UPPSALA UNIVERSITET

UPTEC STS
Examensarbete 30 hp
Maj 2022

Load profile assessment and techno-economic analysis of decentralized PV in Addis Ababa, Ethiopia

Bezawit Tsegai

Civilingenjörsprogrammet i System i Teknik och Samhälle

UPPSALA
UNIVERSITET

Load profile assessment and techno-economic analysis of decentralized PV in Addis Ababa, Ethiopia

Bezawit Tsegai

Abstract

Access to electricity might in some parts of the world seem evident. However, Ethiopia struggles to provide its large and growing population with electricity. Although around all the households in the capital Addis Ababa are connected to the electricity grid, the grid is unreliable and results in daily outages. As the photovoltaic (PV) potential in Addis Ababa on the other hand is great, this thesis examines the feasibility and profitability of decentralized PV adoption with battery and hydrogen storage respectively. Based on an ongoing construction project in the sub-city Yeka, Addis Ababa, a reference building was used to simulate the PV systems with battery and hydrogen storage. Furthermore, a load profile based on time-use diaries was developed and used in the simulations, as data on household electric consumption was non-existent. The load profile resulted in an average daily use of 1341 kWh and a 165 kW peak for all of the 130 apartments in the reference building. The results of the simulations indicated that neither of the two systems were feasible nor profitable to implement on the reference building. The PV-system with battery storage was cheaper and required less installed PV capacity, however the cost of energy for both systems was significantly higher than the current cost of energy in Ethiopia. The installed PV capacity of both systems exceeded the maximum capacity that was feasible on the reference building.

Teknisk-naturvetenskapliga fakulteten

Uppsala universitet, Utgivningsort Uppsala

Handledare: Viktoria Walldin, Marja Lundgren & Rickard Nygren Ämnesgranskare: Joakim Munkhammar

Examinator: Elísabeth Andrésdottír

Populärvetenskaplig sammanfattning

Skapandet av motståndskraftiga, klimatvänliga energisystem har under de senaste åren fått ökad betydelse i samband med klimatkrisen (Mertens, 2018). Samtidigt ökar faktorer som växande befolkning, urbanisering och industrialisering efterfrågan på el och betonar behovet av ren, förnybar elproduktion (IEA, 2022). Tillgång till el är dock inte en självklarhet. År 2010 definierade World Economic Forum (2010) termen "energifattigdom" som bristen på tillgång till hållbara, moderna energitjänster och -produkter. Det finns för närvarande ingen universell definition av begreppet, men FN (2010) beskriver tillgången till el som avgörande för samhällsutveckling. Mer än en miljard människor i världen saknar dock tillgång till el, med den största andelen i Afrika, söder om Sahara (OurWorldData, 2019).

Etiopien, som är beläget i Östafrika, är det näst mest befolkningsrika landet i Afrika, med en befolkning på över 120 miljoner (UNFPA, 2022). Landet har rikliga tillgångar till förnybara energikällor, men trots detta är befolkningen drabbade av allvarlig elbrist och begränsningar i elnätet (ITA, 2021). Mindre än hälften av befolkningen har tillgång till el och 11 % av dessa är decentraliserade lösningar (IEA, 2019).

Under de senaste åren har landet genomgått stora utvecklingar och den redan stora befolkningen växer (ITA, 2021). Urbanisering, särskilt i huvudstaden Addis Ababa, ökar och förväntas fördubblas under det kommande decenniet (World Bank Group & GFDRR, 2015). Till skillnad från resten av landet är den beräknade eltillgången i huvudstaden cirka 98 %, då nästan en miljon hushåll är anslutna till elnätet. Strömavbrott förekommer dock ofta. Data från januari 2015 indikerar att det i genomsnitt förekom omkring 42 avbrott per vecka (World Bank Group & GFDRR, 2015).

Elnätet både i Addis Ababa och resten av Etiopien står inför många svårigheter. För det första är nätverket åldrat och överbelastat. För det andra är transmissionsledningarna och distributionssystemet, tillsammans med transformatorstationerna, i behov av reparation, förstärkning och utbyggnad. Dessutom är effektiviteten låg och förlusterna höga. Det nuvarande elnätet kan följaktligen inte tillhandahålla effektiv och pålitlig el till sina användare. Eftersom elbehovet för bostäder förväntas öka avsevärt under de kommande åren kommer detta att påverka möjligheten att möta framtida elbehov (World Bank Group & GFDRR, 2015).

För att överkomma bristerna i elnätet och möta ellastbehovet undersökte detta examensarbete möjligheten till att använda solceller för hushållselproduktion. Solceller beskrivs spela en särskild roll i övergången till miljövänliga energikällor, då omvandling av solljus till elektrisk energi möjliggör utsläppsfri elproduktion (Mertens, 2018). Då solcellssystem även kan byggas “off-grid”, det vill säga inte att de inte är kopplade till elnätet, möjliggjorde detta en undersökning av decentraliserad solenergi med lagring som lösning för det bristande elnätet i Addis Ababa.

Tillsammans med White Arkitekter och ett lokalt byggföretag i Addis Ababa undersöktes genomförbarheten och lönsamheten för två olika solcellssystem, ett med batterilagring och ett med vätgaslagring. Detta genom en fallstudie, i vilken en referensbyggnad användes som utgångspunkt. Då data på hushållselanvändning saknades togs även en lastprofil initialt fram, genom en undersökning av tidsanvändning i etiopiska hushåll.

Ellastprofilen som togs fram för referensbyggnaden resulterade i ett dagligt behov på 1341 kWh samt en effekttopp på 165 kW. Resultaten visade dock att de två solcellssystemen varken var tekniskt möjliga att implementera på referensbyggnaden samt inte var ekonomiskt lönsamma. Takytan som var tillgänglig för solceller räckte inte för att möta lastbehovet och energikostnaden för de båda systemen var fem respektive 12 gånger högre än den nuvarande energikostnaden.

För framtida studier skulle en undersökning av exempelvis en mindre byggnad med mindre lastbehov vara lämplig. Användning av decentraliserad solenergi med lagring skulle därutöver också kunna undersökas i mer avlägsna områden, där hushållen inte har tillgång till elnätet, vilket skulle kunna resultera i större lönsamhet. Då elproduktion i Etiopien idag härstammar från förnybara källor samt solinstrålningen i landet är väldigt hög, skulle följaktligen användningen av solfångare för uppvärmning av tappvarmvatten också vara intressant att undersöka.

Acknowledgements

This thesis was conducted for Uppsala University in collaboration with White Arkitekter. Further, a collaboration with SNABB Sustainable Construction, a local construction company in Addis Ababa, was realized through White Arkitekter.

Firstly, I would like to thank my supervisor at Uppsala University, associate professor Joakim Munkhammar, for helping and guiding me throughout the thesis. His support has been very appreciated and severely improved the quality of the study.

Secondly, I would like to thank my supervisors at White Arkitekter, Viktoria Walldin, Marja Lundgren and Rickard Nygren. Their support and input have brought many new and important perspectives to the study, improving the overall quality of the study.

Lastly, I would like to thank Anteneh Tadesse at SNABB Sustainable Construction for allowing me to use their current project as a case study and for providing essential input regarding the project and the Ethiopian context in general.

Stockholm, 2022-05-24

Bezawit Tsegai

Table of contents

List of Figures

List of Tables

Abbreviations

AC	Altering current
DC	Direct current
CoE	Cost of Energy
DoD	Depth of Discharge
GERD	Grand Ethiopian Renaissance Dam
GHI	Global Horizontal Irradiance
GoE	Government of Ethiopia
HOMER	Hybrid Optimization of Multiple Energy Resources
ICC	Initial Capital Cost
NPC	Net Present Cost
O&M	Operation and Maintenance
PEM	Proton Exchange Membrane
POWER	Prediction Of Worldwide Energy Resources
PV	Photovoltaics
P2H2P	Power to Hydrogen to Power

1. Introduction

Creating climate-resilient energy systems has in the past years become important as the awareness of the climate crisis has increased (Mertens, 2018). Simultaneously, factors such as growing population, urbanization and industrialization are increasing the electricity demand and stressing the need for clean, renewable electricity generation (IEA, 2022). However, access to electricity is not apparent. In 2010, the World Economic Forum (2010) defined the term "energy poverty" as the lack *of access to sustainable, modern energy services and products*. There is currently no universal definition of the term, but the UN (2010) describes access to electricity as vital for the development of society. More than one billion people in the world lack access to electricity, with the largest share in Sub-Saharan Africa (OurWorldData, 2019).

Ethiopia, located in East Africa, is the second most populated country in Africa with a population of over 120 million (UNFPA, 2022). Despite being one of the poorest countries in the world, the country has abundant access to renewable energy resources. However, Ethiopians are severely affected by electricity shortages and limitations in the electrical power grid (ITA, 2021). Less than half of the population has access to electricity, whereas 11% of these are decentralized solutions (IEA, 2019).

In the past years, the country has undergone major developments and the already large population is growing (ITA, 2021). Urbanization, especially in the capital Addis Ababa, is increasing and is foreseen to double in the coming decade (World Bank Group & GFDRR, 2015). Contrary to the rest of the country, the estimated access rate to electricity in the capital is around 98%, as almost one million households are connected to the power grid. However, outages and interruptions occur frequently. Data from January 2015 implies that there were around 42 interruptions per week on average (World Bank Group & GFDRR, 2015).

The electricity grid in both Addis Ababa and the rest of Ethiopia face many difficulties. Firstly, the network is aged and overloaded, with some segments having been in operation for over 40 years. Secondly, the transmission lines and distribution system along with the substations are in need of repair, reinforcement and expansion. In addition, the efficiency is low and losses high. The present grid is consequently unable to provide efficient and reliable electricity to its users. Seeing that the residential load demand is expected to increase significantly in the upcoming years, this will affect the ability to meet future load demand as well (World Bank Group & GFDRR, 2015).

To overcome the shortages in the electricity network and meet the residential load demands, this thesis will examine the possibility of using photovoltaics (PV) for household electricity generation. Photovoltaics is described as playing a particular role in the transitioning to environmentally-friendly energy sources, as it enables emission-free conversion of sunlight into electrical energy (Mertens, 2018). Since PV systems can be constructed off-grid, i.e not connected to the electricity grid, this allows an examination of decentralized PV with storage as a solution to the electrical shortcomings.

Together with the Swedish architecture firm White Arkitekter and a local construction company in Addis Ababa, both working with sustainable development, the feasibility and profitability of decentralized residential PV in Addis Ababa will be examined through a case study.

1.1 Aim and research questions

The purpose of the thesis is to examine if the adoption of decentralized PV with storage can operate as an alternative to the current electricity system in Addis Ababa and generate reliable electricity for households. A techno-economic analysis will be performed, by modeling and optimizing different PV systems on a residential reference building. Two different scenarios will be studied; a PV system with battery storage and a hydrogen storage system. This is done in order to find an optimal solution where the residential electrical load demand is met, with regards to technical feasibility and economic factors.

As there is a lack of data covering electrical household consumption in both Ethiopia and Addis Ababa, a synthetic electrical load profile of the studied building will be developed, which will be done through a time-use survey. The load profile will then be used to simulate the different PV systems.

To fulfill the purpose, this thesis aims to answer the following research questions:

- What is a reasonable electricity use for residential households in Addis Ababa?
- What are the possibilities to design an off-grid PV system with storage in Addis Ababa, where the load demand is met?
- What is the economic feasibility of implementing an off-grid PV system in Addis Ababa, where the load demand is met?

1.3 Limitations and delimitations

Some of the main challenges and limitations of the study have been the lack of data. Data regarding the availability and costs of components are scarce and difficult to find, which will be elaborated further in the study. In addition, data on household electrical use is not available, which resulted in developing a synthetic load profile.

The delimitations of the study concern both the load profile and technical systems. The load profile was delimited to only include electrical appliances in the households. Electrical use for hot water was excluded. In addition, basements, laundry rooms, elevators, stairwells, ventilation, pumps and similar systems requiring electricity were not considered. In addition, a demographic delimitation was implemented in the time-use survey as state officials and/or high-income earners are considered in the real construction project. Hence, an attempt was made to take this social group into account when constructing the electric load profile. Even though the study examines multi-family houses and not villas and terrace houses, this has not been considered in the time-use survey. This is elaborated in section 3.2.2.

Furthermore, the technical system delimitations mainly concern the exclusions of electrical aspects and other components that are needed to implement the systems in reality. In order to keep the study within master thesis limits, the systems were simplified to only include the main components. Additionally, the technical delimitations concern the components in the systems as well. There are several different materials and chemical structures of the components. Some of the types of components that have been used in the simulations are monocrystalline silicon cells for the solar panels, lithium-ion batteries and a proton-exchange membrane (PEM) electrolyzer. In addition, temperature effects on the PV modules and shading are not considered.

1.4 Disposition

The paper is divided into seven chapters. The first chapter introduces the studied topic and the aim of the study. The second chapter provides the reader with a background, focusing on energy security and the Ethiopian electricity system, some basic solar cell theory and the construction project. In the third chapter, the methodology is presented, beginning with a brief overview of the execution of the study. The creation of the load profile and implementation of the time-use survey is then presented. Thereafter, the software HOMER is introduced, followed by its inputs, the economic analysis and calculations of the PV power output. Then the sensitivity analysis is presented. Chapter 4 presents the data and assumptions used in the study. In chapter 5, the results are presented, beginning with the load profile, then the two different scenarios and lastly the sensitivity analysis results. Chapter 6 discusses the results, sources of errors and improvements. Lastly, chapter 7 presents the conclusions and suggestions for future research.

2. Background

In this chapter, background information and context are provided in order to understand the report but also why it is important to examine this topic. It is divided into three sections. The first covers energy security and the Ethiopian electricity system. Secondly, the basics of solar energy are presented and lastly, the case study, being the Sahlete Mehret Residential Compound project.

2.1 Energy security

Energy security is, on the contrary to energy poverty, a term referring to secure energy access. The term is complex, as it is a broad concept that can include a variety of perspectives. There are several definitions of the term and different literature specifies different focus areas, goals and solutions (Jakstas, 2020). Jakstas (2020) describes energy security as an abstract idea, rather than a policy or term. The IEA (2022) defines energy security as *the uninterrupted availability of energy sources at an affordable price*, while the UN (2010) defines it as *access to clean, reliable and affordable energy services for cooking, heating, lighting, communication and other productive uses*.

Access to energy is described as fundamental, since most economic, environmental and development issues in the world today depend on energy (UN, 2010). The UN (2010) explains that developing countries in particular need to increase access to reliable and modern energy services in order to improve the living conditions and health of the population. For instance, lack of electricity leads to cooking with wood and coal, which affects the health. This results in millions of early deaths each year and disproportionately affects women and children (UN, 2010). Furthermore, a basic level of electricity access that includes lighting, for instance, can provide substantial benefits to a household, including cost savings (Meles, 2020).

2.1.1 The Ethiopian electricity system

The Government of Ethiopia (GoE) has in the past years been striving to improve and increase both the electrical production and access, as more than half of the population currently lacks electricity access. In 2017, the GoE launched an Electrification Program that outlines a plan to reach universal access by 2025, with 35% of the solutions off-grid (IEA, n.d). The current electricity generation is dominated by hydropower, corresponding to approximately 90% of the installed production capacity. The remaining 10% consists of wind and thermal sources (ITA, 2021). This implies that just about all of the produced electricity in Ethiopia derives from renewable sources (Our World Data, 2021). In accordance with the aim of improving the electrical situation, a new hydropower plant, the Grand Ethiopian Renaissance Dam (GERD), is being constructed in the Blue Nile. It is expected to be in full operation by 2030 (NE, 2020). The hydropower plant has an installed capacity of 6.45 GW and will produce around 15 000 GWh yearly, making it the largest hydropower plant in Africa (NE, u.d).

The production potential of electricity is great, as the country has abundant access to renewable energy resources (ITA, 2020). The GoE has in recent years begun diversifying the generation mix with other sources such as solar, wind and geothermal, since the hydropower-dominated systems from times have been hit hard by drought and therefore been producing far below capacity. The production mix aims to create a more climate-resistant power system (ITA, 2021). Solar power is, however, not very prevalent at the moment. In 2019, the solar power generation was around 0,02 TWh, which corresponds to 0,14% of the total electricity production (Our World Data, 2021). Yet, the PV power potential is high. In Figure 1, the PV power potential is illustrated.

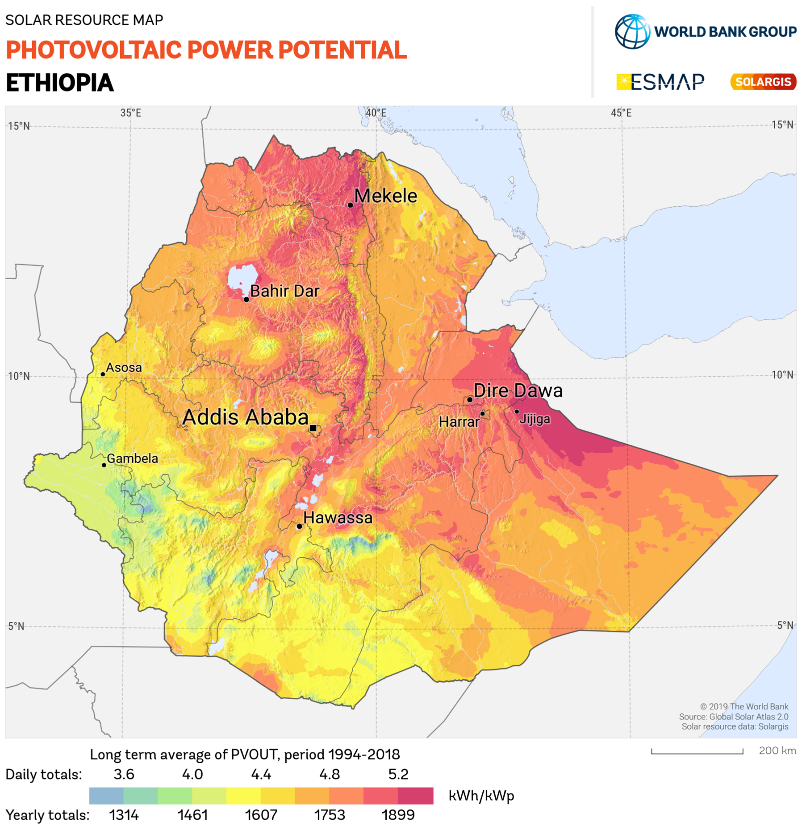

Figure 1. PV power potential in Ethiopia (The world bank group, 2019). The map was obtained from the "Global Solar Atlas 2.0, a free, web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP).

The World Bank Group (2020) explains that high-potential countries, such as Ethiopia, tend to have low seasonality in solar photovoltaic output, resulting in the generated electricity being relatively constant between different months of the year. In addition, Ethiopia has many elevated regions, particularly around the capital Addis Ababa, which has an altitude of around 2 500 m (Topographic map, n.d). High altitudes result in low temperatures, which in turn increases the efficiency of the PV cell (Mertens, 2018), making Addis Ababa a favorable location for solar power.

2.1.2 Reliability in the Ethiopian electricity system

Although Ethiopia has increased both electricity generation and access to electricity in recent years, many of those connected to the grid experience frequent and long hours of power outages. Access to electricity in developing countries has been highly discussed and noticed throughout the years, whereas the reliability, which is part of both the IEAs and UNs definition of energy security, has not. While around 1.5 billion humans in the world have no access to electricity, up to a billion more only have access to unreliable electricity networks (Meles, 2020).

As a result of economic and population growth, industrialization and rural electrification, the electrical load demand in Ethiopia has been increasing significantly, which in turn has led to the power system facing more challenges (Tikenu & Worku, 2018). Power outages and selective disconnection are very common, as the country struggles to serve the large population. Selective disconnection is intentional shutdown of electricity in parts of a power distribution system to prevent the system from overloading when demand strains the system's capacity (ITA, 2021).

In a study made by Tikenu & Worku (2018) on the *Identification of system vulnerabilities in the Ethiopian electric power system,* it was found that the most severe outages occured where the high load centers, as Addis Ababa, interconnected with the rest of the regional power systems. The most vulnerable buses of the network were also mainly found at the high load centers. Consequently, the population in the capital, where the share of connections to the grid is around 98%, experience daily interruptions and outages (World Bank Group & GFDRR, 2015). Data from the Ethiopian Electric Utility for 2015-2016 shows an average blackout duration of 1h and 9 min at the distribution lines level in Addis Ababa. The main reasons behind the recurring unscheduled power outages are the poor physical condition and low capacity of the transmission and distribution lines. However, scheduled and forced blackouts due to shortages in supply are as mentioned common as well (Meles, 2020). These have been widely reported by the National Load Dispatch Center of Ethiopia, though scientific publications are not available (Tikenu & Worku, 2018).

Furthermore, technical issues and low network capacity creates delays of new connections, resulting in a backlog of people who have submitted a request for connection in Addis Ababa. One of the main bottlenecks for electricity access expansion is the difficulty to mobilize financing. The aforethought rapid growth in population, urbanization and GDP growth will require an increase in generation capacity, and an efficient transmission and distribution system. Severe infrastructure developments are required in order to provide reliable electricity supply, which will be costly and take time (World Bank Group & GFDRR, 2015).

Studies have shown that unreliable electricity access affects socio-economic well-being and limits daily life. Meles (2020) has in *Impact of power outages on households in developing countries: Evidence from Ethiopia* identified some of the effects that power outages have on urban households in Ethiopia. One major consequence is increased costs, as additional expenditures are spent on alternative energy sources, such as candles, kerosene, charcoal, firewood, liquefied petroleum gas (LPG) and standby diesel generators. Some social effects are loss of leisure time, fear of walking in unlit areas and inconvenience of using alternative energy sources. In addition, alternative energy sources can, as mentioned, have severe effects on health due to indoor pollution, and negatively impact the environment (Meles, 2020). In summary, it is important to find solutions for the unreliable electricity system in both Addis Ababa and Ethiopia.

2.2 Basic solar energy theory

For further understanding of the technical aspects of the study, basic solar energy theory is described in this section, starting with solar radiation, followed by solar cells, modules and other components and lastly off-grid systems and the storage components batteries and hydrogen.

2.2.1 Solar radiation

Solar energy refers to energy extracted from the sun's radiation and includes both heat and electricity generation (Vattenfall, u.d). Electricity is generated with the use of photovoltaic systems. As solely photovoltaics (PV) are examined in this study, solar energy refers to photovoltaics when further mentioned.

The fundamentals of photovoltaics are the dependence on sunlight. The sun releases energy in the form of radiation into space, which Earth then receives in small fractions. When sunlight passes the atmosphere of Earth, some of the radiation penetrates the atmosphere, while some is reflected. Once passing into Earth, some of the light is absorbed or scattered by particles in the air. Thus, Earth only receives 61% of the original extraterrestrial radiation directly from the sun. However, the scattering of light contributes with another type of radiation, called *diffuse radiation.* The total radiation incident on Earth, global radiation, is then the sum of the *beam* and *diffuse radiation*. In the planning stage of photovoltaic use, it is necessary to obtain data on the global radiation of the site, in order to estimate the yield of a planned use (Mertens, 2018).

2.2.2 Solar cell technology

The basis of converting solar radiation into electricity is the use of *solar cells*. Solar cells are devices usually consisting of semiconductors with two layers of opposite conductivities. To convert incident sunlight into electricity, solar cells exploit the photovoltaic effect, which can be described as the appearance of a potential difference between the opposite layers under the effect of a light stream. When the semiconductor is exposed to light, the photons are absorbed into the cell, which generates free electron pairs. The electrons then flow through the material as an electrical current. The generated current is direct current (DC) and is extracted through conductive metal contacts (Mertens, 2018).

In order to make solar cells manageable for power supply, the cells are assembled and integrated into *solar modules* or *panels*. The solar modules can be connected in series or parallel, which mostly affects the output in the case of shading (Mertens, 2018). Shading effects will however not be considered in the study as the solar panels are not affected by shadow in the reference case. In addition, solar modules are, as mentioned, affected by temperatures. Higher temperatures decrease the voltage output and then in turn the power output (Mertens, 2018). As Addis Ababa is at a high altitude and therefore has lower temperatures, the effects on the cell performance are overlooked in this study.

In order to generate solar power, modules are connected in so-called *strings* or *arrays*. Furthermore, the system usually requires an inverter, as most grids and loads run on alternative current (AC). The inverter converts the DC-produced current from the solar modules to AC. In order to maximize the yield of the solar system, the DC-to-AC ratio, being the ratio of DC capacity (solar modules) to the inverter's AC power rating, needs to be optimally adapted to each other (Mertens, 2018). The typical value for the DC-AC ratio is >1, usually around 1.2. (HOMER Pro [1], n.d).

PV systems can then be installed in many different structures and sizes. The most common form of a PV system is the pitched roof. On flat roofs, however, modules are usually tilted at a tilt β in order to achieve a higher annual yield. Depending on the location of the PV system, modules being mounted at a tilt β relative to the horizontal surface can enable receiving maximum solar irradiation (Mertens, 2018).

Another important factor for roof installations is the orientation of the panels, called the *azimuth* α. The azimuth is the angle between the vertical plane through the Earth and the latitude of the observer (Mertens, 2018). Solar panels in the northern hemisphere usually face the south, while the southern hemisphere faces the north (HOMER Pro [8], 2020). As the azimuth usually is measured from the southern point of the horizon to the west along the horizon, a south-oriented panel usually has an azimuth of 0° (Mertens, 2018). Additionally, the *albedo* ρ, being the ground reflectance, is another factor to be taken into account as it also contributes with solar radiation (HOMER Pro [9], 2020).

Eventually, residential solar systems can either be connected to the electricity grid (on-grid) or function on a stand-alone basis (off-grid), which will be explained further in the following section.

2.2.3 Off-grid

At early stages, PV systems were mainly constructed off-grid, meaning that they were separated from the electricity grid. Today, the use of PV is however dominated by grid-connected systems, so-called on-grid systems. Off-grid systems, or stand-alone systems, are on the other hand usually used in remote areas, where there either is no access to the electricity grid, the electricity grid being unstable or where the costs of connecting to the electricity grid are too high (Mertens, 2018). Stand-alone systems are mainly used in developing countries. With off-grid solutions, the length of delivery time and dependencies on the grid supplies can decrease. The time benefit is especially relevant when there are shortages in generation capacity, as is the case in many developing countries (UN, 2010).

However, due to solar power's inherent nature of intermittency, meaning that the power is unequally distributed both throughout a day and during a year, it is a challenge to match solar power generation with electricity use. This becomes more complicated as the electricity demand in households also differs during the day. The demand is usually higher in the mornings and evenings, when the solar electricity generation on the other hand usually is lower or non-existing (Mertens, 2018). This phenomenon is illustrated in Figure 2.

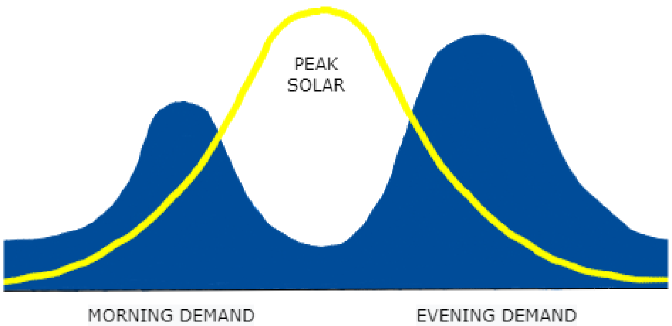

Figure 2. Illustration of electricity demand and hours of sunshine throughout a day, with electricity demand represented in blue. Figure created by the author, inspired by Solential Energy (2021).

The intermittency of solar power results in a need to store any surplus electricity produced, in order for it to be used during high demand periods (Carriveau, R. & Ting, D., 2016). Storage therefore becomes an essential element in order to achieve self-consumption of solar power for households, or a higher self-consumption rate, in off-grid systems. The PV modules in off-grid systems must produce enough electricity to supply the load of electrical appliances and cover inefficiencies in all included components of the system. With the use of storage, one can increase self-sufficiency up to 100% (Mertens, 2018). Some examples of storage solutions are batteries, hydrogen, diesel generator, flywheel, compressed air energy storage etc. (Carriveau, R. & Ting, D., 2016). As batteries and hydrogen are the considered storage solutions, these components will be elaborated in the following sections.

2.2.4 Battery storage

Batteries are devices that store energy for later use and therefore become fundamental in stand-alone renewable systems. Batteries are combinations of electrochemical cells that store chemical energy, which then can be converted into electrical energy and vice versa (Bekele, 2009). The core element of a battery is a cell. While a single cell can satisfy the power demands for smaller portable electronics, larger-scale applications require many cells having to be electrically integrated into modules. The modules are then packed into a battery. A battery's performance is typically characterized by the energy density, power capability, cycle life and safety (Zhang & Zhang, 2015).

There are many different battery chemistries and usage configurations. As batteries in solar systems tend to operate in so-called cycle operations, i.e where the battery goes through a charge and discharge cycle, so-called secondary batteries are used as these are rechargeable (Mertens, 2018). The most commonly used batteries in solar systems are lead-acid and lithium-ion batteries. Lead-acid batteries have a history of 150 years, while the first commercial lithium-ion battery was brought to the market in the 1990s (Mertens, 2018). However, lithium-ion batteries have dominated the market in the past years as a result of their high efficiency, long cycle life and high capacity, amongst other qualities (Lighting Global, 2019). Lithium-ion batteries will due to these characteristics be considered in this study.

Although lithium-ion batteries have been leading in recent years, there still exist safety hazards. Lithium-ion systems must be designed correctly to achieve good performance and avoid serious safety hazards that can result from battery cell abuse and improper operation. Overcharging, overheating, short-circuiting or damaging a charged lithium-ion battery can result in fire or explosion (Global lighting, 2019). In a stand-alone system with battery storage, a charge controller is essential in order to protect the battery from overloading. A charge controller is a device that regulates the input power from the solar modules with the right voltage and current to the battery (Mertens, 2018). However, safety risk aspects are beyond the scope of this study.

2.2.5 Hydrogen gas storage

Another storage solution for stand-alone solar systems is hydrogen, which has been mentioned as a possible storage carrier for the renewable energy sector (Mertens, 2018). Hydrogen is an energy carrier that can be produced from electricity and water. Vice versa, hydrogen can also produce electricity from water by a process called electrolysis. In this process, there are no pollutants generated or emitted (Bossel & Eliasson, n.d). The conversion between hydrogen and electricity is related to a process known as the "hydrogen fuel cycle", which begins and ends with water (Carriveau & Ting, 2016). In this type of system, a Power to Hydrogen to Power (P2H2P) system, there are three main components: an electrolyzer, a fuel cell and a hydrogen tank (Dawood m.fl, 2020). The P2H2P system is illustrated in Figure 3.

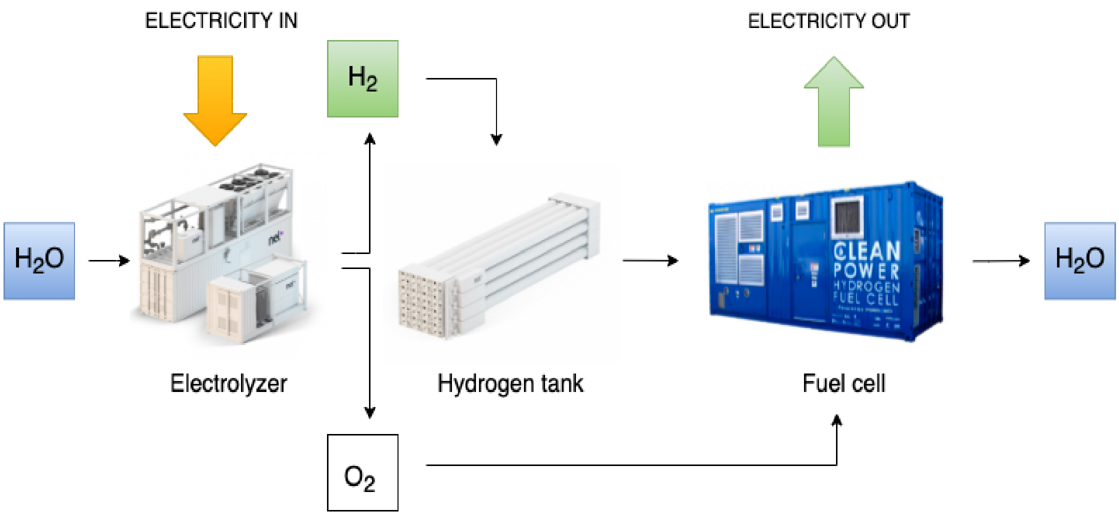

Figure 3. A Power To Hydrogen To Power (P2H2P) system. Figure created by the author: Electrolyzer (Nel Hydrogen US, 2022), hydrogen tank (Nel Hydrogen Denmark, 2022) and fuel cell (US Department of Energy, 2022).

As hydrogen is non-existing in its pure state in nature, it must be produced from, in this case, water (Bossel & Eliasson, n.d). Hence, the cycle begins with an electrolyzer splitting water into hydrogen and oxygen due to the passage of a DC current, i.e electrolysis (Carriveau & Ting, 2016). The process is clean as long as the electricity comes from a clean energy source, such as solar power. Thus, "green" hydrogen can be produced with renewable energy-powered electrolyzers. Accordingly, hydrogen may become an important link between renewable energy and chemical energy carriers. The process is however associated with considerable losses (Bossel & Eliasson, n.d).

The produced hydrogen is thereafter compressed and stored in a hydrogen tank. High-pressure gas steel cylinders are most commonly used to store hydrogen in gaseous form (Bossel & Eliasson, n.d), although it can be stored in liquid form as well (Hirscher, 2020). In order to convert the produced hydrogen into electricity, a fuel cell is used, which directly converts the chemical energy in hydrogen into electricity. The only byproducts of the process are water and potentially useful heat. The fuel-cell process is not only pollution free, but also generates electricity at higher efficiencies than traditional combustion technologies. While traditional combustion technologies have efficiencies of around 35%, a fuel cell can reach up to 60% (US Department of Energy, 2015).

Hydrogen storage for energy systems is however a relatively new field. Currently, it is commonly seen in the transportation field, with trains and ferries already operating in different countries throughout Europe (Hirscher, 2020). The potential of the clean energy carrier has however led to a worldwide development effort for hydrogen technology to power industrial, residential and transportation infrastructure (Bossel & Eliasson, 2020). Nonetheless, new, arising technologies face difficulties, as for example high costs (US Dep. of Energy, 2015), accessibility and scaling of components (Mertens, 2018). There are safety aspects as well, since hydrogen for instance is very flammable. If hydrogen spills or escapes, there are risks of fires and explosions (Rigas & Sklavounos, 2005) The safety aspects are however not considered in this study.

2.3 Case description

In order to investigate if an off-grid PV system with battery or hydrogen storage can replace the current electricity system and provide reliable electricity in Addis Ababa, a reference building as a reference case is used in the study. The building is a part of a current project in Addis Ababa, carried out by SNABB Sustainable Construction. The following description of the project has been provided by the owner of the company, Anteneh Tadesse.

SNABB Sustainable Construction is a construction company operating in Addis Ababa, Ethiopia. The company specializes in solving local problems within the Ethiopian context, such as poor energy, water, and waste management, delay in delivery of projects, low construction quality and ineffective construction management. The implementation of sustainable solutions and technologies is also highly prioritized (SNABB Sustainable Construction, n.d).

Currently, in the north-eastern part of the city, the company is working on a construction project together with the GoE and other companies. The area is called Yeka and is one of Addis Ababa's 10 sub-cities (Awoke, 2019). The sub-city has a population of around 370 000, which exceeds the carrying capacity of the area. Rapid urbanization in the area has resulted in housing shortages, amongst other issues, putting pressure on public utilities like electricity, education, water, transportation etc. (Awoke, 2019). With an area of around 170 000 sqm, owned by the GoE, the project aims to create a complete solution, with not only residential buildings but also a school, commercial center, restaurants etc. However, these are not considered in this study. In Figure 4, the area of the project is displayed.

Figure 4. An overview of the project area, highlighted in red (SNABB Sustainable Construction, 2022).

One of the goals of the project is both to minimize the need for electricity from the GoE, since it as previously described is unreliable, and build with high regards to sustainability. For example, waste incineration is intended to be used for hot water and cooking with gas. However, in this thesis cooking will be included in the use of electricity as the goal is to examine if solar power can meet the total load demand. Heating and cooling are not considered, as it is not commonly used in the capital. A part of the sustainability aspect, common laundry rooms will be in the basements. As drying takes a huge amount of electricity, large balconies will be constructed in order to enable air drying. Laundry is also not considered in the study, due to time and feasibility limitations.

To further describe the project, it is going to consist of 29 identical residential buildings, each with 13 floors (G+12). In each building, there will be 10 apartments per floor with four three-bedroom apartments, four two-bedroom apartments and two one-bedroom apartments. The targeted group of residents is state officials and/or high-income earners. In Figures 5 and 6, a prototype of a residential building is presented. In the real project, solar power has been considered, however not as a sole provider of electricity. In total, each residential building will have a roof area of 1250 sqm available for installing solar power. The school will have a rooftop area of 12 000 sqm and the commercial building of 8500 sqm, both also available for installing solar power. In this study, however, only the rooftop area of the residential building will be considered for installing solar power. The blueprint for the intended arrangement of the apartments on one floor is presented in Figure 7.

Figure 5. Prototype of the reference building (SNABB Sustainable Construction, 2022). Used with permission from the owner.

Figure 6. Prototype of the reference building (SNABB Sustainable Construction, 2022). Used with permission from the owner.

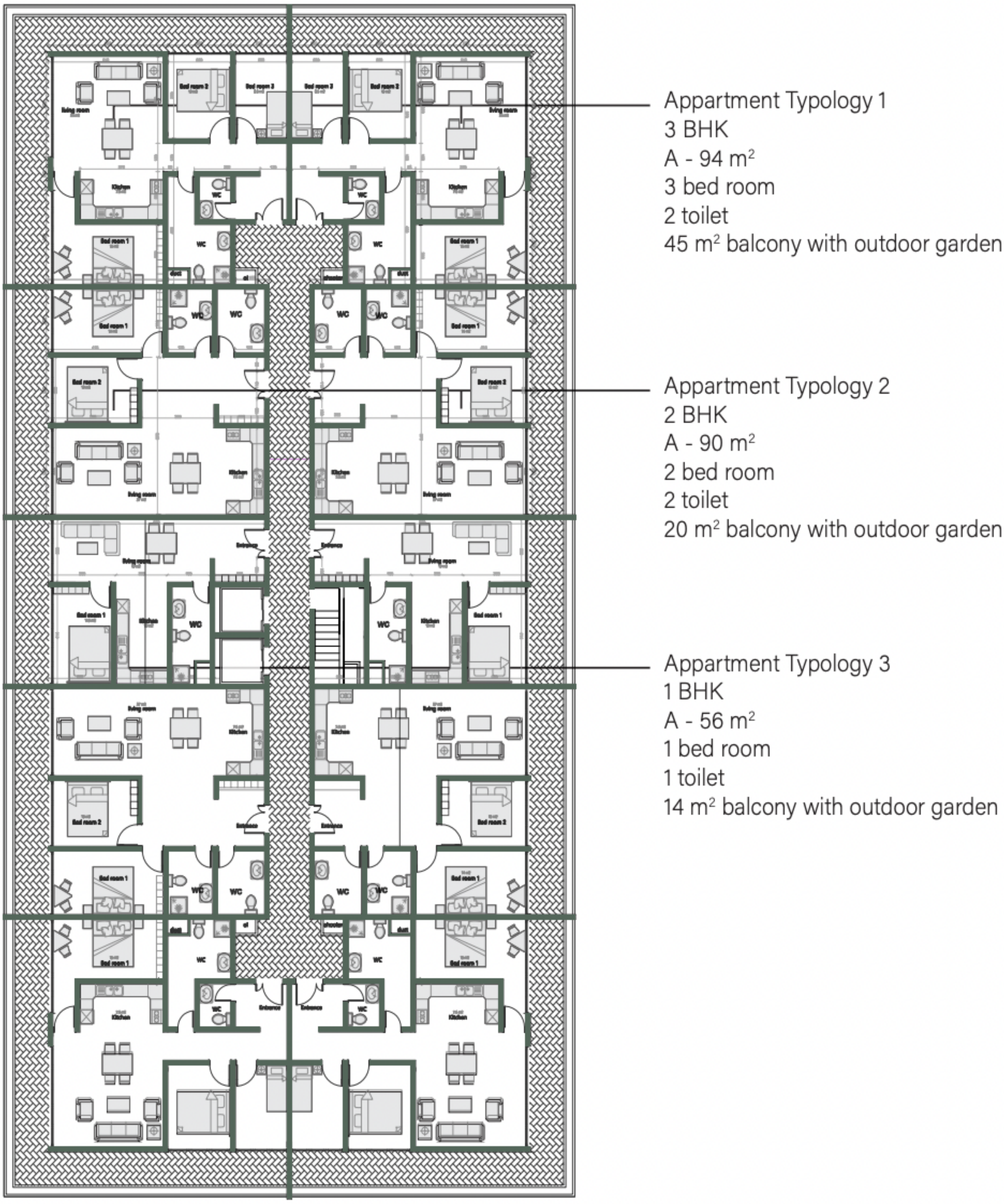

Figure 7. Blueprint for one floor with four apartments of Typology 1, four of Typology 2 and two of Typology 3 (SNABB Sustainable Construction, 2022). Used with permission from the owner.

3. Methodology

In this section, the overall approach of the study is described firstly, followed by the load profile assessment including sources of error, then a description of the software HOMER and lastly how the sensitivity analysis was performed.

3.1 The approach

This study primarily aimed to investigate if an off-grid PV with battery or hydrogen storage could function as a reliable provider of electricity for households in Addis Ababa. To evaluate the two different scenarios, a reference building described in the previous section, was used. The study was then conducted in several steps.

Initially, a load profile was developed due to the electricity demand of the studied building being necessary for the dimensioning of the PV systems. A time-use survey on domestic electric use was therefore firstly conducted, with the aim of investigating and evaluating the electricity demand. Time-use diarys were designed and answered by respondants in Addis Ababa. The goal of the time-use diraies was not to give an exact representation of reality, but rather to describe behaviors and get an estimation of the domestic electricity consumption. Following, a model for the reference building was constructed by compiling the collected data and calculating the electricity demand on an hourly basis, similarly to the approached used by Widen et al. (2009) in *Constructing a load profile for residential household consumption*. This is elaborated further in Section 3.2.

Further, the load data was used to simulate the different PV systems, by using a software called HOMER. In the software, the system components were dimensioned and optimized to meet the electrical demand. The economic analysis was also performed in the software. The goal was to find the most cost-effective system and evaluate the technical feasibility. HOMER, its inputs, the system components characteristics and the economic analysis are described in section 3.3. Lastly, a sensitivity analysis was performed to assess how the results are affected by changing conditions. This was also executed in HOMER and is explained in section 3.4.

3.2 Load Profile Assessment

Constructing electric load profiles for domestic use is important for simulations of small-scale energy systems (Widen et al., 2009). However, it is a highly complex task as residential energy usage is closely linked to lifestyle-related factors, which in turn are subjective and difficult to define with precision (Capasso et al., 1994). Capasso et al. (1994) and Widen et al. (2009) have in their respective studies implied that time-use data can be used to disclose this problem and provide an understanding of residential electricity usage.

Time-use data can be explained as an empirical sequence of activities, in this case in households. It is normally collected through time-use diaries, where household members write down their daily activities, which provides a rich and varied material (Widen et al., 2009). Widen et al. (2009) explains that time-use data is a rather unutilized resource in the energy field. The study implies that it could provide better modeling of the behavior element in residential energy use and be a complement, or even an alternative, to measurements (Widen et al., 2009). The methodology of the time-use diary survey is presented in the following section, while the data compilation is elaborated in section 3.2.3 and load profile construction in section 3.2.4.

3.2.1 Time-use diary

In order to acquire an understanding of the Ethiopian electrical household consumption and construct the load profile, time-use data was collected through time-use diaries. Capasso et al. (1994) and Widen et al. (2009) emphasize that individual-based questionnaires are advantageous, since it allows the smallest unit of analysis to be the household member. However this was considered impossible due to both time and feasibility constraints. Hence, the surveys were based on one household and not each individual household member.

Time-use surveys can further be conducted in several ways. In this study, the UN's (2005) guide Guide to Producing Statistics on Time-Use: Measuring Paid and Unpaid Work was used. Even though the guide examines paid and unpaid work, the authors explain that the guide is intended as a response to the increasing interest in the development of methods and concepts in the field of time-use statistics (UN, 2005) and was therefore selected for this study.

Time-use data consists of information on activities, the time of the day they occurred and their duration. The main focus in each time period is "what were you doing?". It seeks to capture human behavior in terms of what is being done and when (UN, 2005). The two key factors *activities* and *time* can further be approached differently in the time-use diary, depending on what type of survey that is conducted. The guide presents two different types of diaries; a 24-hour diary which records the time at which activities occur over a 24-hour day or a version that records the duration of one activity over a specified period of time. As the aim was to collect data on all daily activities that consumed electricity, a diary that recorded all activities during a 24-hour diary was chosen (UN, 2005).

The 24-hour diary can either be a *full* or *light* diary. The basic difference is the manner in which activity descriptions are recorded. In a full diary, respondents write down all activities which are coded later on, while a light diary has restricted, pre-coded activities. Choosing between a full and light diary depends on the objectives of the survey. Time-use diaries with pre-coded activities cannot serve the same wide range of objectives, as the set of activities is substantially more limited (UN, 2005). Pre-coded activities require knowledge of activities and appliances used in the Ethiopian context. Thus, a full time-use diary is considered, in order to not limit or exclude any activities.

Time is another important aspect that has to be considered in the diaries. In the 24-hour diary, time can either be recorded in open or fixed time intervals. In open intervals, respondents report the start and finish times of each activity, while the fixed intervals consist of non-overlapping time segments of uniform length, covering the 24- hours of a day. Tests have indicated that the open method yields larger variations in obtained data, as fixed time intervals measure time less precisely, resulting in short-duration activities risking to be unreported. Results have also indicated that fixed interval diaries record a smaller number of activities. On the other hand, the fixed interval method simplifies editing and processing (UN, 2005). Open time intervals have however been chosen in order to obtain larger variations in the quality of data and avoid unreported activities.

Another dimension of time relevant to activity is the day on which the activity occurs (UN, 2005). Electrical consumption differs between weekdays and weekends, and different seasons, which both Capasso et al. (1994) and Widen et al. (2009) have taken into consideration. Given that the seasonal differences in Addis Ababa are quite small, it has been chosen to not consider seasonality in the survey. By however carrying out the survey for one weekday and one weekend day, the differences in electrical use for different days can be acquired.

In summary, the basic format of the full 24-hour time-use diary consists of a column for recording the starting and ending time of an activity and a column for describing the main activity and appliances used, with one table for a weekday and one for a day of the weekend. The survey can be found in Appendix A. Apart from the diary, supplementary information about respondents is usually required for the time-use analysis. Background information on the household characteristics is therefore collected as well. The background information in this study consists of the household size and the number of household members (adults and children respectively) and is presented as part of the survey in Appendix A. These factors were chosen as they were considered relevant for the construction of the load profile. Several other personal characteristics such as age, sex and marital status can be considered as well, for analyzing differences in activity patterns (UN, 2005), however, these were not considered in the load profile due to feasibility constraints.

3.2.2 Target group

Eventually, the diaries were administered as leave-behind or "tomorrow" diaries, where respondents were given instructions to write down their activities as they go about their day (UN, 2005). The targeted group was residents in Addis Ababa. Initially, only respondents living in apartments were targeted. This group was however small, hence, the studied group had to be widened and include people living in houses. As the project in the case study is directed towards state officials and/or high-income earners, respondents in a similar social group or with similar living conditions were targeted. It was however difficult to both find respondents willing to participate in the study and how these would be reached, as the study was performed on distance.

The targeted group in the study therefore mainly consisted of returning diaspora, i.e Ethiopians who have lived in Sweden and then moved back, whom I or family members knew. Some of the respondents were contacted through a Facebook group for Ethiopians in Sweden, in which some lived in Addis Ababa. Furthermore, some respondents were friends of family members living in Addis Ababa. This methodology consists of several deficiencies. Firstly, it was difficult to control the respondents' living conditions. This could have been avoided by for example having the income of the household in the background information, to make the methodology more scientific. Nonetheless, it can be invasive to ask about income, since most respondents were family friends. The survey was however anonymous.

The survey was conducted on distance, whereas some respondents were emailed the survey and some surveys were distributed on site through family members. Not being in direct contact with some of the respondents resulted in difficulties reassuring that they understood the instructions, although instructions were written on the survey. Additionally, English was the language used for the survey, thus requiring the respondents to understand English. These factors increased the risk of misinterpretations or misunderstandings.

3.2.3 Compilation of data

The first step in constructing the load profile was to compile the collected data. The UN guide (2005) explains that the data-processing cycle involves many activities, where some are quality assurance and coding the activities. The data-processing cycle inputs consist of the surveys, while the basic output is the data files that serve as input to the analysis (UN, 2005).

Initially, a quality assurance was executed, which consisted of excluding diaries that were incomplete or lacked enough details to be useful. Hence, surveys that only had reported for one day were excluded. Surveys with less than five activities were also excluded, as they were considered to lack enough details. Furthermore, activities that either did not include electricity use or that were delimited in this study, such as laundry or hot water, were overlooked. Lastly, households that consisted of more than three bedrooms were omitted since no larger than three-bedroom apartments were considered in the reference building. The household profiles that would be used in the construction of the load profile were then created by the remaining surveys.

Following the quality assurance was the coding of the activities. When coding the activities recorded by a respondent, the main aim is to determine which group in the activity classification the activity belongs to and record it correctly (UN, 2005). Both Widen et al. (2009) and Capasso et al. (1994) coded the activities into different categories as well. The activity categories in Capasso's (1994) study were for example *cooking, housework, personal-hygiene* and *leisure*. The categories that were chosen for this study were *cooking, electronics, additional, cold appliances* and *lighting.* Electronics covered appliances such as TV, computers and chargers, whilest cold appliances included the base load. Other appliances where covered in the additional load. Lighting was calculated separately, due to difficulties of being report in the surveys, which is elaborated in the following section.

3.2.4 Constructing the load profile

Proceeding the quality assurance and activity coding, the load profile was created, which was done in MATLAB. When creating the model structure, the main aim was to keep it as simple as possible, while maintaining a realistic performance of the model. The activities were reported on an hourly basis, from midnight to midnight.

The first step in this process was to identify the appliances, either described in the survey or connected to activities that were reported. The ratings of the appliances were also identified in this step and can be found in Appendix B. The ratings were provided by SNABB construction.

The second step consisted of identifying the power use for each activity in each time-step, being an hour. The total power use in each time-step was calculated by multiplying the rating of the appliance by the time duration of the activity (Eon, 2007), with the following equation:

$$Power\ (kWh)\ =\ Appliance\ rating\ (kW)\ *\ duration\ (h) \tag{1}$$

The power use of the activities for each household profile was added during the time of the day they were reported in the surveys, in the respective categories *cooking, electronics, additional* and *cold appliances*. This was done separately for a weekday and a day of the weekend. The household profiles' electricity use for each time step throughout a 24-day, within each category for the different days of the week, had then been created. In Figures 8 and 9, two examples of how the appliances were added during each time step in the load profile construction are illustrated visually.

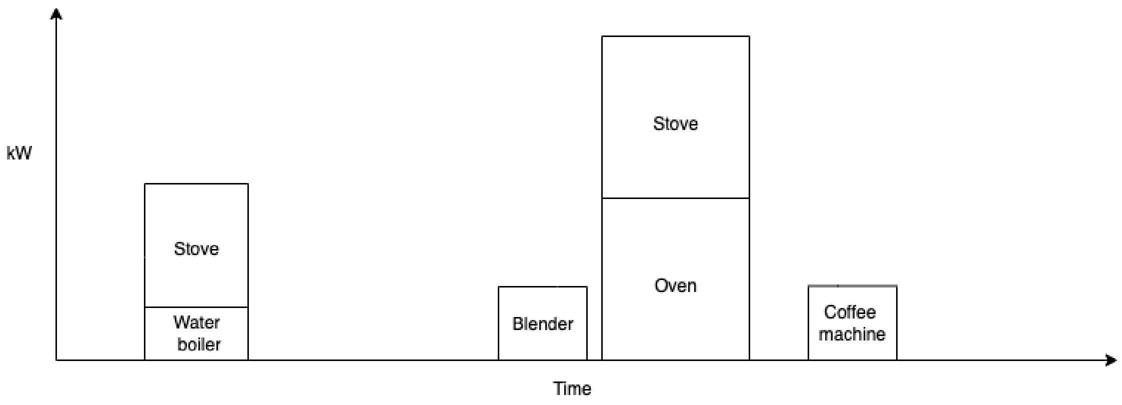

Figure 8. A simplified visual example of the cooking category load profile construction during a weekday.

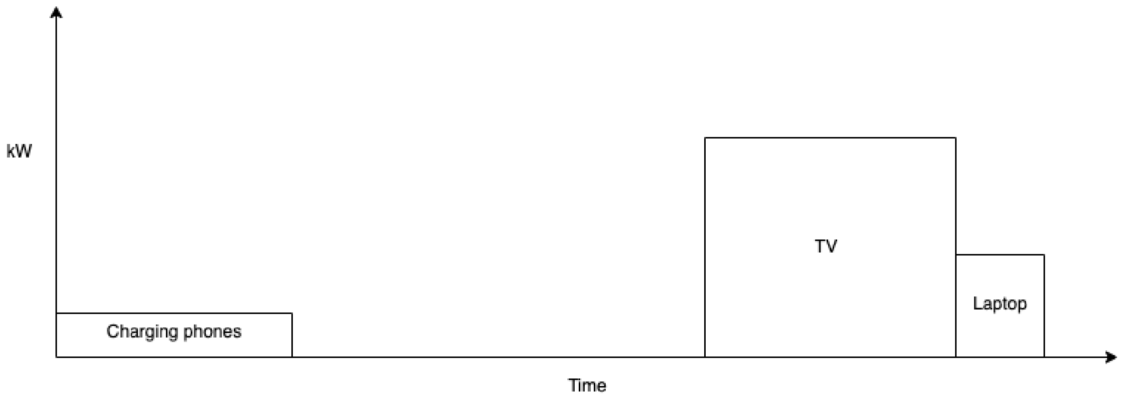

Figure 9. A simplified visual example of the electronics category load profile construction during a weekday.

Since lighting was not reported detailed enough in the surveys, the use of lighting was modeled separately. The need for lighting is related to daylight (White Arkitekter, n.d) and was therefore calculated by analyzing daylight availability. Data for the average sunrise and sunset hours in Addis Ababa, throughout the year, was used. The respondents also reported at what time they woke up and went to bed, as well as their availability at home. Lighting was therefore assumed to be used before the sunrise and after the sunset hours, if when the respondents were awake and at home. When these conditions were fulfilled, it was assumed that three lights were on, which was a choice by the author. This is of course an assumption. More or fewer lights can be used, during longer or shorter periods. Lighting can also be used even though there is daylight.

The methodology for calculating the daylight availability could have been improved by taking the daylight factor into account. The daylight factor is related to the design of the building. By analyzing factors such as window size, room height, room depth and balcony depth together with daylight hours, daylight availability could be simulated closer to reality (White Arkitekter, n.d). Consequently, a better estimation of the need for and use of lighting could have been achieved. However, these additions are out of the scope of this thesis and are left for future work.

The next step consisted of a simulation of all the apartments in the building, with the use of the created household profiles. The different categories were first assembled, to obtain the total load for the different household profiles for one weekday and one weekend day. The profiles were then simulated according to the arrangement that was planned for each floor in the reference building, i.e four three-bedroom apartments, four two-bedroom apartments and two one-bedroom apartments for each floor. The load was then simulated for 13 floors. Following, a time-series for the whole year was simulated by using the weekday and weekend day profiles accordingly, with five weekdays and two weekend days.

By using the same profiles to simulate all apartments in the reference building, the peak loads coincided at the same hours, resulting in very high peaks. Half of the load of the total building was therefore shifted one hour forward, in order to avoid the peaks coinciding and achieve a more varying, realistic result. Furthermore, some assumptions were made due to a lack of details on the exact time use of many of the kitchen appliances. If specific time use of appliances like blender, boiler, microwave, etc. had not been specified, it was assumed that they were used for 10 minutes. This was however also an assumption, which could be both longer or shorter than the actual time.

3.2.5 Sources of errors

It is important to highlight that there are several sources of error in the conducted time-use survey and model construction. Identifying the sources of errors is important in order to interpret the validation results correctly. Some of the main sources of errors are presented further.

One major source of error was using household surveys instead of individual-based surveys, which resulted in difficulties capturing individual consumption behaviors. Following, the approach of contacting the respondents lead to uncertainties regarding the targeted group. Some demographic factors, such as age and sex, were also not considered, although they can affect consumption patterns, which was emphasized by Capasso (1994).

Another source of error is that the electricity consumption has been assumed to be the same throughout the whole year. Although weekdays and weekends have been taken into account, holidays, vacations etc. also affect electricity consumption. Additionally, the lighting load was also assumed to be the same throughout the whole year. A rainy or cloudy day can for example affect the use of lighting, which has been overlooked. This would increase the load demand and result in a higher load.

Furthermore, some appliances have standby powers, meaning that they consume power even when they are shut off. This was overlooked in this study, although it would increase the calculated load. In addition, there are usually peaks in the first moments of using an appliance. This was however overlooked due to insufficient data.

One of the main challenges with the development of the load profile is not being able to verify the constructed model, as there are no available measurements of the electricity consumption in Addis Ababa. This creates difficulties in verifying whether the results are a good approximation of reality or not. However, the goal of constructing the load profile was to achieve a better understanding of the behaviors, appliances and during what time different activities occur in the Ethiopian context, rather than an approximation valid only for a different location.

3.3 Introducing HOMER

After the load profile construction, the following step was to simulate the PV battery and hydrogen systems respectively, which was done with the NREL-developed software HOMER.

HOMER, an abbreviation of **H**ybrid **O**ptimization of **M**ultiple **E**nergy **R**esources, is an energy system modeling software that enables techno-economic simulations of stand-alone microgrids (HOMER Energy, n.d). HOMER is structured around three core capabilities; simulation, optimization and sensitivity analysis. Initially, the software attempts to simulate a viable system for all possible combinations in the designed energy system. Then an optimization follows, in which the most cost-effective system with the least number of components and sizes needed to meet the required load is found, according to the criterias defined by the author. A sensitivity analysis is optional, however it allows an analysis of for example costs and other factors depending on the type of energy system that is simulated (HOMER Pro [1], 2020).

In Figure 10, an overview of the course of action using HOMER is illustrated. Firstly the load, solar radiation data and system components' characteristics and cost were all entered. The software then performed an optimization of both the technical and economic aspects. Lastly, a sensitivity analysis was executed.

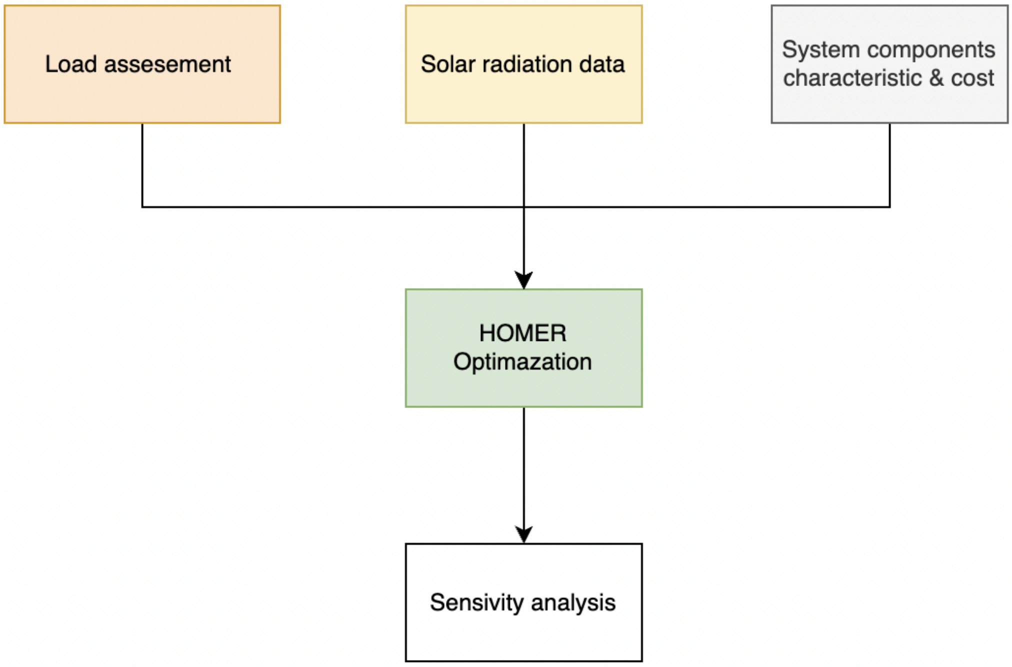

Figure 10. An overview of the methodology for this study using HOMER.

3.3.1 Simulation setups

The software requires several data inputs for the simulations. Firstly, the location (latitude and longitude) was entered to obtain the solar radiation data, i.e the Global Horizontal Irradiation (GHI) and the clearness index. The GHI is the total solar radiation incident on a horizontal surface, which is the sum of Beam Horizontal Irradiance (BHI), Diffuse Horizontal Irradiance and ground-reflected radiation (HOMER Pro [2], n.d). The GHI is expressed in kWh/m^2, on an hourly average throughout the year. The clearness index is a measure of the clearness of the atmosphere and is expressed in a number between zero and one. It represents the fraction of solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. Cloudy days therefore have a lower clearness index (HOMER Pro [3], 2020). HOMER uses the GHI and clearness index to convert the incident radiation on the PV modules to the PV module's power output **(**HOMER Pro [4], 2020).

Secondly, a time-series of the electrical load on a time-basis over a year was entered, expressed in kW. When further modeling the system, components such as PV modules, inverters, storage and a controller were added. Regarding the PV modules, the costs, performance characteristics, such as capacity, lifetime and derating factor, and the orientation of the array were entered. The orientation includeed the module tilt, azimuth and ground reflectance, i.e albedo. As the load was on the AC bus and the output from the solar panels was on the DC bus, an inverter was used as well. Characteristics such as costs, capacity, lifetime and efficiency were also entered.

Furthermore, lithium batteries and hydrogen, consisting of a hydrogen tank, electrolyzer and fuel cell, were the storage components considered in the study. The battery inputs included costs, lifetime in years, initial state of charge (%) and minimum state of charge (%). For the electrolyzer, characteristics such as costs, lifetime and efficiency were added. The fuel cell characteristics included costs, lifetime in hours and a fuel curve, i.e the efficiency. When using storage, a controller is also available. The controller can follow different strategies, such as cycle charging or load following. The load following strategy tends to be optimal in systems with a lot of renewable power that sometimes exceeds the load demand, which made it suitable for the simulations in this study.

To estimate the size needed for the components, in order to satisfy the load demand, a search space was used for each component respectively. The search space was found by testing different values and observing how it affected the results. Eventually, when the search space was set and the system was modeled, the optimization was performed by the software (HOMER Pro [1], 2020).

3.3.2 Economic analysis

In the optimization, HOMER performs an economic analysis. The factors that were considered in this study are presented in Table 1 and are all from the following reference HOMER Pro [5] (2020).

The cost inputs included: The *Initial Capital Cost* (ICC) of a component, which is the total installed cost of that component at the beginning of the project. The *Replacement cost*, which is the cost of replacing a component at the end of its lifetime, as specified by the lifetime parameter in the component model. This cost can be different from the initial capital cost for several reasons. The *Operation and Maintenance (O&M) cost* of a component is the cost associated with operating and maintaining that component. As O&M costs could not be found for all the components, this factor was excluded. It is however an important factor to take into consideration when evaluating the costs of energy systems.

The cost outputs consist of: The total ICC of the system, which is the sum of the ICCs of all system components. The total replacement cost of the system, being the sum of the replacement costs of all system components. The *Salvage*, which represents the value remaining in a component of the power system at the end of the project lifetime. The *Net Present Cost (NPC)* of a component is the value of all the costs of a component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime, being the salvage. HOMER then calculates the NPC of the total system. The levelized *Cost of Energy (CoE)* is the average cost per kWh of useful electrical energy produced by the system.

Other factors, such as transportation- and installation costs are also significant, especially since most components need to be imported to Ethiopia from other countries. However, due to a lack of data, they have been overlooked in this thesis. One can therefore assume higher costs than in the final result.

Table 1. The considered economic factors in the optimization.

Input (Per component)	**Output (Total)**
Initial Capital Cost	Initial Capital Cost
Replacement Cost	Replacement Cost
	Salvage
	Net Present Cost (NPC)
	Cost of Energy (CoE)

In the economic analysis, the current electricity prices in Ethiopia will be used for comparison to the CoE in the simulations. In Addis Ababa, the residential tariffs are divided into different blocks depending on how much electricity is used per month. In this study, block 5 is considered as the apartments use around 300 kWh/month. As of December 2021, electricity for households using up to 400 kWh/month costs 2.20 Ethiopian Birr/kWh, which translates into 0.04 US$/kWh (Ethiopian Electric Utility, 2021).

3.4 Sensitivity Analysis

The sensitivity analysis was performed to assess how the simulated system was affected by changing conditions. Parameters that were summed to have an impact on the results were therefore tested. These parameters concerned PV modules prices, the load and size of the installed PV capacity.

Trends such as increased capacities, efficiencies and scalability of PV modules during the past years have resulted in decreasing prices (Vattenfall, 2019). The learning curve theory assumes that the production cost of a product is continuously reduced with mass production, and that competition causes production to become more efficient and introduces new technologies. Thus, according to the learning curve theory, the decreasing price trends can be expected to continue (Mertens, 2018). This results in this aspect becoming relevant to examine. By reducing the PV module cost by half, the effect on the NPC and CoE was examined.

It was also interesting to examine how, for example, a smaller number of floors in the reference building and in turn a smaller load, would affect both the feasibility and profitability of using solar power with storage. A simulation with seven floors was therefore evaluated instead of 13. In order to avoid coincident peaks, three of the floors were shifted. Furthermore, the installed capacity of the PV modules was reduced in order to evaluate how this affects the feasibility, NPC and CoE. The sensitivity analysis was only performed on the most cost-effective system.

4. Data

In this chapter, data that is used in order to carry out the study is presented. The first section consists of data necessary for the load profile assessment. In the second section, the solar radiation data used in HOMER is presented. Lastly, the system components data is presented.

4.1 Load profile assessment

When modeling the lighting usage in the households, data for the sunrise and sunset hours was used. The daylight hours are shown in Figure 11. The daylight hours are relatively constant throughout the year, with sunrise around 6-6.30AM and sunset around 6-6.30PM (World Data, n.d). It was therefore assumed that lighting was used before 8AM and after 4PM, in order to have margins.

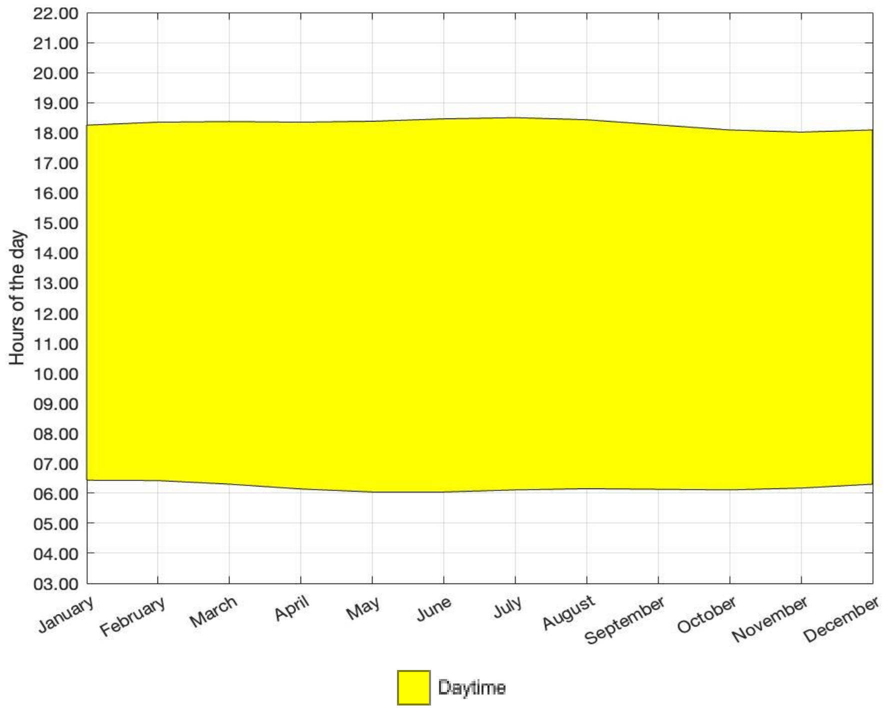

Figure 11. Daytime throughout the year in Addis Ababa. Figure made by author with data on average sunrise and sunset hours per month (World Data, n.d). The daytime is illustrated in yellow.

4.2 Solar radiation data

The solar radiation data, being the GHI, was needed to calculate the PV module's power production in HOMER. The GHI data was retrieved from NASAs' database *POWER*, abbreviation of *Prediction Of Worldwide Energy Resources*, and is brought forward by monthly averages for GHI over a 22-year period (July 1983 to June 2005) (NASA POWER, 2021). It was retrieved in HOMER by entering the latitude and longitude of the project. The latitude and longitude are presented in Table 2, while the solar radiation data and clearness index are presented in Figure 12.

Table 2. Latitude and longitude for the studied project.

Latitude	Longitude
9.021531	38.829368

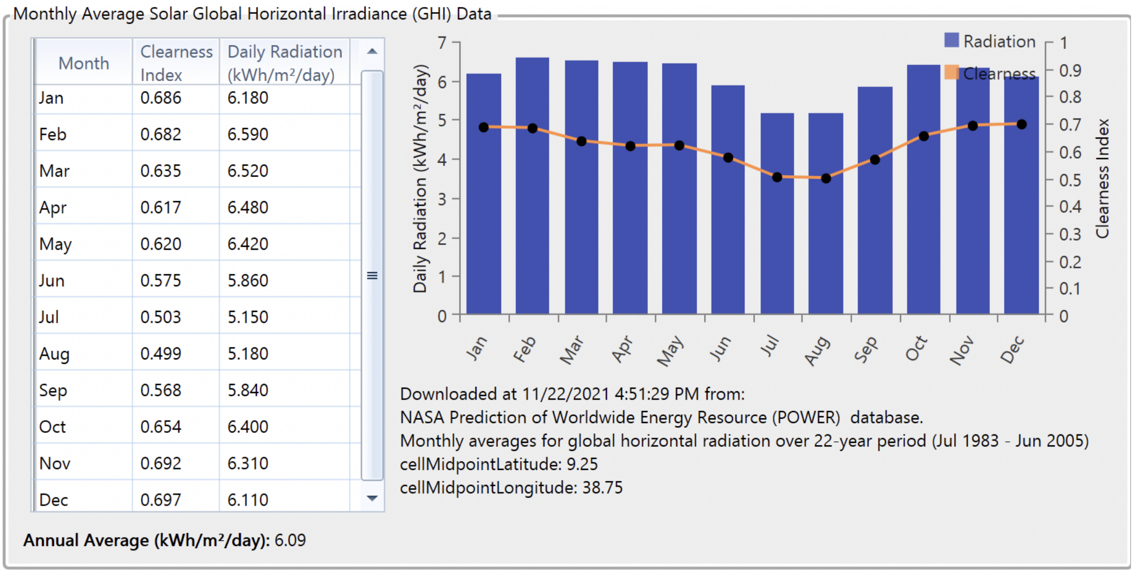

Figure 12. GHI and clearness index at the projects' location.

4.3 System dimensioning/Simulation setups

When dimensioning the system in HOMER, several parameters and constraints needed to be defined. These parameters are presented in Table 3. The lifetime of the project was set to 25 years, which corresponds to the lifetime of a solar panel. Regarding the tilt, HOMER uses a default tilt, which is explained to maximize the yield when roughly equal to the latitude (HOMER Pro [6], 2020). The azimuth was set to 0°, corresponding to south-oriented panels, as the location of the project is in the northern hemisphere of the equator (HOMER Pro [7], 2020). The ground reflectance, i.e albedo, was set to 0.2 and represents the sunlight that is reflected from the ground. A value of 0.2, i.e 20% reflection, usually corresponds to a grass-covered area (HOMER Pro [8], 2020). Further, seeing that the aim was to investigate if the solar systems could cover the load demand, the amount of capacity shortage allowed was set to 0%.

Table 3. Parameters used to define the systems in HOMER.

Parameters	**Value**
Lifetime of project	25 years
Tilt	9.02°
Azimuth	0°
Albedo	0.2
Constraints (Capacity shortage)	0%

In the following sections, data for the system components and search space is presented.

4.3.1 PV modules

The PV modules used in the simulations were Sunpower MAXEONs SPR-MAX3-420-BLK model, with a nominal power of 420 W. The model is a monocrystalline solar module with an efficiency of around 22% and a lifetime of 25 years (Sunpower MAXEON, 2022). The model was chosen due to monocrystalline solar modules being one of the most common types and have the highest efficiencies. The derating factor, which is a scaling factor of the reduced PV power output in real-world operating conditions, was pre-set to a default value of 88% in HOMER (HOMER Pro [9], 2020). Furthermore, the modules have an area of 1.9 m^2 (Sunpower MAXEON, 2022), while the rooftop area of the reference building is 1200 m^2. The maximum number of solar panels that could fit the roof was therefore calculated by:

$$Number\ of\ modules\ =\ Rooftop\ area\ /\ Module\ area \tag{2}$$

which resulted in 631 modules. As each panel had a capacity of 0.42 kW, the maximum total installed PV capacity was calculated by:

$$Total\ installed\ PV\ capacity\ =\ Number\ of\ modules\ *\ Module\ capacity\ (kW) \tag{3}$$

resulting in a maximum of 265 kW. In the results, the possibility of fitting the optimized systems on the rooftop area will be evaluated. As the initial capital cost (ICC) of the modules was not specified by Sunpower, it was found at a vendor where the price for a module was US$ 410 (SecondSol, 2022). The replacement cost was assumed to be the same as this could not be found. In some cases, the replacement cost can however be lower, resulting in a lower NPC. The O&M of PV modules consists of annual controls, ensuring that the system is operating correctly, but also preventive maintenance and cleaning (NREL, 2018).

4.3.2 Inverter

An inverter manufactured by Rosen Solar was chosen for the PV systems. The company is located in China and manufactures several components required for a PV system, including inverters with large capacities (Rosen Solar, 2019). The chosen inverter has a capacity of 100 kW, a lifetime of 20 years and 95% efficiency. The ICC for the inverter is US$ 16,720 (Rosen Solar, 2022). The replacement cost was assumed to be the same as this was not specified. The O&M of an inverter encompasses cleaning of filters, control of internal components, minor equipment repair, etc. (Electric Power Research Institute, 2015).

4.3.3 Battery

A 100 kWh lithium-ion battery, also manufactured by Rosen Solar, was chosen for the simulations (Rosen Solar, 2019). The battery has a lifetime of 20 years and ICC is US$ 32,026 (Rosen Solar, 2022). The replacement cost was assumed to be the same. Further, the batteries had an initial charge of 100% in the simulations. As the depth of discharge (DoD) is 80%, the minimum state of charge was set to 20% (Rosen Solar, 2022).

4.3.4 Hydrogen components

The hydrogen storage simulations consisted of the three main components; electrolyzer, hydrogen tank and fuel cell. It is important to mention that the ICCs and O&M can vary substantially for the hydrogen components, due to being project-specific (Mongird, K. et al., 2020). The prices presented further are therefore an estimation of what a system could cost.

The electrolyzer used in the simulations was based on Nel Hydrogen's Proton Exchange Membrane (PEM) electrolyzer MC250 (Nel Hydrogen, n.d). The electrolyzer has a capacity of 1.25MW, with a production rate of 22 kg/h and a consumption rate of 50.4 kWh/kg (Nel Hydrogen, 2021). Some advantages to a PEM electrolyzer are that they have high current densities and voltage efficiency and rapid system response, however a disadvantage is that they are usually very expensive (Carmo m.fl, 2013). The default efficiency of the electrolyzer in HOMER was 85% and as this could not be found, this value was chosen. The lifetime of an electrolyzer usually depends on operating conditions and variable loads, amongst other factors. For a PEM electrolyzer the lifetime ranges between 10-20 years (Taibi, E., et al., 2020) and was therefore assumed to be 15 years. The MC250 electrolyzer costs US$ 2,800,000 (Nel Hydrogen US, 2022). The replacement cost could not be found and was therefore set to the same as the ICC.

Although Nel Hydrogen also manufactures hydrogen storage tanks, technical specifications and costs could not be found. Other hydrogen tanks were also not found, resulting in having to use a generic tank from HOMER, where costs were provided. For a 1 kg tank, the ICC was US$ 1400 and replacement cost US$ 1200. The lifetime of the generic hydrogen tank was 25 years (HOMER Pro [10], 2020).

Lastly, the fuel cell used was also a generic fuel cell found in HOMERs components catalog, with a lifetime of 60 000h. The costs for the generic fuel cell were already set in HOMER with an initial capital cost of US$ 750 000 and a replacement cost of US$ 625 000 for a 250 kW fuel cell. The efficiency was however set to 58% (US Department of Energy, 2015), as this had to be entered manually.

4.3.5 System design

In the following figure, the two different PV systems that were simulated are demonstrated. Scenario 1 consists of a PV system with battery storage and scenario 2 PV with hydrogen storage.

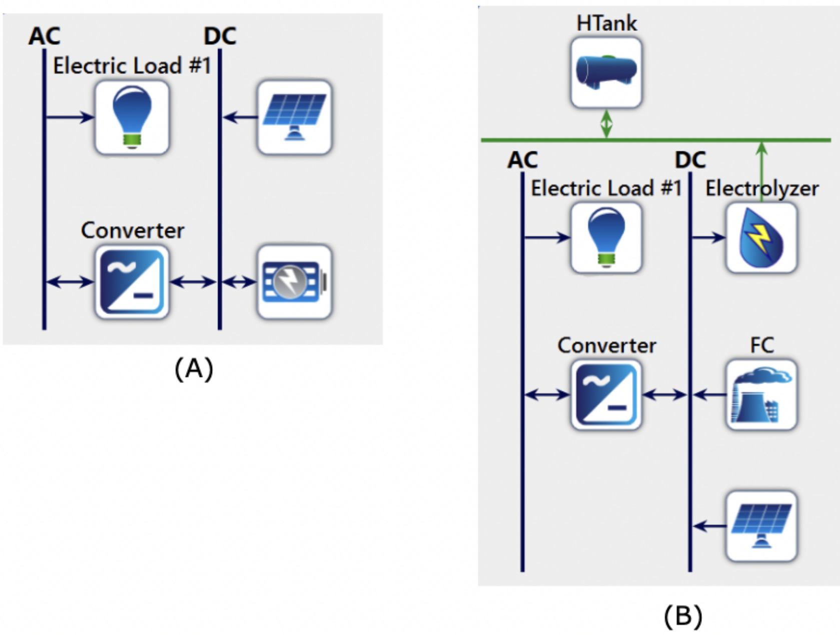

Figure 13. An illustration of the two different scenarios simulated. (A) PV system with battery storage, (B) PV system with hydrogen storage.

5. Results

This chapter presents the results from the simulations in MATLAB and HOMER, consisting of three parts. Firstly, the results from the load profile assessment are presented, which includes the household profiles, the availability and sleeping hours, the load for each category and finally, the daily and yearly load profile. Secondly, the three different scenarios are presented separately and lastly the results from the sensitivity analysis.

5.1 Load profile

5.1.1 Household profiles

A total of 16 surveys were collected in the time-use survey. However, six of these were omitted due to either being incomplete (only answering for one day), lack of details (less than five activities reported) or household size being larger than three-bedrooms. This resulted in 10 household profiles. The number of bedrooms (household size) and number of household members in the 10 household profiles are presented in Table 4. It can be observed that the number of adults in the households ranges from one to four, with half of the households consisting of more than two adults. In some of the households, the number of household members also exceeds the number of bedrooms.

Table 4. Household demographics of the household profiles used for the load profile modeling.

Household	Household size	Adults	Children
Household 1	3	3	0
Household 2	3	3	1
Household 3	2	3	0
Household 4	2	2	3
Household 5	1	2	0
Household 6	2	3	2
Household 7	3	4	3
Household 8	2	2	2
Household 9	1	1	2
Household 10	3	2	3

5.1.2 Availability and sleeping hours

In Figure 14, the availability at home for the 10 household profiles is presented, for weekends and weekdays. The black color represents residents being away from home. The residents in a majority of the households reported being home on the weekends, and in four of the households, also on the weekdays. It was reported that it was common for family or friends to visit on the weekends. In Figure 15, the sleeping hours for weekdays and weekends are presented, where the black color represents the residents sleeping.

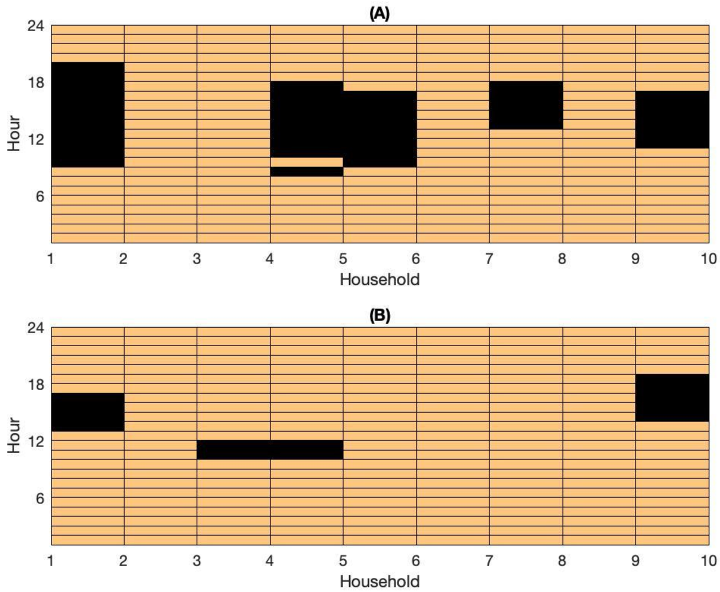

Figure 14. Availability at the house for weekdays (A) and weekends (B) for the 10 households, whereas being away from the house is represented in black.

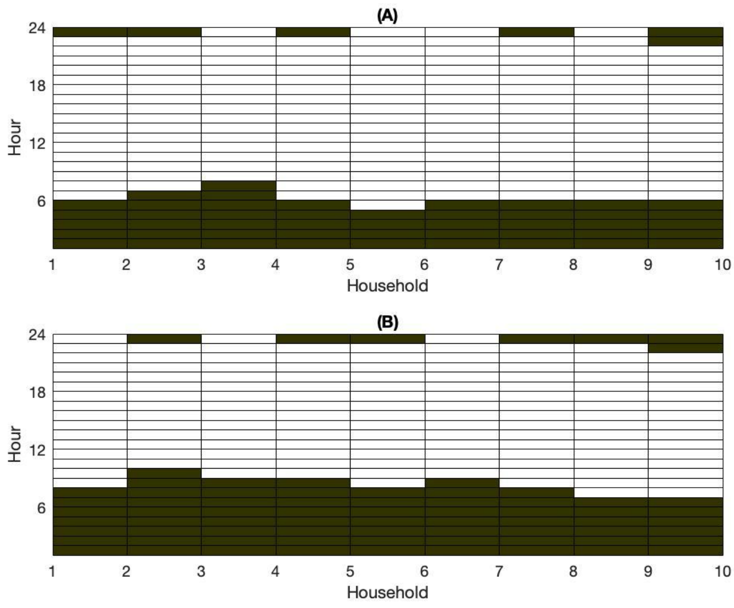

Figure 15. Sleeping hours for weekdays (A) and weekends (B) for the 10 households, whereas sleeping is represented in black.

5.1.3 Load per category

The appliances that were identified in the time-use survey, excluding lighting, were assembled into the four categories *Cooking, Electronics, Additional* and *Cold appliances.* These are presented in Table 5, within their respective category. The ratings of the appliances are given in Appendix B.

Table 5. Compilation of appliances within respective categories.

Cooking	**Electronics**	**Additional**	**Cold appliances**
Stove	TV	Hairdryer	Refrigerator
Oven	Laptop	Flat iron	WIFI router
Microwave	Phone charger	Iron	
Blender	Radio	Treadmill	
Waterboiler		Ballonpump	
Coffee machine		Shave machine	
Coffee blender		Humidifier	
Ethiopian coffee stove			
Injera stove			

Activities and appliances that were identified in the time-use survey and considered specific to the Ethiopian context consisted of making Ethiopian coffee and the Ethiopian bread injera. Blending coffee beans with a coffee blender and boiling the coffee with a, in this study referred to as an “Ethiopian coffee stove”, were part of almost all the households’ daily routines. Cooking injera with a special injera stove was also reported in most surveys, at least once a week. Furthermore, no one reported the usage of for example a freezer, dishwasher or vacuum cleaner.

In Figure 16, each load category is presented separately, with the load for a weekday to the left and a weekend day to the right. Lighting is also presented as a separate category in Figure 16, with one load profile for a weekday and one for a weekend day. Only one daily load profile was brought forward for the cold appliances due to the power use being the same for weekdays and weekends. The cold appliances, consisting of refrigerators and WIFI-routers, have a power use of around 7 kW, as demonstrated in Figure 17.

It can be observed that cooking stands for the largest share of the total load, with peaks over 100 kW both during weekdays and weekends. On the weekdays, cooking mostly occured in the evening around 7PM. On the weekends, on the other hand, cooking peaks around noon. The respondents also reported cooking longer during the weekends. The electronics category also has high peaks with around 20 kW. Electronics were mostly used in the evenings, where a large majority of the respondents reported that they watch TV together with the family in the evenings. The usage of lighting and additional appliances, on the other hand, represents smaller shares of the total load, with power use peaks of around 4-10 kW. Three of the households reported that they always sleep with a light on.

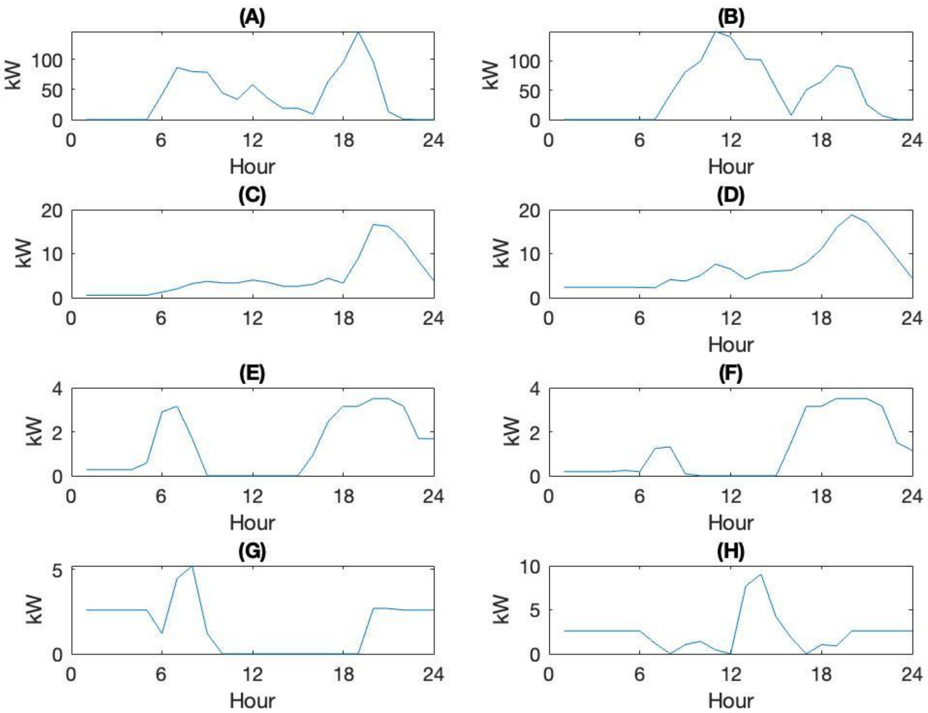

Figure 16. Daily load per category for the total building: (A) cooking weekday, (B) cooking weekend, (C) electronics weekday, (D) electronics weekend, (E) lighting weekday, (F) lighting weekend, (G) additional weekday and (H) additional weekend.

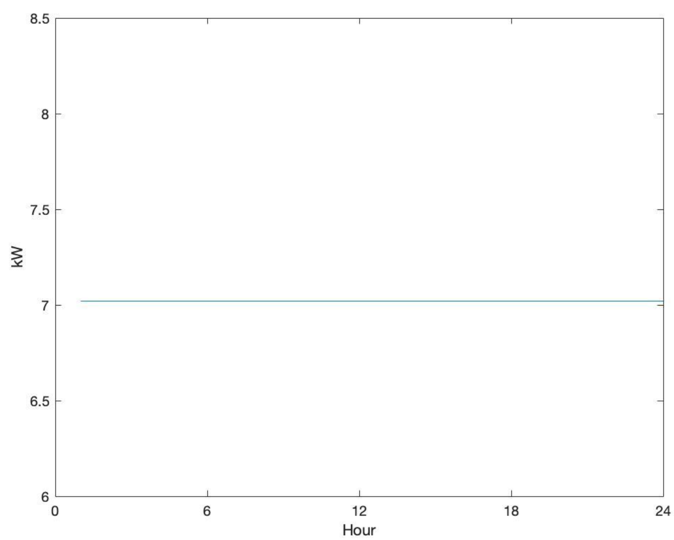

Figure 17. Daily load cold appliances, total building.

5.1.4 Final load profile

In Figure 18, an illustration of the average daily electricity use is presented, in which the categories were assembled. The load profile has a peak of 165 kW and average use of 1341 kWh/day.

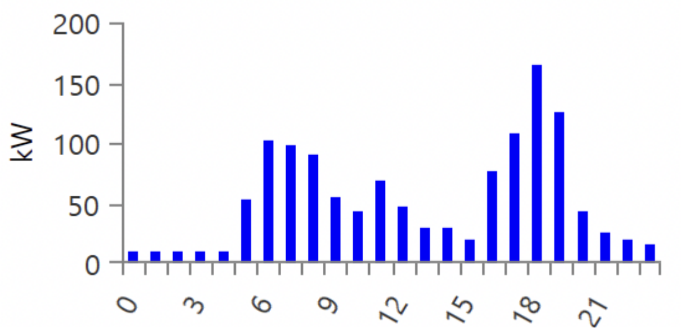

Figure 18. Daily load profile for the total building.

It can be observed that the load profile follows a pattern of higher electricity use in the mornings and evenings. The yearly load profile, which was derived from the time-series of the calculated load, is illustrated in Figure 19. As there was no seasonal variation, the yearly load profile has the same pattern throughout the year.

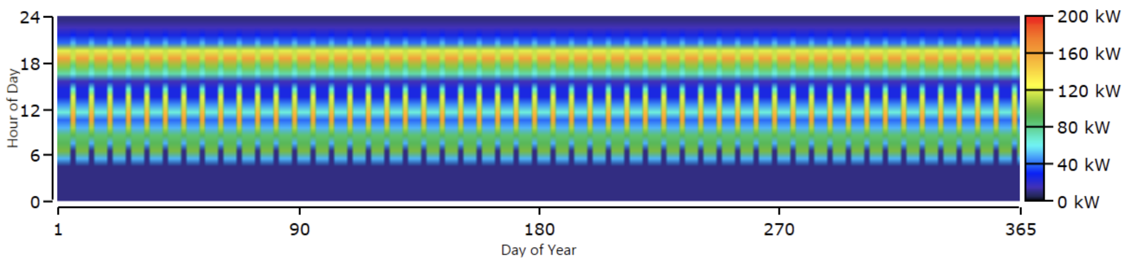

Figure 19. Yearly load profile for the total building.

5.2 Scenarios

In this section, the results from the two different scenarios that were simulated are presented, beginning with the PV system with battery storage, followed by hydrogen storage system.

5.2.1 Battery storage

The optimized PV system with battery storage simulated in HOMER required an installed PV capacity of 800 kW, an inverter with an installed capacity of 200 kW and 20 batteries. The component sizes and search space are presented in Table 6.

Table 6. Sizes and search space for components in PV-battery system.

Component	Optimal value	Unit	Search space
PV modules	800	kW	[700, 750, 800, 850]
Inverter	200	kW	[180, 200, 220]
Battery	20	Quantity	[20, 22, 25]

The total PV production, AC load, excess electricity and capacity shortage per year for the system are presented in Table 7. It can be observed that the system overproduces electricity, as 66.20% of the total produced electricity is excess electricity. Although the unmet electricity constraint was set to 0%, the capacity shortage per year in the simulated system was 0.07%.

Table 7. Specifications for the PV-battery energy management system.

Category	kWh/year	%
PV production	1,591,000	-
Battery input	239,000	-
Battery output	216,000	-
AC primary load	489,000	-
Excess electricity	1,052,000	66.20
Capacity shortage	351	0.07

Visual presentation of the PV power output and state of charge for the batteries through a year is presented in Figures 20 and 21. The PV modules operate between around 6AM and 6PM, which coordinates with the hours of sunlight. The state of charge of the batteries is around 100% during these hours, corresponding to the batteries being charged. The state of charge between midnight to 7AM and 6PM to midnight is lower, indicating output power. The state of charge is slightly higher in the evenings, as they are charged during the day and discharged after 6PM, until being charged again the day after. A time-series plot of the PV production, battery input and load served throughout a year is illustrated in Figure 22. The negative value of the battery input is the output power.

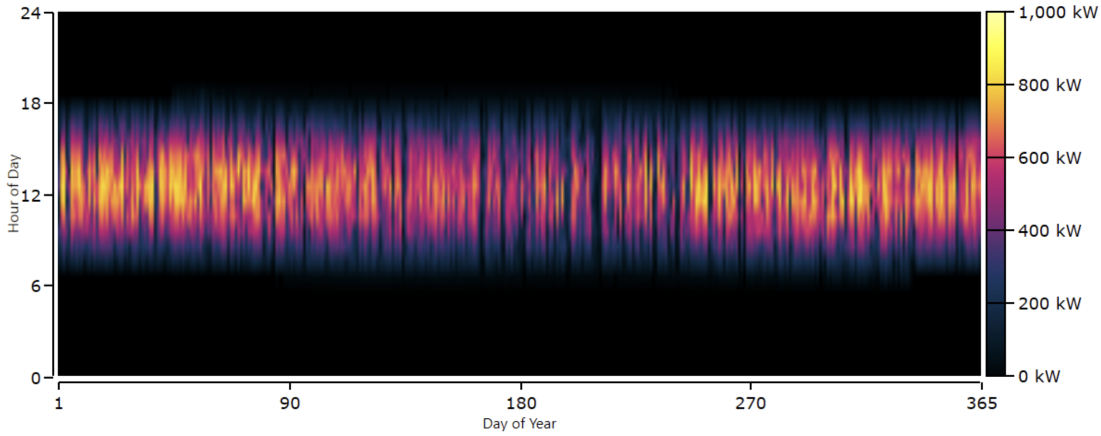

Figure 20. PV power output throughout a year.

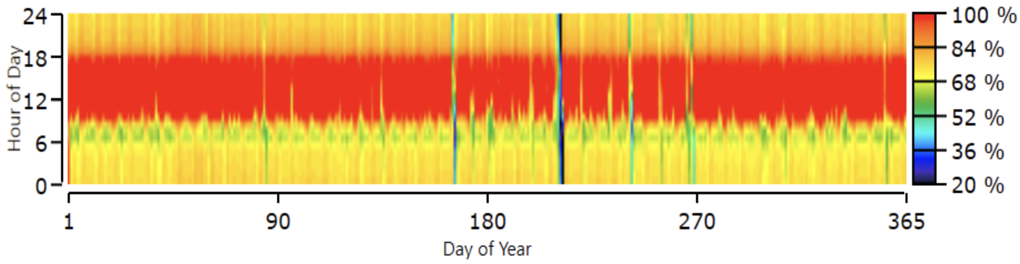

Figure 21. Battery state of charge throughout a year. 100% represents a fully charged battery, while 20% is the lowest discharged state.

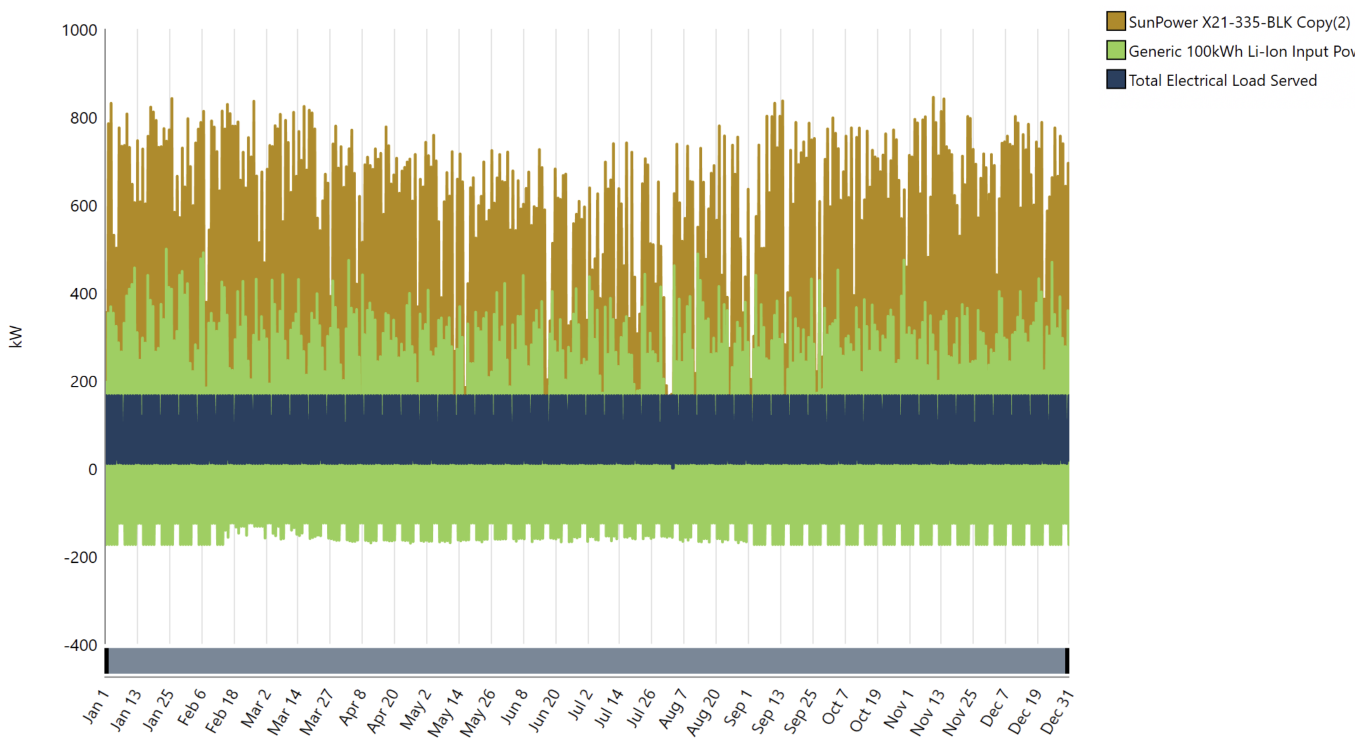

Figure 22. Time-series plot of the PV production, battery input and total load served throughout a year.

The costs for the system and its components throughout its lifetime are presented in Table 8. The NPC for the system, marked in yellow in Table 8, is US$ 1,556,000, while the CoE is 0.25 US$/kWh. It can be observed that the NPC of the PV modules represents the largest share of the total NPC. However, the NPC of batteries is almost equal to the NPC of the PV modules. The replacement cost and salvage for the PV modules are US$ 0, as the lifetime is the same as the system lifetime.

Table 8. Economics of the PV-battery system.

Component	Initial Capital (US$)	Replacement (US$)	Salvage (US$)	NPC (US$)
PV module	781,000	0	0	781,000
Inverter	33,000	14,000	(2,670)	45,000
Battery	641,000	204,000	(115,000)	730,000
System	1,453,000	218,000	(117,000)	1,556,000

5.2.2 Hydrogen storage

The optimized PV system with hydrogen storage simulated in HOMER required an installed PV capacity of 900 kW, inverter with an installed capacity of 200 kW, a 300 kW electrolyzer, a 250 kg hydrogen tank and a 250 kW fuel cell. The component sizes and search space are presented in Table 9.

Table 9. Sizes and search space for components in the PV-hydrogen system.

Component	Optimal value	Quantity	Search space
PV modules	900	kW	[600, 700, 800, 900, 1000]
Inverter	200	kW	[180, 200, 220]
Electrolyzer	300	kW	[200, 250, 300, 350, 400]
Hydrogen tank	250	Kg	[150, 200, 250, 300]
Fuel cell	250	kW	[200, 250, 300, 350]

The total PV and fuel cell production, electrolyzer hydrogen production, together with the excess electricity and capacity shortage per year for the system are presented in Table 10. The fuel cell production represents around 10% of the total electricity production. Comparing the PV-battery system, the excess electricity is smaller, with a value of 34.90% of the total electricity production. In this case, the capacity shortage per year in the simulated system was 0.07%, which is somewhat smaller than the PV-battery system.

Table 10. Specifications for the PV-hydrogen energy management system.

Category	**kWh/year**	**%**
PV production	1,789,000	-
Fuel cell production	213,000	-
Electrolyzer Hydrogen Production	17 000 [kg/year]	-
AC primary load	489,000	-
Excess electricity	698,000	34.90
Capacity shortage	349	0.07

The share of electricity generated by the PV modules and fuel cell per month is visually presented in Figure 23. It can be observed that the PV modules represent a large share of the electric production.

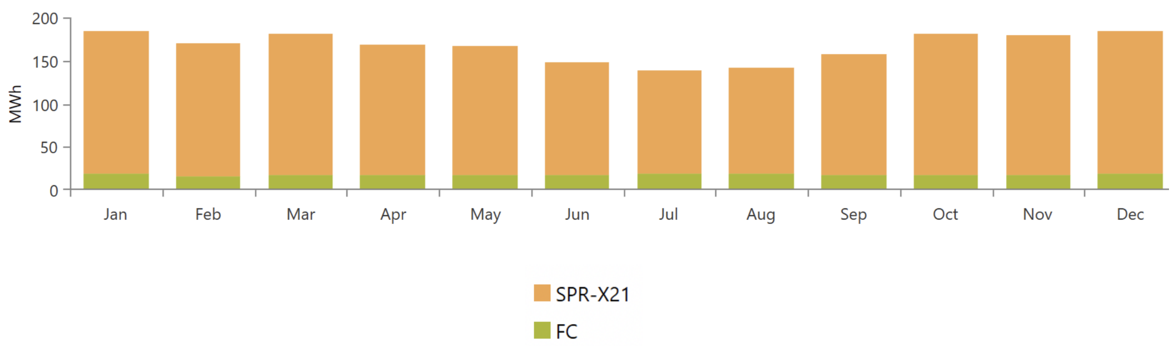

Figure 23. PV (SRX-X21) power and fuel cell (FC) power output per month.

In Figures 24, 25 and 26, a visual presentation of the hourly PV power output, electrolyzer input and fuel cell power output for a year is presented. It can be observed that the PV power output and electrolyzer input power occur during the same hours, while the fuel cell power output during these hours is around 0. The fuel cell operates in the mornings and evenings, when the PV power output and electrolyzer input power is 0.

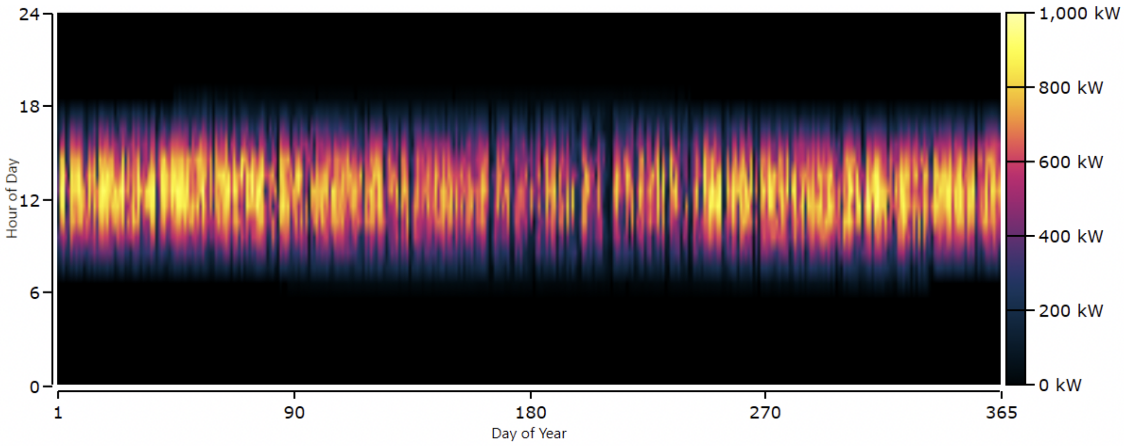

Figure 24. PV power output throughout a year

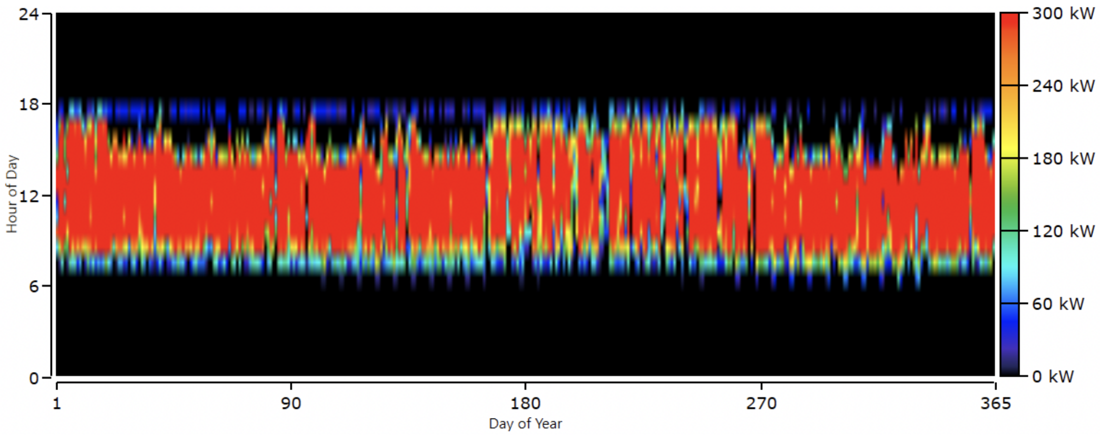

Figure 25. Electrolyzer input power throughout a year.

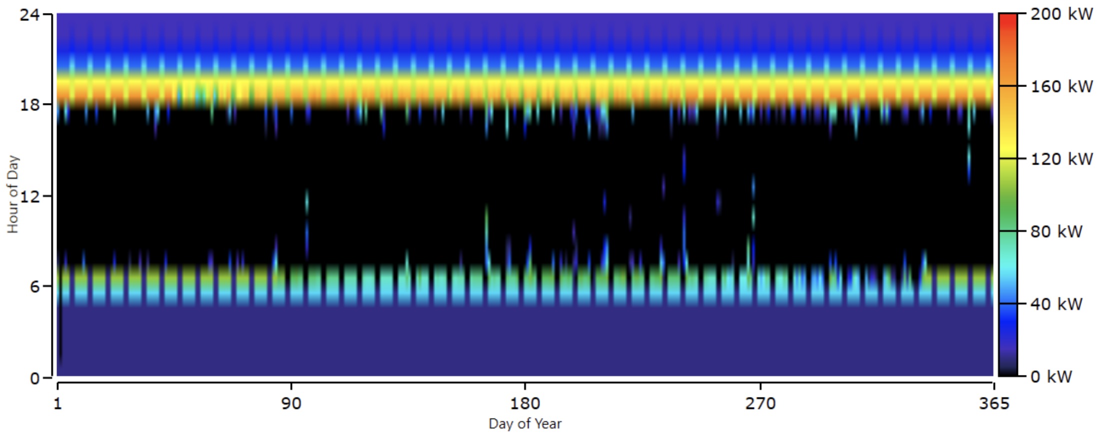

Figure 26. Generator power output throughout a year.

A time-series plot of the total PV production, AC load served and fuel cell power output per day throughout a year is illustrated in Figure 27.

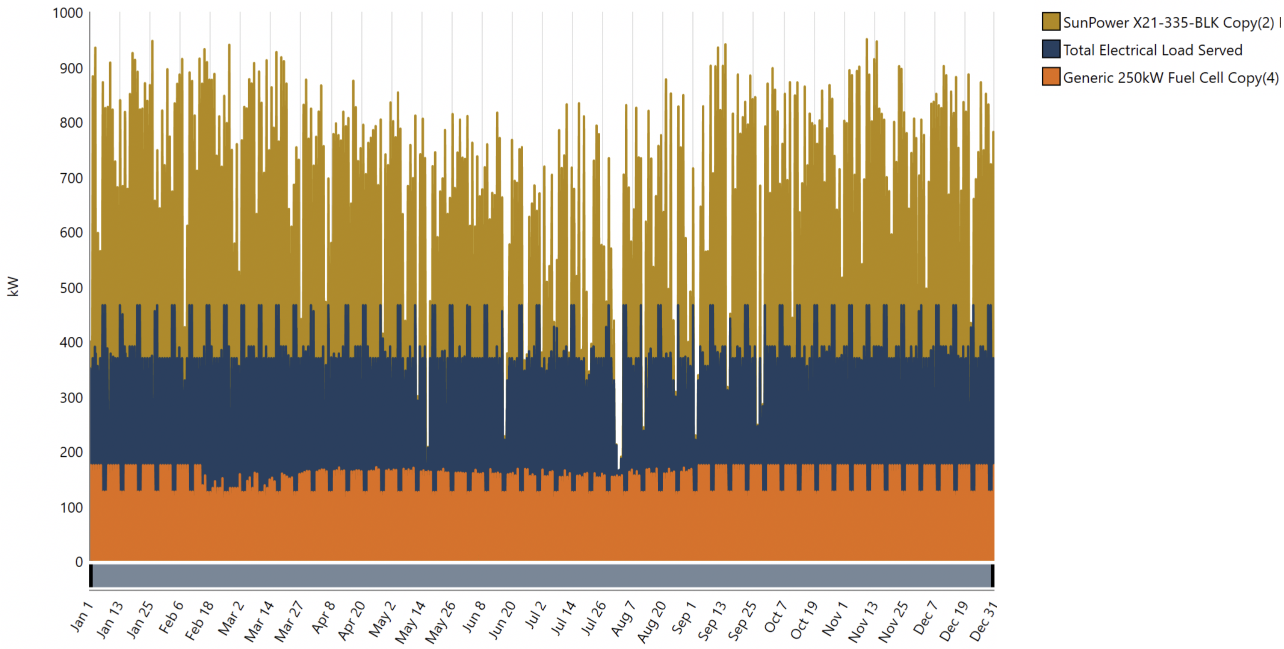

Figure 27. Time-series plot of the PV production, total load served and fuel cell production throughout a year.

Finally, the costs of the PV-hydrogen system and components are presented in Table 11. The NPC cost for the system, marked in yellow in Table 11, is US$ 3,450,000 and the CoE 0.55 US$/kWh. The replacement cost and salvage are US$ 0 for the PV modules as their lifetime is the same as the system lifetime. The fuel cell stands for the largest share of the NPC, closely followed by the electrolyzer and PV modules. In summary, the PV-hydrogen system is thus more expensive than the PV-battery system.

Table 11. Economics of PV-hydrogen system. The total NPC of the PV-battery system is marked in yellow.

Component	**Initial Capital (US$)**	**Replacement (US$)**	**Salvage (US$)**	**NPC (US$)**
PV module	879,000	0	0	879,000
Inverter	33,000	14,000	(2,670)	45,000
Electrolyzer	672,000	285,000	(54,000)	903,000
Hydrogen tank	350,000	0	0	350,000
Fuel cell	700,000	602,000	(29,000)	1,273,000
System	2,634,000	901,000	(85,000)	3,450,000

5.3 Sensitivity analysis results

The sensitivity analysis was performed on the most cost-effective system, being the PV-battery system.

5.3.1 Reduced PV price

Given the continuous trend of decreasing PV prices and the large share of the NPC that the ICC of the PV modules correspond to, a sensitivity analysis was performed on the PV-battery system by reducing the PV price by half. The search space and sizes of all the components remained the same.

The ICC, NPC and CoE of the system are presented in Table 12. It can be observed that the ICC was reduced by half. The NPC for the total system decreased from US$ 1,556,000 to US$ 1,165,000, which is a decrease by 25% of the initial NPC. The CoE decreased from 0.25 US$/kWh to 0.18 US$/kWh, which is a decrease by 25% as well.

Table 12. Sensitivity analysis costs of PV-battery system.

	Initial Capital (US$)	**NPC system (US$)**	**CoE (US$)/kWh**
System	390,000	1,165,000	0.18

5.3.2 Reduced load

In this part of the sensitivity analysis, a reduced load with seven floors was evaluated. The search space needed to be changed, due to smaller electricity demand. The new load had a peak of 90 kW and average electricity use of 723 kWh/day. The sizes of the components and search space is presented in Table 13. This system required an installed PV capacity of 450 kW, a 100 kW inverter and 10 batteries.

Table 13. Sizes and search space for components in PV-battery system.

Component	**Optimal value**	**Unit**	**Search space**
PV modules	450	kW	[400, 450, 500, 550]
Inverter	100	kW	[90, 100, 110, 115]
Battery	10	Quantity	[5, 10, 15]

In Table 14, the NPC and CoE for the system with reduced load is presented. Although the NPC was reduced significantly, there were no major changes to the CoE. Regarding the feasibility, the installed PV capacity still exceeds the 265 kW that would fit the roof of the reference building.

Table 14. Sensitivity analysis costs with reduced load for PV-battery system.

	NPC System (US$)	**CoE (US$)/kWh**
System	827,000	0.25

5.3.3 Reduced installed PV capacity

In this section, the PV capacity was minimized in order to investigate how it would affect the rest of the components, the NPC and CoE. Eventually, the goal was to evaluate a system that had an installed PV capacity that would fit the reference building. The sizes of the other components for a system with an installed PV capacity of 265 kW are presented in Table 15. The system required an inverter of 200 kW and 450 100 kWh batteries. A reduced installed PV capacity therefore results in a larger storage need.

Table 15. Sizes and search space for components in PV-battery system.

Component	**Optimal value**	**Unit**	**Search space**
PV modules	265	kW	[400, 450, 500, 550]
Inverter	200	kW	[180, 200, 210]
Battery	450	Quantity	[200, 250, 300, 350, 400, 450, 500]

The NPC for the system is US$ 16,721,000, marked in yellow in Table 16, and the CoE 2.64 US$/kWh. The other costs for the components and system are presented in Table 16. The NPC of the batteries represents almost the total NPC of the system.

Table 16. Economics of the PV-battery system. The total NPC of the PV-hydrogen system is marked in yellow.

Component	**Initial Capital (US$)**	**Replacement (US$)**	**Salvage (US$)**	**NPC (US$)**
PV module	259,000	0	0	259,000
Inverter	33,000	14,000	(2,670)	45,000
Battery	14,412,000	4,595,000	(2,590,000)	16,417,000
System	14,704,000	4,609,000	(2,592,000)	16,721,000

6. Discussion

In this chapter, the results are discussed, as well as the delimitations, sources of errors and improvements of the methodology. Firstly, the load profile is discussed and then the two PV-systems that were simulated in HOMER.

6.1 Discussion of results

6.1.1 Load profile

When simulating and dimensioning energy systems, it is necessary to have an apprehension of the load demand. Understanding the electricity usage therefore becomes important. As there was a lack of data on domestic household consumption in Ethiopia, and particularly in Addis Ababa, the time-use survey provided an insight into the Ethiopian domestic behaviors and electricity use.

Behaviors and appliances that were distinguished in the surveys were first and foremost making coffee and the Ethiopian bread injera, which involved specific electrical appliances. As coffee was reported to be made and drunk daily, it corresponded to coffee being a significant part of Ethiopian culture. Cooking injera bread, which also is part of the Ethiopian culture and context, was also reported to occur at least once a week in most households. Cooking occurred around 6-8 PM on the weekdays and mostly in the forenoon on the weekends. In addition, cooking was reported to occur during 30 minutes to two hours. Cooking during longer hours might be a cultural phenomenon, which in turn requires larger electricity use.

It is, however, interesting to discuss if behaviors and culture affect electricity use, or if the availability of electricity affects the behaviors. None of the households reported the usage of for example a freezer, dishwasher or vacuum cleaner. One can thus wonder if, for instance, not using a freezer and instead eating freshly cooked food is based on culture or that the lack of reliable electricity results in risks of food being destroyed. The same applies to the use of dishwashers and vacuum cleaners. If the access to electricity is unreliable, perhaps the behaviors and habits form accordingly. The use of these appliances may therefore not be common or considered a priority. Another possibility is that it is an economic question. The socio-economic status of the targeted group was not statistically controlled. Information on the socio-economic status of the studied group could therefore have provided better conditions to make a distinction between economics and culture.

Furthermore, it was observed that the number of adults in half of the households was between three to four. If it represents an adult child, elderly family members, domestic help, a polyamorous relationship etc. is difficult to determine since the age and marital status of the respondents were not covered in the surveys. It was also observed that the total number of household members in some households exceeded the number of bedrooms. As the number of household members affects electricity use, the understanding of the family constellations and demographics in the Ethiopian context becomes important when modeling the load profile, which Capasso et. al. (1994) also emphasized. The methodology could therefore have been improved by including factors such as sex, age, marital status etc. in order to acquire a better understanding of family constellations, individuals' electricity consumption and generate more solid conclusions. As the survey also was performed on distance, including more demographic factors could have minimized errors.

Other behaviors and habits that were identified were the availability at home, foremost on the weekends. Even though some reported that one member was out or working, the overall status of the household became "available at home". As the smallest unit of analysis was the households and not the individual household members, the distinction between different family members could not be made, which in turn affects the results. It was however reported in most surveys that it was common for family or friends to visit on the weekends, which could be a cultural occurrence. By staying home on the weekends, the electrical consumption increases.

Furthermore, watching TV with the family in the evenings on both the weekdays and weekends was reported by almost all household profiles. If this is cultural or depends on the fact that only one weekday or one weekend day was reported, remains unclear. It is important to highlight that the households only reported two days of a week. The use of electricity and availability at home naturally differs from day to day. As the survey only included two days, an estimation is made that the same behaviors and electricity use occur for the whole week and in turn year, which is a weak generalization that could be improved upon in further studies.

Another important remark is that the use of lighting was modeled and not reported by the respondents. The daylight hours, availability at home and sleeping hours were used to model the use of lighting. This is clearly an estimation, which entails results that might not correspond well to reality. As mentioned, the household member could use lighting even though there is sunlight. In addition, the structure of the building, i.e the windows, window sizes, room depths etc. were not taken into consideration. This might result in some areas in the apartments needing lighting although there is sunlight. Furthermore, three lights were assumed to be used when lighting use occurred, which is an assumption and could be improved in future studies.

Overall, the load profile resulted in an average electricity use for the total building of 1341 kWh/day and a daily peak of 165 kW. In addition, the daily load profile correlates with higher electricity use in the mornings and evenings. Although the methodology encompasses multiple deficiencies and sources of errors, it was a first step to construct a load profile and an attempt to acquire a better understanding on how electricity use could appear in Addis Ababa. The method could be improved for future studies by using household members as the smallest unit of analysis, including more demographic factors in the surveys, reporting diaries over a longer period and using a larger number of respondents for statistical results, included factors concerning the building structure for better estimation of lighting use and finally use measured data on electricity consumption to verify the model.

6.1.2 Scenarios

The technical aspect of the simulations of the PV-battery and PV-hydrogen system mainly consisted of evaluating the possibility of both covering the load demand and fitting the PV modules on the available rooftop area on the reference building. The PV-battery system required an installed PV capacity of 800 kW, while the PV-hydrogen system required 900 kW of installed PV. The rooftop area, being 1200 m^2, could fit a total of 265 kW installed PV capacity, resulting in both PV-systems being technically impossible to install. By using larger PV panels of, for example, 1 kW, the systems might have been feasible, even if the modules would have a larger area. However, suppliers of 1 kW PV modules were not found and could therefore not be used in the simulations, although it would have been interesting to examine.

The third part of the sensitivity analysis indicated that it was theoretically possible to implement a PV-battery system that could fit the rooftop area of the reference building and cover the load demand. However, the simulated PV-battery system required 450 100 kWh batteries. It is unlikely that it would be possible to implement a PV-system with 450 100 kWh batteries, both from a technical point of view and due to space and safety aspects. In addition, the NPC and CoE for that system were very high. On the other hand, the second part of the sensitivity analysis implied that a reduced load would require less installed PV capacity. However, the most cost-effective system for the reduced load scenario still required an installed PV capacity of 450 kW, making it impossible to install on the rooftop. If the system with a reduced load would have been examined with a PV capacity of 265 kW, the number of batteries needed for storage might have been less and in turn technically feasible to implement in reality.

Furthermore, both PV systems were over-dimensioned, resulting in a lot of excess electricity production, 66.20% and 34.90% of the total electricity production respectively. If this affects the safety aspects of the system is to take into consideration, though beyond the scope of this study. The excess electricity could, however, in a real case scenario be used for property electricity or other parts of the building that requires electricity. In the PV-hydrogen system, the share of the excess electricity was smaller, which might be due to the electrolyzer using the electricity produced by the PV modules. In addition, there was still a small capacity shortage in both simulations, even though the unmet electricity constraint was set to 0%. The system could thus cover almost 100% of the electricity. The effects of 0.07% capacity shortage are debatable. It is however apparent that systems would provide the residents with more reliable electricity than the current electricity system.

Lastly, it is important to emphasize that the components in all systems were delimited to a certain type and model. There exist several different types of PV modules, inverters, batteries, electrolyzer etc. By using components of other materials or chemistries, the outcome could have been different.

The economic aspects of the simulations involved an evaluation of the NPC and CoE. The NPC for the first scenario was around US$ 1.6M and for the second US$ 3.5M. Whether the NPC is reasonable or not is difficult to evaluate as no data on costs for a PV system were used for comparison in the study. Given that the real project consists of constructing 29 buildings, it can however be perceived as high. The CoE, on the other hand, was 0.25 US$/kWh for the PV-battery system and 0.55 US$/kWh for the PV-hydrogen system. The current CoE in Addis Ababa is 0.04 US$/kWh, resulting in none of the PV-systems being profitable. The CoE is just over five times larger than the current CoE for the PV-battery system and over 12 times larger for the PV-hydrogen system.

Although the electricity system in Addis Ababa is unstable, it is difficult to justify the investment costs of a PV system with storage. Particularly since the electricity generation in the country already derives from renewable sources and is relatively cheap. As the Ethiopian electricity generation is expanding with the new hydropower plant GERD, and the GoE is both improving and expanding the electricity grid, the question remains if the residents find access to reliable electricity worth paying more for or rather would wait for the electricity situation to improve. The use of off-grid PV systems might therefore be more justifiable and profitable in remote areas, where there is no access to electricity or where the costs of connecting to the grid are too high, opposite to areas where the electricity grid is accessible.

In the sensitivity analysis, it was however observed that the NPC and CoE decreased by 25% with a decreased ICC by half of the PV modules. According to the learning curve theory, the costs of batteries and hydrogen components can be expected to decrease in the near future as well. Hydrogen is, for instance, an upcoming and developing technology, making it a relevant option to examine for energy storage. If the trend of decreasing prices continues, an off-grid PV system with storage might be more profitable in the near future. The sensitivity analysis also indicated that a reduced load would result in a smaller NPC. However, the CoE was barely changed, resulting in the system still being economically unjustifiable.

There are nonetheless several sources of errors in the economic analysis of the systems. Firstly, the O&M costs were excluded. O&M can, especially for large systems and components as the ones simulated, be extensive. By including the O&M costs, both the NPC and CoE would increase. On the other hand, the replacement costs were for most components assumed to be the same as the ICC, which could have resulted in a higher NPC and CoE. Yet, transportation and installation costs were overlooked in the study, as well as other components needed for the systems. By including these costs, the NPC and CoE would evidently be higher. In summary, the costs of the system are rather an estimation and approximation than indisputable results.

7. Conclusions

Ethiopia faces many challenges in terms of energy security, considering uninterrupted electricity access. Increasing population and urbanization in the capital are simultaneously increasing the electricity demand and stressing the already over-loaded electricity systems' constraints. With the aim to provide households with reliable electricity, the possibilities of decentralized PV adoption with battery and hydrogen storage were examined respectively in this study. Furthermore, a load profile was developed by the use of time-use diaries.

The constructed load profile resulted in a daily average electricity use of 1341 kWh/day and a daily peak of 165 kW for the total building, consisting of 130 apartments. It was found that most households consisted of more than two adults and in some cases more household members than the number of bedrooms, which could result in higher electricity consumption. The activity that consumed the greatest share of electricity was cooking, which mainly occurred in the evenings during weekdays and in the forenoon on the weekends. Some of the main activities in the cooking category included making Ethiopian coffee and injera. Other common occurring activities that consumed electricity included watching TV with family members. There is room for improving the methodology, which for further studies could generate statistical data.

The results of the optimized PV-systems with battery and hydrogen storage indicated that neither of the two systems were technically possible to implement on the reference building. The PV-system with battery storage required 800 kW installed PV, while the PV-system with hydrogen storage required 900 kW, which both exceeded the maximum installed capacity of 265 kW. However, it was theoretically possible to install a 265 kW PV system with battery storage, though it required 450 100 kWh batteries and was concluded to be non-feasible. The CoE for both simulated systems was significantly higher than the current CoE in Addis Ababa, resulting in neither system being profitable. Although the sensitivity analysis of the PV-battery system resulted in a CoE decrease, with decreasing ICC of the PV modules, the system was still not profitable.

In conclusion, the adoption of decentralized PV with storage is neither feasible nor profitable on the studied reference building. The second part of the sensitivity analysis however indicated that a smaller load, i.e a smaller building, could result in a more feasible system. It would therefore be interesting to examine a smaller building for future research. In addition, it would be relevant to examine decentralized PV adoption in remote areas as it is difficult to justify the investments costs in Addis Ababa as electricity generation already deraving from renewable sources. PV adoption in remote areas may be more profitable due to grid inaccessibility. With electricity generation already being renewable, another interesting aspect to examine of solar energy would be heat generation, for heating water.

References

Awoke, E. (2019), The Impact of Urbanization on the Environment in Africa. The Case of Yeka Sub City, Addis Ababa, V916337, GRIN Verlag: Munich.

Bekele, G. (2009), Study into the potential and feasibility of a standalone solar-wind hybrid electric energy supply system, 1102-0245, Universitetsservice US AB: Stockholm.

Bossel, U., Eliasson, B. (n.d), Energy and the Hydrogen Economy. Available online: https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf (2022-02-29)

Carmo, M., Fritz, D., Mergel, J., Stolten, D. (2013), "A comprehensive review on PEM water electrolysis", International Journal of Hydrogen Energy, vol. 38, issue 12, p. 4901-4934.

Carriveau, R., Ting, D. S-K. (2016), Methane and Hydrogen for Energy Storage. The Institution of Engineering and Technology, London, United Kingdom.

Capasso, A., Grattieri, W., Lamedica, R., Prudenzi, A. (1994), "A bottom-up approach to residential load modeling", IEEE Transactions on Power Systems, vol. 9, issue 2.

Dawood, F., Shafiullah, GM., Anda, M. (2020). "Stand-Alone Microgrid with 100% Renewable Energy: A Case Study with Hybrid Solar PV-Battery-Hydrogen", Sustainability, vol. 12, issue 5.

Ethiopian Electric Utility (2021), Domestic Tariffs. Available at: http://www.eeu.gov.et/index.php/com-youtubegallery-menu/statistics-tariffs/tariffs/domestic (2022-04-12)

Hircher, M., Yartys, V., et al. (2020), "Materials for hydrogen-based energy storage – past, recent progress and future outlook", Journal of Alloys and Compounds, vol. 827.

HOMER Energy (n.d). HOMER software. Available at: https://www.homerenergy.com/ (2022-01-15)

HOMER Pro [1] (2020), Welcome to HOMER. Available at: https://www.homerenergy.com/products/pro/docs/latest/index.html (2022-01-15)

HOMER Pro [2] (2020), Global horizontal irradiation (GHI). Available at: https://www.homerenergy.com/products/pro/docs/latest/global_horizontal_irradiance_ghi.html (2022-03-24)

HOMER Pro [3] (2020), Clearness index. Available at: https://www.homerenergy.com/products/pro/docs/latest/clearness_index.html (2022-03-24)

HOMER Pro [4] (2020), How HOMER Calculates the Radiation Incident on the PV Array. Available at: https://www.homerenergy.com/products/pro/docs/latest/how_homer_calculates_the_radiation_incident_on_the_pv_array.html (2022-03-24)

HOMER Pro [5] (2020), Index. Available at: https://www.homerenergy.com/products/pro/docs/latest/index.html (2022-03-24)

HOMER Pro [6] (2020), PV Slope. Available at: https://www.homerenergy.com/products/pro/docs/latest/pv_slope.html (2022-03-29)

HOMER Pro [7] (2020), PV Azimuth. Available at: https://www.homerenergy.com/products/pro/docs/latest/pv_azimuth.html (2022-03-29)

HOMER Pro [8] (2020), Ground reflection. Available at: https://www.homerenergy.com/products/pro/docs/latest/ground_reflectance.html (2022-03-29)

HOMER Pro [9] (2020), Derating factor. Available at: https://www.homerenergy.com/products/pro/docs/latest/photovoltaic_panels_pv.html (2022-03-29)

HOMER Pro [10] (2020), Hydrogen tank. Available at: https://www.homerenergy.com/products/pro/docs/latest/hydrogen_tank.html (2022-04-05)

International Energy Agency (IEA) (n.d), Ethiopia. Available at: https://www.iea.org/countries/ethiopia (2022-03-10)

International Energy Agency (IEA) (2019), Ethiopia Energy Outlook. Available at: https://www.iea.org/articles/ethiopia-energy-outlook (2021-11-29)

International Energy Agency (IEA) (2022), Energy security: Reliable, affordable access to all fuels and energy sources. Available at: https://www.iea.org/topics/energy-security (2022-03-10)

International Trade Administration (ITA) (2020), Ethiopia - Country Commercial Guide. Available at: https://www.trade.gov/knowledge-product/ethiopia-energy (2021-11-29)

Jakstas, T. (2020), “Chapter 5 - What does energy security mean?”, Energy Transformation Towards Sustainability. p. 99-112.

Lighting Global (2019), ”Lithium-ion Batteries Part I: General Overview and 2019 Update”, Technical Notes, issue 30.

Meles, T.H. (2020), “Impact of power outages on households in developing countries: Evidence from Ethiopia”, Energy Economics, vol. 91.

Mertens, K. (2018), Photovoltaics: Fundamentals, Technology, and Practice. 2nd edition. John Wiley & Sons: USA.

Mongird, K., Viswanathan, V., Alam, J., Vartanian, C., Sprenkle, V. (2020), 2020 Grid Energy Storage Technology Cost and Performance Assessment. U.S Department of Energy: USA.

NASA Prediction Of Worldwide Energy Resources (2021). NASA Surface Meteorology and Solar Energy.

Nationalencyklopedin (NE). (n.d), Stora etiopiska renässansdammen. Available at: https://www-ne-se.ezproxy.its.uu.se/uppslagsverk/encyklopedi/l%C3%A5ng/stora-etiopiska-ren%C3%A4ssansdammen (2021-11-20)

Nationalencyklopedin (NE) (2020), Etiopien. Available at: https://www-ne-se.ezproxy.its.uu.se/uppslagsverk/encyklopedi/l%C3%A5ng/etiopien (2021-11-20)

National Renewable Energy Laboratory (NREL) (2016), Distributed Generation Energy Technology Operations and Maintenance Costs. Available at: https://www.nrel.gov/analysis/tech-cost-om-dg.html (2022-04-05)

Nel Hydrogen (n.d), Water electrolyzers / hydrogen generators. Available at: https://nelhydrogen.com/water-electrolysers-hydrogen-generators/ (2022-03-17)

Nel Hydrogen (2021), M Series Containerized - Proton Exchange Membrane (PEM) Hydrogen Generation Systems, Nel Hydrogen: USA.

NREL (National Renewable Energy Laboratory) (2018), Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition. NREL: Denver, USA.

Our World Data (2019), Access to electricity. Available at: https://ourworldindata.org/energy-access (2022-03-16)

Our World Data (2021), Ethiopia: Energy Country Profile. Available at: https://ourworldindata.org/energy/country/ethiopia (2022-01-29)

Rigas, F., Sklavounos, S. (2005), "Evaluation of hazards associated with hydrogen storage facilities", International Journal of Hydrogen Energy, vol. 30, issue 13-14.

Rosen Solar (2019), Battery Energy Storage System. Available at: https://www.rosensolar.com/h-pd-489.html#_jcp=3_70 (2022-04-05)

SecondSol (2022), SunPower 420 W MAXEON 3 Black. Available at: https://www.secondsol.com/en/anzeige/30007/solar-panel/crystalline/mono/sunpower/sunpower-420-w-maxeon-3-black-spr-max3-420blk (2022-04-06)

SNABB Sustainable Construction (n.d), About us. Available at: https://snabbcon.com/ (2022-01-29)

SNABB Sustainable Construction (2021), Sustainable Housing Project Pilot Prototype Project Proposal. SNABB Sustainable Construction: Addis Ababa, Ethiopia.

Solential Energy (2021), Solutions - battery storage. Available at: https://www.solential.com/solutions/ (2022-03-08)

Sunpower MAXEON (2022), MAXEON 3 Solar panel. Available at: https://sunpower.maxeon.com/au/sites/default/files/2022-02/SPR-MAX3-420-BLK%20SPR-MAX3-415-BLK%20SPR-MAX3-410-BLK.pdf (2022-03-23)

Taibi, E., Blanco, H., Miranda, R., Carmo, M. (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal. International Renewable Energy Agency: Abu Dhabi.

Electric Power Research Institute (2015), Budgeting for solar PV plant operations & maintenance: practices and pricing, The Electric Power Research Institute: California, USA. https://www.osti.gov/servlets/purl/1234935

The World Bank Group (2019), Global Solar Atlas - Ethiopia. Available at: https://globalsolaratlas.info/download/ethiopia (2022-03-10)

The World Bank Group (2020), Solar Photovoltaic Power Potential by Country. Available at: https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country (2022-03-11)

Tikuneh, M., Worku, G. (2018). "Identification of system vulnerabilities in the Ethiopian electric power system", Global Energy Interconnection, vol. 1, issue 3, p 358-365.

Topographic map (n.d), Addis Ababa. Available at: https://en-gb.topographic-map.com/maps/lpsf/Addis-Ababa/ (2022-03-11)

UNFPA (2022), World Population Dashboard - Ethiopia. Available at: https://www.unfpa.org/data/world-population/ET (2022-04-14)

United Nations (UN) (2005), Guide to Producing Statistics on Time-Use: Measuring Paid and Unpaid Work. United Nations Publication: New York, USA.

United Nations (UN) (2010). Energy for a Sustainable Future - report and recommendations. New York, USA.

U.S Department of Energy (2015), Fuel cell technologies office. Available at: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf (2022-01-14)

Vattenfall (n.d), Vad är solenergi? Available at: https://www.vattenfall.se/solceller/hur-fungerar-solceller/solenergi/ (2021-11-23)

Vattenfall (2019), Solcellsrapporten Uppsala. Available at: https://www.vattenfall.se/494fc6/globalassets/content-hub/hus--hem/solfaktorn/2019/solrapporten-2019-uppsala.pdf (2021-11-23)

Widen, J., Lundh, M., Vassileva, I., Dahlquist, E., Ellegård, K., Wäckelgård, E., (2009), "Constructing load profiles for household electricity and hot water from time-use data—Modelling approach and validation" Energy and Buildings, vol. 41, issue 7, p. 753-768.

World Bank Group & GFDRR (2015), Addis Ababa, Ethiopia - Enhancing Urban Resilience. The world bank group: Washington, USA.

White Arkitekter (n.d), Verktyg för dagsljusberäkning. Available at: https://whitearkitekter.com/se/wise-dagsljus/ (2022-03-23)

World Data (n.d), Average length of day in Addis Ababa. Available at: https://www.worlddata.info/africa/ethiopia/sunset.php (2022-01-18)

Zhang, Z., Zhang, S. (2015.) "Challenges of Key Materials for Rechargeable Batteries", Rechargeable batteries. Springer: Switzerland.

Personal communication

Nel Hydrogen US. Email. 2022-03-23.

Nel Hydrogen Denmark. Email. 2022-03-30.

Rosen Solar. Email. 2022-04-05.

U.S Department of Energy. Email. 2022-03-31.

Appendix A

The time-use survey for the time-use diary.

TIME-USE DIARY

The purpose of this study is to understand the usage of electricity in your household. So for one weekday and one weekend I would appreciate it if you could write down all the activities you do in your household that include the use of electricity and at what time. Including what time you wake up, leave the house, come back home and what time you go to bed. Please don't forget the lighting. ***OBS!*** *If you are the only one answering for your household, please include the activities of your family members*.

For example: “ 7.00: Wake up. Turning on the bedroom light”
“ 7.15 - 7.30: Make coffee with a coffee machine”
“ 7.30 - 7.45: Iron clothes”
…
…

“ 17.30: Coming home”
“ 18.00 - 19.00: Cooking dinner with food blender and stove”
“ 20.00-21.00: Watch TV with X family members”

The survey is ***anonymous*** *so you do not have to write any names in the study.*

Background information	
Household size	
Number of household members (Adults)	
Number and age of household members (Children)	

Time-use diary for a weekday. Day:___________

Starting time	Ending time	Activity & Appliance

Time-use diary for a weekend. Day:____________

Starting time	Ending time	Activity & Appliance

Appendix B

Appliances and ratings (W) used to model the load profile.

```
A.FRIDGE_POWER = 42;

A.STOVE = 3000;

A.OVEN = 2300;

A.MICROWAVE = 600;

A.BLENDER = 300;

A.IRON = 400;

A.COFFEEMACHINE = 600;

A.COFFEEBLENDER = 180;

A.ETHIOPIANCOFFEEMACHINE = 1100;

A.WATERBOILER = 2200;

A.TV_POWER_ACTIVE = 150;

A.PHONECHARGER = 3;

A.LAPTOP = 50;

A.AUDIO_POWER_ACTIVE = 30;

A.HAIRDRYER = 400;

A.FLATIRON = 150;

A.SHAVEMACHINE = 15;

A.INJERAMAKING = 1450;

A.TRENDMILL = 600;

A.HUMIDFIER = 200;

A.BALLONPUMP = 300;

A.WIFIROUTER = 12;

A.LEDLIGHTBULD7 = 7;

A.LEDLIGHTBULD9 = 9;
```