * (1+charge_loss)

        #Logging excess electricity and unserved demand:
        excess[h, Qi[h,:] > Qmax] = G[h, Qi[h,:] > Qmax] - L[h, Qi[h,:] > Qmax]
        unserved[h, Qi[h,:] <= Qmin] = L[h, Qi[h,:] <= Qmin]

        Qi[h, Qi[h,:] >= Qmax] = Qmax  #Updates charge to maximum battery capacity
        Qi[h, Qi[h,:] <= Qmin] = Qmin  #Updates charge to minimum battery capacity

    return t, Qi, unserved, excess,G, L,

t,Qi,unserved,excess, G, L = sim(G,L1/1000,L2/1000,L3/1000)
#Demand is divided by 1000 to convert from Wh to kWh
```

Code for simulation of connected solar home systems

```
#Import hourly generated electricity:
data = pd.read_excel (file1)
GO = pd.DataFrame(data, columns= ['E'])

#Import hourly demand:
data = pd.read_excel (file2)
L1 = pd.DataFrame(data, columns= ['Total'])

data = pd.read_excel (file3)
L2 = pd.DataFrame(data, columns= ['Total'])

data = pd.read_excel (file4)
L3 = pd.DataFrame(data, columns= ['Total'])

def sim(GO,L1,L2,L3, Qmax = 1.2, Qmin =0.36):#Qmax and Qmin are battery
                                             #max and min capacity
    nt=len(GO)
    t = np.linspace(1,nt,nt)
    n = 3                                    #Number of households
    G = np.dstack([GO.E.values]*n).squeeze() #Defines produced electricity, G.
    L = np.dstack((L1,L2,L3)).squeeze()      #Defines electricity demand, L.

    Qi = np.zeros((nt,n))                    #Battery charge
    Qi[0,:]= Qmax                            #Battery charges begin at Qmax
    unserved = np.zeros_like(Qi)             #Unserved demand
    excess = np.zeros_like(Qi)               #Excess electricity
    deliveries_low_charge = np.zeros_like(Qi)#Low-charge transfers
    deliveries_excess = np.zeros_like(Qi)    #Deliveries for excess electricity
    deliveries_total = np.zeros_like(Qi)     #Sum of all deliveries
    reception = np.zeros_like(Qi)            #Rreceived electricity
    t_loss = np.zeros_like(Qi)               #Transmission loss

    charge_loss = 0.1
    discharge_loss = 0.1
    R = 1.68*10**-8        #Resistivity of copper
    length = 300           #Length of cables
    A =  6*10**-6          #Cross sectional area of cables
    V  = 12                #System voltage

    for h in range(1,len(t)):
        low = (Qi[h-1,:] <= 0.6)  #Battery charges below 0.6
        n_low = low.sum()         #Number of batteries with charge below 0.6

#If any batteries have charges below 0.6, the low charge transfer is activated.
#The transfer takes place if one or more other batteries have charges above 0.8.
#Low charge transfers are always 0.01 kWh in size.
        if n_low > 0:
            enough = (Qi[h-1,:] >= 0.8)
            sources = enough
            sinks = low
            deliveries_enough = np.zeros_like(sources)
            deliveries_enough = enough *0.01
            supply = deliveries_enough.sum()/n_low
            cable_loss = (1-(supply*1000*R*length/(A*V**2)))
            supply_with_losses = supply*cable_loss*(1-discharge_loss)
```

```
#If no charges are below 0.6, the code instead checks for excess electricity:
        else:
            full = (Qi[h-1,:] >= Qmax) & (G[h,:] > L[h,:]) #Defines a full battery
            not_full = ~full
            sources = full
            sinks = not_full
            deliveries_enough = np.zeros_like(full)
            n_not_full = not_full.sum()  #Number of batteries that are not full

#If one or more other batteries have spare capacity, excess transfers are activated.
#There is no discharrge loss for this transfer as electricity is delivered directly
#from the solar panel.
            if n_not_full > 0:
                surplus = G[h,full]-L[h,full]
                deliveries_full = surplus.sum()/full.sum()
                supply = surplus.sum()/n_not_full
                cable_loss = (1-(supply*1000*R*length/(A*V**2)))
                supply_with_losses = supply*cable_loss
            else:
                supply = 0
                deliveries_full = 0

#Battery charge is updated:
        total_inn = G[h,:] + supply_with_losses * sinks
        total_out = L[h,:] + deliveries_enough
        dE = total_inn - total_out
        Qi[h,:] = Qi[h-1,:] + dE*(dE>=0) * (1-charge_loss)
                  + dE*(dE<0) * (1+discharge_loss)

#Logging of excess electricity, unserved demand, deliveries, receptions and
#transmission losses:
        excess[h, Qi[h,:] > Qmax] = G[h, Qi[h,:] > Qmax] - L[h, Qi[h,:] > Qmax]
        excess[excess<0] = 0
        unserved[h, Qi[h,:] <= Qmin] = L[h, Qi[h,:] <= Qmin]
        deliveries_low_charge[h,sources] = deliveries_full
        deliveries_excess[h,:] = deliveries_enough
        deliveries_total = np.add(deliveries_low_charge , deliveries_excess)
        reception[h,sinks] = supply_with_losses
        t_loss[h,:] = (1-cable_loss)

        Qi[h, Qi[h,:] >= Qmax] = Qmax #updates battery charge to maximum value
        Qi[h, Qi[h,:] <= Qmin] = Qmin #updates battery charge to minimum value

    return t, Qi, unserved, excess, deliveries_low_charge, deliveries_excess,
           deliveries_total, reception, t_loss, G, L

t, Qi, unserved, excess, deliveries_low_charge, deliveries_excess, deliveries_total,
reception,t_loss, G, L = sim(GO,L1/1000,L2/1000,L3/1000)
#L divided by 1000 to convert from Wh to kWh
```

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