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Master's thesis

Decentralized Energy Systems for Africa in times of Climate Change

An exploratory study of how challenges with off-grid PV and battery systems can be overcome for the region, focusing on technology advancement in sodium-ion batteries and affordable solutions

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Preface

This master's thesis is the conclusion of my Master's degree in Renewable energy systems at the department of Technology Systems (ITS), at the University of Oslo (UiO). This thesis addresses the issues with providing access to electricity for rural parts of Sub-Saharan Africa.

I would like to thank my supervisor Prof. Josef Noll, for guidance through my thesis, and for sharing his knowledge, advise and network with me. He gave me advise on how to approach the subject and put me in contact with the right people. I would also like to thank Julia Wind from IFE, who went above and beyond to help me with literature and contacts in the battery field, and shared her input on the topic.

Of course, I would like to thank my experts in the field, who provided valuable insight into the situation in the area and shared their experience with me. Finn Helge Tolpinrud, Dr Albert Awopone and Charles Ogalu, this thesis would not be the same without you. I would also like to thank everyone in that work in the field of renewables and sodium-ion batteries that I have talked to, who have met me with support and enthusiasm about my thesis.

Last, but not least, I would like to express my gratitude towards my family and friends for all their support through this journey.

Oslo, May 2024

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Abstract

Challenges with high temperature, resulting in increased degradation of batteries and worse performance for PV is one of the main issues for off-grid energy systems for rural Sub-Saharan Africa. The lack of knowledge from the users on how to properly operate and maintain their system is also an issue. Solutions that overcome these challenges are studied, with special focus on the possibility to use sodium-ion batteries in a decentralized energy system.

A possibility for batteries lies in the newly commercialized sodium-ion batteries, with promising performance in higher temperatures, and being anticipated to be more affordable than lithium-ion batteries in the next coming years. Sodium ion batteries are shown to have a larger operating temperature range than lithium-ion batteries (LFP), at -40 to 80 ^oC, compared to -20 to 60 ^oC, respectively. Cycle life is also comparable, at around 6000 to 10000 cycles at optimal condition, and 3000 to 4500 cycles at sub-optimal conditions. Sodium-ion batteries are still in its infancy of commercialization, and needs more testing and in-field validation before it can be rolled out.

For PV, choosing monocrystalline silicon PV over polycrystalline and ensuring proper ventilation is the most important for performance. Choosing panels with higher rated capacity has been shown to be more affordable.

To ensure that the 600 million people living without access to electricity in Sub-Saharan Africa today, mainly being poor, rural households, gain this as fast as possible, measures on making decentralized energy systems affordable needs to be done. This thesis studies the challenges of such systems and finds solutions, using in-depth litterature reviews, validity analysis from experts in the field and available data.

Sammendrag

Utfordringer knyttet til høy temperatur, som resulterer i økt degradering av batterier og lavere ytelse for PV, er et av hovedproblemene for energisystemer som er utenfor nettet i landlige Afrika sør for Sahara. Mangelen på kunnskap fra brukerne om hvordan de skal betjene og vedlikeholde systemet er også et problem. Løsninger på disse problemene studeres i denne oppgaven, med spesielt fokus på muligheten for å bruke natrium-batterier i et desentralisert energisystem.

En mulighet for batterier ligger i de nylig kommersialiserte natium-ione batterien, med lovende ytelse i høyere temperaturer, og som forventes å være rimeligere enn litium-ione batterier i de neste kommende årene. Natrium-ione batterier har vist seg å ha et høyere driftstemperatur-område enn litium-ione batterier (LFP), ved henholdsvis -40 til 80^{o}C og -20 til 60 ^{o}C. Syklus-levetiden er sammenlignbar, på rundt 6000 til 10000 sykluser under optimale forhold, og 3000 til 4500 sykluser under sub-optimale forhold. Natrium-ione batterier er fortsatt i sin spede begynnelse av kommersialisering, og trenger mer testing og validering i felt før det kan bli rullet ut.

For PV er det å velge monokrystallinsk silisium PV over polykrystallinsk og å sikre nok ventilering av panelene det viktigste for ytelsen. Å velge paneler med høyere klassifisert kapasitet har vist seg å være det rimligste.

For å sikre at de 600 millioner menneskene som i dag lever uten tilgang til elektrisitet i Afrika sør for Sahara, som hovedsaklig er fattige husholdninger på landsbygda, får dette så raskt som mulig, må det gjøres tiltak for å gjøre desentraliserte energisystemer rimeligere. Denne oppgaven studerer utfordringene til slike systemer og finner løsninger ved å bruke dyptgående litteraturstudier, validitetsanalyser fra eksperter på området og tilgjengelige data.

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Chapter 1

Introduction

In today's world of technology, it might be hard to imagine not having access to electricity. But, unfortunately, that is still the situation for 750 million people (2022) [21]. Out of these people, 600 million of them live in Africa, which is why focus on finding ways to provide access to electricity in this area is so important. In the last decades, major development in the area has been done, but the overall access to electricity in Sub-Saharan Africa is still only 50,6%[1]. One of the main problems and reasons for this has to do with the fact that Africa is a large continent, with the majority of the people living in rural areas[2]. When combined with the countries of Africa having low GDP and historically not seen the same technological developments as other continents, means that grid connectivity is too expensive in many cases[30]. In fact, 58% of the 1.2 billion population of SSA lives in rural areas[3][4], meaning that for many, the only viable option is an off-grid system[46]. For the already grid-connected population of the SSA, these are mainly people living in and around cities and population centers, simply because they are the easiest to electrify by grid due to high population density. The urban population is a large portion of the population that already have access to electricity, and out of the 600 million that still are without electricity access, 80% of them are living in rural areas[19]. This shows the importance of creating energy solutions for these people, which is what this thesis will focus on.

To be able to reach climate targets, as well as giving these people electricity in the best and most efficient way possible, decentralized energy systems based on renewable energy have been shown to be a good solution[10]. For households, they would be able to generate enough electricity from solar

[1] https://data.worldbank.org/country/ZG
[2] https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ZG
[3] https://data.worldbank.org/country/ZG
[4] https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ZG

cells, but would also benefit greatly by having batteries implemented, so they also have electricity when the sun is not shining. With both technologies, prices have dropped significantly[5][6], but because of many people still earning very little money, there is still quite a mismatch between the cost of such an electricity system and what they can afford. We also see challenges with performance, especially with the batteries in the harsh environment, especially struggling with shortened lifetime due to elevated temperatures. We have also seen a lack of knowledge, quality and transparency in previous projects, which again creates challenges.

1.1 Motivation

There are several reasons why "Decentralized energy systems for Africa in times of climate change" became the topic of my master thesis. Personally, it all started with a visit to a rural village living on floating islands on Lake Titicaca in Peru in 2019. I was finished with high school and was not sure which way I wanted to go academically, so I was backpacking around the globe. In this village, people lived off of trading fish and goods, and they really did not have any economy at all. But after the Peruvian government installed a PV panel on the roof and a battery in the living room of each family, it meant that the people could charge their phone, row into the nearest city and drive a bike-taxi to earn money. This completely changed their life, and meant that they could buy the things they needed, and did not have to rely solely on trading. When I saw how little is needed to make such a big change and how many more opportunities it gave, I knew that this was something I wanted to be a part of. So, the following summer, I started a bachelor's degree in Material science for Energy- and Nano Technology at the University of Oslo, following a master's degree in Renewable Energy Systems, which is concluded with this thesis.

My interest in doing this for Sub-Saharan Africa comes from the fact that it is one of the places in the world with the lowest electricity access rates [30]. This is because there are limited with electrical grids built in the area, the distances are far and the population densities is low, making grid extensions to rural communities too costly. While the region has low energy use and emissions both now and historically, compared to others, it is especially sad to see that it is one of the regions who will probably experience the most severe effects from climate change [10] [19]. The

[5]Prices of PV was reduced by 89% in 10 years (2009-2019): https://ourworldindata.org/cheap-renewables-growth

[6]Prices for PV was reduced 82% in 10 years (2013-2023): https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/

potential for providing electricity access to a large part of the population here is huge, which can lead to social and economic development [36].

Academically, this thesis gives me the opportunity to apply the knowledge that I have built through my courses at the University of Oslo to a practical context. Especially, the courses TEK5440 – Batteries: technology and systems, TEK5310 – Solar cells, TEK5330 – Solar energy systems, TEK5370 – Grid, Smartgrid and IoT, TEK5340 – Energy system analysis: modelling, methods and scenarios, TEK5350 – Energy markets and regulation, FYS3280 – Semiconductor components and KJM3110 – Electrochemistry has been of huge interest, and have been important for realizing this thesis.

We can also see how this master thesis is in line with several of the United Nations Sustainable development goals, which is another motivation to do this work. Especially development goal 7, "Ensure access to affordable, reliable, sustainable and modern energy for all", specifically target 7.1 ("universal access to electricity") and 7.2 ("increase sustainability share of energy mix") are in focus. Under these targets, the thesis covers the indicators 7.1.1 ("Proportion of population with access to electricity"), 7.1.2 ("Proportion of population with primary reliance on clean fuels and technology") and 7.1.2 ("Renewable energy share in the total final energy consumption"). Other goals, targets and indicators are met as well, such as target 3.3 and 3.7 (by making access to information about health and deceases possible), 4.1 and 4.2 (by facilitating for quality learning and education) and 10.1 (income growth for bottom 40% of the population) and 10.b (Encourage official development assistance)[7].

1.2 Objective

This thesis main objective is to investigate the challenges of implementing decentralized energy systems in Sub-Saharan Africa, studying the technical, economical and educational aspects, and to provide insight in what the important actions are towards enabling universal access to electricity. Components of a decentralized energy systems are explored in regards of how they operate at elevated temperatures, with special focus on Sodium-ion and Lithium-ion batteries. Developing energy systems specifically adapted for the regions hot climate will be crucial, as this will improve lifetime and efficiency of such systems [35], which again can influence the costs.

Commercial Li-ion batteries (LIB) and Sodium-ion batteries (SIB), which

[7] UN Sustainable development goals: https://sdgs.un.org/goals

are on the verge of commercialization, are compared. The most common batteries today are LIB and lead-acid batteries, however they both have challenges with lifetime. The main challenge today is that the temperature is too high for the batteries. LIB have an operating temperature of around -20 to 45/60 ^{o}C[17], resulting in an early death of the system, as well as it still being too expensive for people with lower income. Because of this, the thesis aims to investigate the possibility of using SIB instead, as it is known to have comparable performance to types of LIB, have a wider temperature range of around -40 to 80 ^{o}C [17][8][9], and are competitive on price. Because these batteries have just recently been commercialized, studies including SIB for stationary storage is still scarce, and this thesis aims to contribute to the development of knowledge in this field.

By studying data from the industry, doing in-depth literature reviews and expert interviews, a basis is created to analyze and explore different scenarios and how variables related to the technology such as temperature dependency, cost and lifetime influence the scenarios and outcome. In many techno-economic studies of off grid energy systems does not consider the heightened degradation of the system because of the elevated temperatures[54][43]. The aim is to overcome some of the specific challenges that energy systems in the area has today. The thesis is exploratory and focuses on the possibilities that lie in existing and near-future technology, so that decision makers can make the right call and invest in the right solutions. This thesis aims to answer the overall research question:

- What are the challenges of performance, durability and affordability for decentralized energy systems in Sub-Saharan Africa, and how can they be overcome?

1.3 Methodology

This chapter aims to explain the methods being used in this thesis. The aim of the thesis is to find solutions for decentralized energy systems that can overcome the specific challenges of Sub-Saharan Africa. In this master thesis, a combination of scientific methods has been used to find the results and conclusions. Naturally, with the research question, the thesis can be divided into three sub-categories, being performance, durability and affordability. These will all be looked at individually as well as combined, and results for both where we are today, and where we can expect to be in the coming years will show which actions that are needed to take to ensure

[8] https://www.kiterise.at/wp-content/uploads/2023/11/Kite-Rise_Whitepaper_20230601-1.pdf

[9] https://www.catl.com/en/news/665.html

reliable energy systems in rural Africa.

Literature review: An in-depth literature review was conducted and forms the basis for the specifics of the targeted area (SSA). The review can be divided into two main categories, the first focusing on energy systems in the area, including load profiles, challenges and knowledge from previous projects, and the other on scientific research of technologies and performance in various conditions, and the technicalities of implementing these in a system in SSA. The literature was generally gathered through four databases: elicit.org (semanticscolar), ScienceDirect, ResearchGate and Google Scholar, as well as standalone scientific papers published in different scientific journals. Also, general knowledge from courses in my degrees gave a fundamental understanding of the technologies, policies, markets and systems.

Validity analysis: Then, a validity analysis was conducted by cross referencing the knowledge from the literature review with expert sources. The sources are people that work with or have experience with these kinds of systems in countries all over SSA and people working with specific technologies, such as batteries or PV, and their experiences and challenges stated in the conversations were categorized, compared with the challenges of the literature review and taken into consideration in the analysis and of the scenarios of this thesis.

Data extraction and analysis: The data was extracted and collected from literature and further used in this thesis to generate synthetic load profiles, technology development, price development and cost estimates for the coming years. One of the main problems for stand-alone systems in Africa today lies in that batteries have shortened lifetime and are too costly to include, and the main focus for this study has been on solutions here. The data has been used for different battery technologies to study how they can handle the elevated temperatures and how they handle different cycles (DOD and cycle life). This gives valuable information of how the different battery technologies are able to handle different demands and environments, and makes it clearer which one is the best solution for our case.

Results and discussion: The cumulative information gathered were then used to study how the price of a system that meets estimated demands would affect the user's overall economy, and if different sized systems and demand are viable. Scenarios were made to study how scale, technology, demand and cost are affecting each other. Several possibilities were discussed and explored, and the results and discussion aimed to answer the research question:

- What are the challenges of performance, durability and affordability for decentralized energy systems in Sub-Saharan Africa, and how can they be overcome?

1.4 Scope of work

The scope of this thesis will focus on off-grid energy systems for rural households with low to middle income, as this takes up the majority of the people lacking electricity in SSA[19]. The main focus will be on the technology and solutions for this, with the largest focus being on battery technology. There are a lot happening in this technology, and to be able to keep up with and understand this part of the system, the main focus lies here. Studies of different battery chemistries, their performance in high temperature, lifetime and cost will be studied thoroughly. There will also be studied other parts of the system, such as PV, and other aspects, such as costs. There are still several parts of an energy system that will be studied, but are not in focus here, such as inverters and BOS (Balance of system), and while these have their own challenges to be overcome, this is out of the scope of this thesis. They will however be part of the cost estimation for such a system.

There are several challenges that will be taken into account in this thesis, and more in-depth analysis are found later in the thesis, but to give an introduction to the situation:
- SSA is dealing with having little grid infrastructure, and unstable grids with high electricity prices[10]
- 58% of the population lives in rural areas[10], meaning that the population density is low, and grid extension is not a cost-effective option in many cases
- Off-grid systems might be the only viable solution, and this has large upfront costs, so ways to lower or move these costs are important, especially for the low income households[10]
- Performance of the off-grid energy systems are often a problem due to the high temperatures, meaning the lifetime and performance decreases, which again lead to increased cost[29]
- Local understanding/education on the energy systems are low, and many use their energy system in an un-optimal or destructive way[27]

To sum up, by studying challenges in decentralized energy systems in hot climates, the thesis aims to find solutions that can help towards the goal of

[10] https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ZG

universal electricity access. Before the challenges can be solved, the needed knowledge and understanding of the situation and technologies are presented in chapter 2. There are of course several challenges, and they are all important, but within the scope of this work, the main focus is on solutions for the technology. Other factors such as funding, policy, acceptance and other are known to the author, and will be touched upon, but will not be the focus of this thesis.

Chapter 2

Theoretical background

This chapter covers the needed theoretical background to understand the topic, technologies, scenarios and challenges that will be faced with in the decentralized energy systems. It starts by looking into the geographical area of Sub-Saharan Africa (SSA), and studies the electricity access, population and climate of the area. It then goes into the fundamentals of the main components of a decentralized energy system, namely PV-panels and batteries, before it goes into the complex situation of both single components and the entire system, including if it would be grid connected or off-grid. It finishes with studying typical load profiles and consumption patterns and the use of appliances.

2.1 Sub-Saharan Africa

This subchapter investigates the region studied in this thesis. It aims to explain the general facts and the situation in the region and what specifically can affect our energy system.

Sub-Saharan Africa is the region of the continent of Africa that is south of the Sahara Desert[1]. It is a large and diverse area consisting of almost 50 countries and 1.2 billion people [2].

2.1.1 Geography

It is important to know the geographical area to map out expected electricity production. Sub-Saharan Africa covers a land area of around 24 million km^2[3], and is part of the 2nd largest continent in the world, after Asia. It stretches from around 15^o N in the Sahel, the transition zone from

[1] https://snl.no/Afrika_sør_for_Sahara
[2] https://data.worldbank.org/country/ZG
[3] https://data.worldbank.org/country/ZG

the Sahara Desert, through the equator and all the way down to 34^o south in the Cape Floristic region of South Africa. It covers 6 time zones[4], covering around 70 degrees of longitude. The terrain is highly diverse, with savannas, highlands, rainforests, deserts, great lakes, mountain ranges and valleys[5].

2.1.2 Climate

To study the performance of an energy system, it is important to know which climate it is operating in. When it comes to climate, the Sub-Saharan African region can be divided into climate zones. The Köppen-Geiger climate classification system is used to characterize the zones[6], as seen in 2.1[7]. From the classification, it can be noted that there are mainly two categories of climate types: tropical and arid/dry. There are also some areas with more temperate climate. Both tropical and arid/dry regions are known for having high temperatures but differs from one another when it comes to type of vegetation, humidity and rainfall.

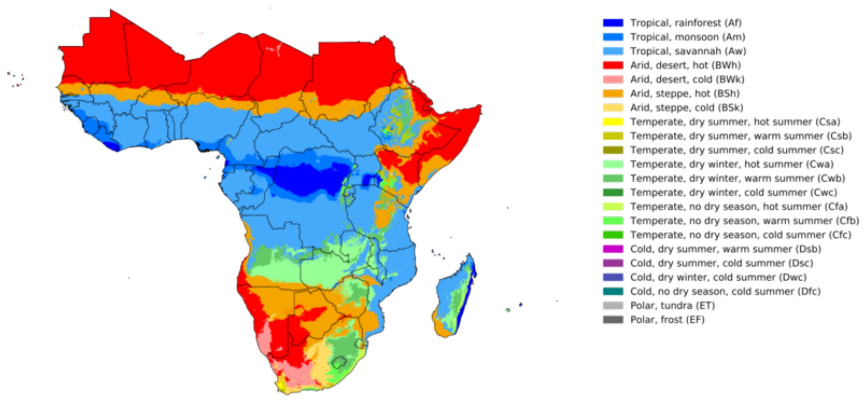

Figure 2.1: The Köppen-Geiger climate classification system for Sub-Saharan Africa (ref: footnote 7)

The type of climate is going to affect how the energy system operates, so it is important to understand this in order to make the best suited system for the area. Both solar cells and batteries performance will be affected by elevated temperatures, and problems related to high humidity also need to

[4]https://en.wikipedia.org/wiki/Time_in_Africa
[5]https://en.wikipedia.org/wiki/Sub-Saharan_Africa
[6]https://en.wikipedia.org/wiki/Köppen_climate_classification
[7]https://commons.wikimedia.org/w/index.php?curid=127825400

be accounted for. The area in focus is also big and has variations, so recommendations and the best suited system might vary for different parts. As seen in 2.2[8], which studied the outdoor and indoor temperature of the SSA region using weather data spanning 30 years, it can be observed that in large parts, both indoor and outdoor, the mean temperature is in the high 20^oC or over 30^oC for extended periods of time. This shows again that the climate in the area is warm, and with temperature-dependent things, like an energy system, this needs to be taken into consideration.

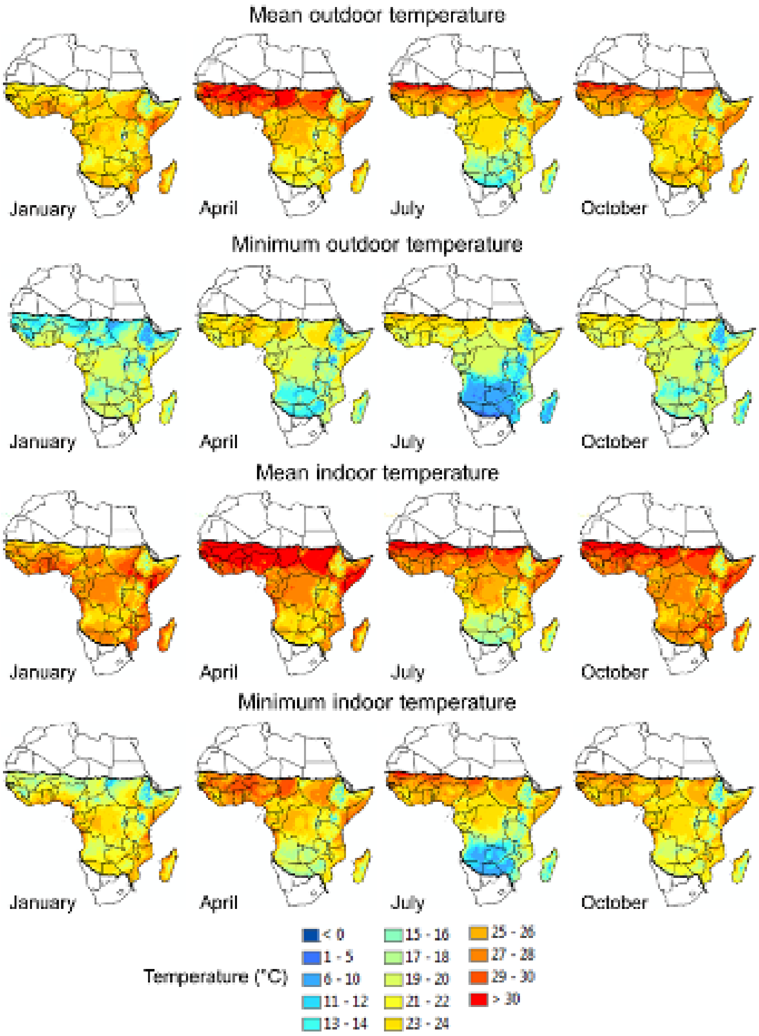

Figure 2.2: Mean and minimum indoor and outdoor temperature for SSA through the seasons, generated from weather station data 1960-1990 (in some cases of limited data records: -2000) (ref: footnote 8)

[8]https://journals.plos.org/plospathogens/article/figure?id=10.1371/journal.ppat.1003602.g001

2.1.3 Demography and electricity access

There are currently over 1.2 billion people living in the Sub-Saharan African region[9], and the vast majority of the 600 million people living without electricity in Africa are located south of the Sahara[19]. The overall access to electricity is at 50,6%[10], and 80% of the people without electricity lives in rural areas[19]. These are areas where grid electrification is a challenge, because of the low population density (see 2.4[11] [12]) and the lack of investments in these areas, meaning grid extension is too expensive[13]. In many cases, the only viable option will be an off-grid system. This is why making the right system for these people is so important[19].

The people that do have access to electricity are largely based in cities and population centers, where grid connection is more economically feasible. However, the infrastructure is poor, unstable or under-dimensioned in many areas. It is not uncommon occurrence with blackouts and brownouts/rolling blackouts[14] [15] [16][48].

[9] https://data.worldbank.org/country/ZG
[10] https://data.worldbank.org/country/ZG
[11] https://www.grida.no/resources/8200
[12] https://journals.plos.org/plospathogens/article/figure?id=10.1371/journal.ppat.1003602.g001
[13] https://population.un.org/wup/
[14] " Rolling blackouts are power outages scheduled by utilities or electricity providers designed to reduce strain on the energy grid during specified time periods" https://blog.ecoflow.com/za/rolling-blackouts-in-south-africa/
[15] https://www.nytimes.com/2023/12/11/world/africa/kenya-blackout.html
[16] https://en.wikipedia.org/wiki/Brownout_(electricity)

Figure 2.3: Grid disconnected and PV panel installed instead. Picture taken by Prof. Josef Noll in the village of Selela, Tanzania

The grid is also 66% fossil fueled[10], so from an environmental perspective, including more renewables would be beneficial, although this number is expected to decrease. There is also a lack of investment in grid across borders, hindering the development of new utility-scale developments[10]. This is stated to be due to a combination of lack of funding, local knowledge and suitable business models.
Grid access is low in the area and will likely continue to provide service to only a portion of the inhabitants in SSA. The DNV forecast estimates that 1 in 5 people will be grid connected in the SSA area in 2050[10], meaning having other solutions for the remaining 4 in 5 people is important. Even though the population density is low in many areas, the lack of investments in grid overall is a major factor for the low estimates. Regarding grid investments, it is estimated to only be 330 km grid length pr 100.000 inhabitants by 2050[10]. For comparison, the next worst region regarding grid length will be the Indian Subcontinent, with 1500 km grid length pr 100.000 inhabitants(almost 5 times higher). Because of this, the world bank, DNV and IEA all consider solar off grid systems essential complimentary tools to close the energy access gap as quickly as possible [47][10][19].

With SSA being such a large area, consisting of many countries, the development as well as energy use vary vastly across the region. South Africa and Nigeria are as of today the highest energy-demanding countries,

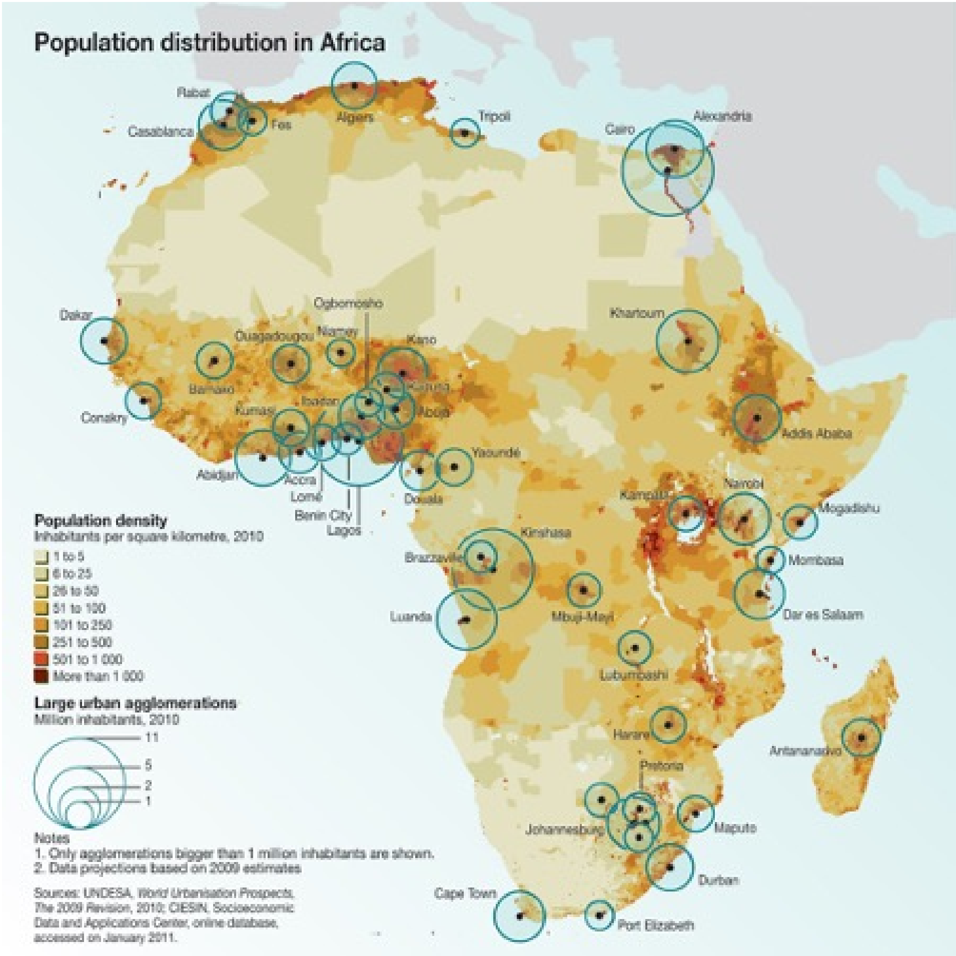

Figure 2.4: Population distribution in Africa (2011). The population is large in and around population centers, while the population density is very small in large areas of the map (ref: footnote 11, 12)

accounting for around half of the total energy demand of the SSA[10]. These countries have larger areas of high population density, as well as a more developed electricity infrastructure, so here, it might make more sense with grid extensions. In fact, an IEA least cost analysis showed that around 80% of Nigeria's population will have the least cost of getting access to electricity by grid extension[19]. This shows that there are several solutions that need to be developed simultaneously to create access to electricity for all, and the needs and solutions might vary drastically.

When it comes to generating scenarios of how people will get their first access to electricity, several studies have been conducted[19][10][17]. In all studies, at a certain distance from the grid, it is cheapest to do mini-grid or stand-alone systems. The IEA scenario, seen in 2.5 considers what kind of settlement, distance to the grid and demand level. Because this thesis focus on rural settlements, this validates the need for some sort of off-grid system, whether it is mini-grid or a stand-alone system. The Grommyr analysis also concludes with stand-alone systems or microgrid depending on demand and distance. However, it should be noted that there is not a sharp point where grid vs off-grid is least costly, but a gradual development towards one or the other.

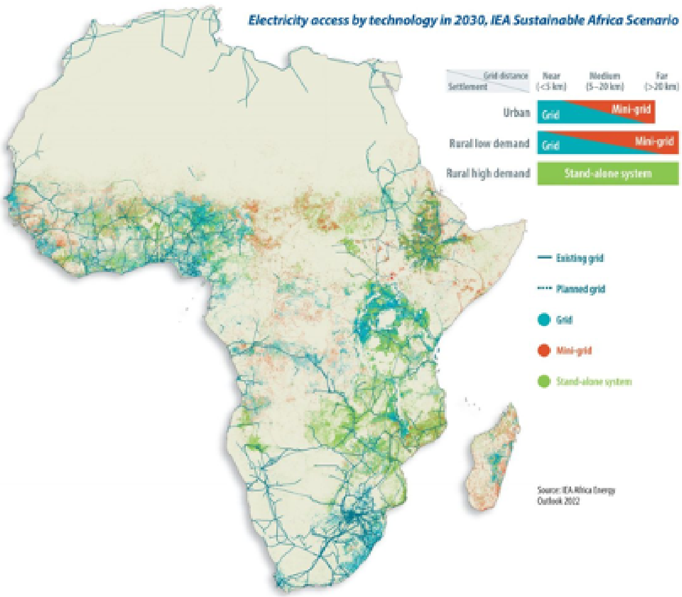

Figure 2.5: Geospatial least cost analysis, considering distance to grid, expected demand and size of community, giving a picture of cheapest way of getting first access to electricity by 2030[19]

The IEA scenario clearly shows that an investment in both grid and off-grid systems is needed to connect new users. As already mentioned, this thesis focuses on the off-grid part, and to end this sub-chapter, 2.6[18] is presented, which is showing African countries (green) practical PV power output vs access to electricity by the rural population[3]. This is to emphasize the huge potential that lies in using PV to provide electricity access. The x-axis shows electricity access as % of the rural population,

[17]http://microgrid-symposiums.org/wp-content/uploads/2018/07/ArnaudHenin_Bucharest-Microgrid-Symposium-MG_Sep2018.pdf

[18]https://solargis.com/maps-and-gis-data/tech-specs

and the y-axis shows the practical PV power potential, meaning a higher score here means better gain from PV compared to others. The size of the circles shows the population size. What can be observed here, is that many African countries have high PV power potential, which means a great possibility to use this to give energy access to the population.

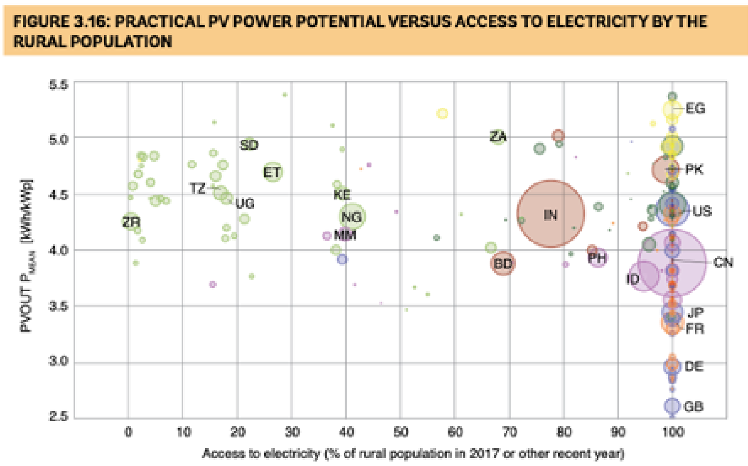

Figure 2.6: Practical PV power potential vs access to electricity by the rural population. The African countries are colored green. Note that they are all high on the potential PV power output (y-axis), but generally low on electricity access (x-axis), meaning it has great potential to increase the electricity access by utilizing PV (ref: footnote 18)

2.2 Technology

This subchapter goes into the fundamentals of the technology and technical tools used to study our energy system.

2.2.1 PV

PV, or photovoltaics uses semiconductor materials to convert sunlight (photons) into electricity[19]. The amount of electricity generated depends on several factors, such as PV type, irradiation, mounting angle, geography, topology, temperature, season and other climatic factors.

SSA has a large potential for utilizing PV, as it has high receives high amounts of irradiation, have little seasonal variability and is situated close to the equator. However this also means higher temperatures, which has

[19]https://en.wikipedia.org/wiki/Photovoltaics

negative effect on the PV. The mounting angle is also dependent on the geography, and needs to be done right in order to ensure maximum power output.

There are several ways of finding the optimal tilt, and several ways of trying to utilize the most of the irradiation as possible. Arranging PV panels in alternating east/west orientation means a generation curve which is more stable through the day, as the light hits more directly in the morning/afternoon, when the irradiation is lower, and on an angle in the middle of the day when the irradiation is higher. Solar tracking is also a possibility, both single and dual axis, however, this means the implementation of moving parts, and is for example hard to implement when the panels are installed at a roof.

For household purposes, it is typical to place PV panels on the south facing roof (in the northern hemisphere), and be within an acceptable angle from an optimum. A general rule of thumb for mounted PV panels is to mount the panel at the angle of the latitude ±15 degrees. Depending on if you want the most consistent production each month of the year or maximize production during summer would influence the choice of angle. Typically in Norway they are favored towards summer production as the panels tend to be covered by snow during winter. The seasonable variability varies depending on location as well, and luckily for countries in SSA, the seasonal variability is quite low, as seen in fig 2.7[20],

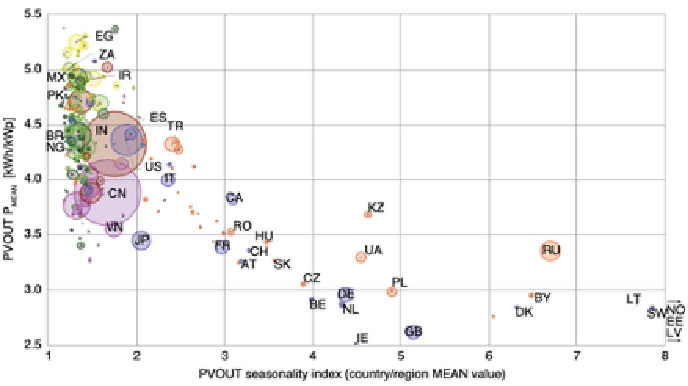

Figure 2.7: Mean PVOUT values vs seasonality index, showing African countries (green) have little seasonable variability and high PV power potential, meaning they are good areas to place PV panels and have consistently good output throughout the year (ref: footnote 20)

and the photovoltaic power potential is high, making investing in and

[20]https://solargis.com/maps-and-gis-data/tech-specs

installing PV in the area easy. This means the production can be more consistent through the year, and it is easier to go towards a more general optimal tilt.

Solargis, together with the World Bank, have created maps of optimum tilt angle and the photovoltaic power potential (PVOUT). The PVOUT is a good parameter to use, as instead of only studying the global horizontal irradiation (GHI) is not proportional to what the actual power output. PVOUT takes into account the temperature dependence and applies the optimal tilt, making the output of the figure more realistic, see fig 2.8[21]. As already mentioned, Africa in general is a good area for utilizing PV, and in fact, it is home to around 60% of the best solar resources in the world, however, PV capacity in Africa still only account for 1% of the total installed capacity, so the potential for new installations is enormous[19].

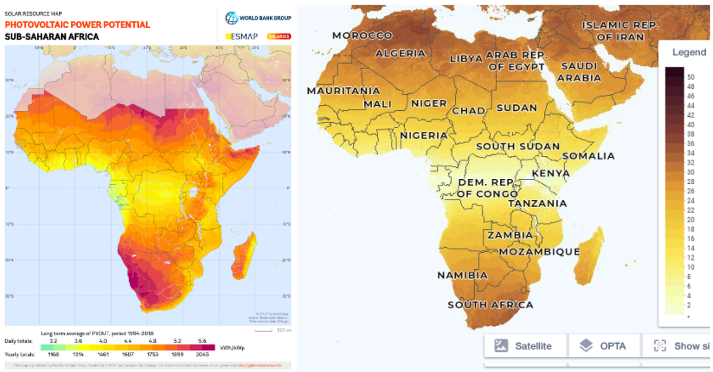

Figure 2.8: Photovoltaic power potential (left) and optimal tilt angle for Africa (right)(ref: footnote 21)

An important factor for the case in this thesis is how the PV operates at elevated temperatures. An increase in operating temperature leads to a lower bandgap in the material, meaning less energy is needed to excite the electrons. The effect influences the V_{oc} (open circuit voltage) the most, and increased temperature means that the generated voltage is reduced, which reduces the power output. A visual representation of this can be seen in fig 2.9[22] [23], showing IV curves in different temperatures. A general rule of thumb is that for every degree over the standard temperature, the PV panel looses around 0,5% efficiency. This will vary depending on type, mounting and technology. A study conducted in Iraq, which can be comparable to some areas of SSA measured an operating temperature of

[21] https://solargis.com/maps-and-gis-data/tech-specs
[22] https://www.sciencedirect.com/science/article/pii/S0378778822004455
[23] TEK5330 – Solar energy systems course

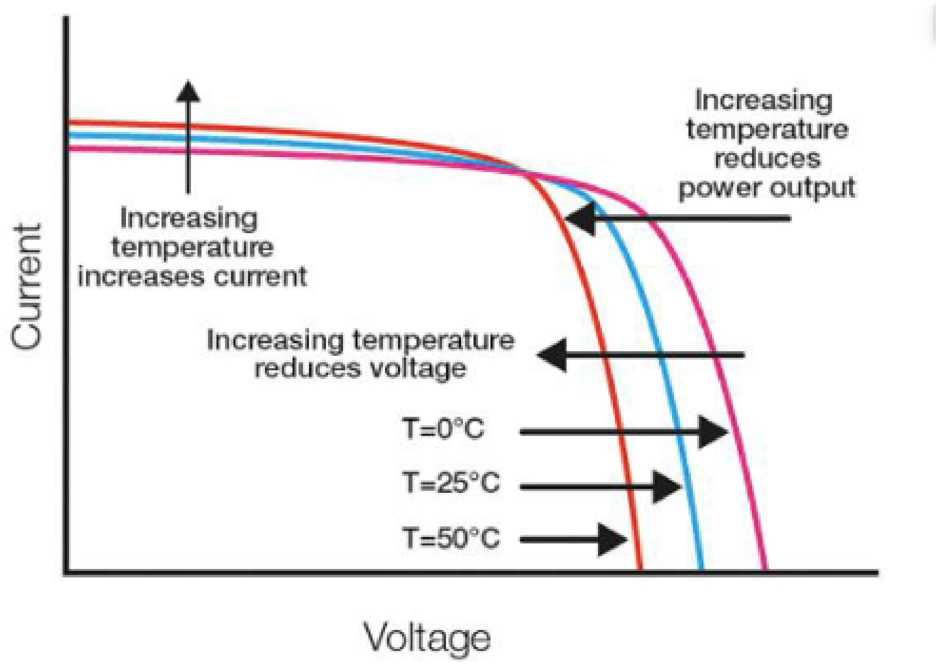

Figure 2.9: PV temperature dependency shown as IV curve, showing the large influence on the voltage, which decreases the power output. Curves are not of scale and is used for visual representation only (ref: footnote 22, 23)

over 70 ^oC [15]. To avoid high temperatures, one could install free standing modules, as this will allow for airflow, or by having ventilation or space between the panel and the roof, if roof mounted[12][22][50][40][2].

The temperature dependency also has different effect on the two most common types of PVs today: monocrystalline silicon PV and polycrystalline silicon PV. Polycrystalline was the most common a few years back, but monocrystalline is taking a higher and higher market share each year and is the most common type as of today. The difference in temperature dependency lies in that the monocrystalline consists of a single crystal, while the polycrystalline have several crystals together, and how the modules are designed[24][22].

In the same operating conditions, this means that the polycrystalline PV would have a higher operating temperature on the cell compared to the monocrystalline. This is due to more grain boundaries and recombination

[24]https://ases.org/monocrystalline-vs-polycrystalline-solar-panels/

centers, basically meaning that the cell will heat itself up more in the same conditions. This leads to higher temperature dependency and a higher reduction in power output at elevated temperatures for the polycrystalline[25]. In general, the monocrystalline is known to have efficiency of 20% or above, and being more expensive, while polycrystalline is known to have an efficiency of around 16%, and being cheaper[26]. However, as will also be discussed later, the price of PV is decreasing and the performance of monocrystalline PV is better at elevated temperatures, and should be considered and chosen when possible. New designs, like glass-glass cells or bifacial cells should also be considered, as these dissipate heat differently, and can have higher power output, because of the lower temperature effect and higher quality and performance in the first place[22].

2.2.2 Battery

Batteries are electrochemical cells that convert chemical energy to electricity. They can either be primary batteries, meaning they are only discharged once, or secondary, where they can be charged and discharged several times[27]. It is this second group of batteries, the rechargeable ones that are of interest, as they can store the energy that are produced from solar panels during daytime, and discharged during nighttime.

Batteries are characterized by its chemical composition and their performance. There are several important metrics to know to understand the differences between batteries and how they will perform. Typically, there have been a battle between the heavy, cheap and low-performance lead-acid batteries, and the light, expensive and high-performing lithium-ion batteries, where lead-acid often has come out as the winner and the chosen chemistry in stationary storage projects simply because it outperforms lithium-ion batteries on upfront cost. However, they have shorter lifetime, and would have to be swapped earlier. This thesis aims to explore sodium-ion batteries, as a new market contender, and will be compared to LIB, as they are comparable in performance and cost, as will be discussed more in-depth in the analysis.

Different tasks will also value different characteristics from the battery, and for stationary storage, this is usually high safety, long cycle life and low cost, as seen in fig 2.10. The charge and discharge rates are low compared to electric vehicles for instance, and the weight and size of the batteries are not of high importance either, since it is not supposed to be moved around or be in a confined and limited space. Batteries for this thesis also have

[25]https://ases.org/monocrystalline-vs-polycrystalline-solar-panels/
[26]TEK5330 – Solar energy systems course
[27]TEK5440 - Batteries: Technology and systems

another important characteristic which will be studied, which is the operating temperature range, as there are issues with the mismatch between the rated operating temperature, and the actual operating temperatures that the batteries are experiencing in the field in SSA. Both LIBs (specifically a lithium chemistry called LFP) and SIBs are a good match to the wanted characteristics of BESS, but they are still a little different, as can be seen in fig 2.10. The further out on the chart the black BESS line is, the more important that characteristic is, and the LFP and SIB are almost filling the criteria. But they are still both far behind on cost, and lack a little on cycle life and temperature. With new generations of batteries, these challenges are hopefully overcome.

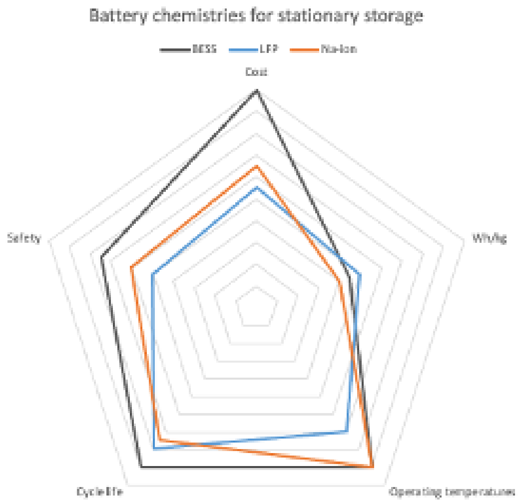

Figure 2.10: Spider chart of different characteristics of battery chemistries of LFP and Na-ion batteries, compared to the wanted characteristics of a battery for battery electric stationary storage (BESS) for SSA. Chart created by the author, based on literature, expert interviews and knowledge from TEK5440 Batteries: Technology and systems

Here are some important metrics explained[42][28]:

- Gravimetric energy density: This represents the amount of Wh pr weight, simply Wh/kg, and is a metric used to understand how much energy the battery is able to store pr kg. This is important, as higher gravimetric energy density means that the battery is able to store more energy in the same amount of material, which means less material use and can make transport and installing easier. For stationary storage, this metric is not as

[28] TEK5440 - Batteries: Technology and systems

important as for cars or drones, where the weight is important. However, the cost of the battery is typically reflected as higher with higher energy density, and it is a good thing to compare, and it shows that batteries with the highest energy density might not be feasible for stationary storage due to high cost. For the SSA, this metric can be important with shipping fees, as heavier batteries cost more to transport. It can also mean that for instance a shipping container filled with batteries that are heavy, the shipping container becomes too heavy, and cannot be filled all the way[29]

- Volumetric energy density: How much energy the battery is able to store pr volume, given as Wh/L. This means that lower volumetric energy density takes up more space for the same amount of storage capacity. This is also not the main characteristic in focus for stationary storage, but are tied to cost and bulkiness. Again, for SSA this metric is most important during shipping, as if the batteries are bulky, with little Wh/L, this means that a shipping container is shipping fewer batteries or fewer Wh if the batteries have low volumetric energy density[30]

- State of charge (SOC): This is a metric providing information of how much percent of the energy of a fully charged battery that are left in the battery at a given time, given as . This can simply be described as the battery percentage you can see on your phone. SOC is not measured directly, but through other metrics, like capacity and voltage. However, because the SOC estimation is usually done during operation, the system is not in a stable state, meaning the estimation is with uncertainty, and estimating of SOC can be challenging. Too high or too low SOC can lead to faster degradation for the battery. For SSA, this metric is important to teach and give knowledge about, so that batteries are used as optimally as possible, keeping the lifetime high

- Depth of discharge (DOD): Describes how much of the capacity the battery is discharged in a cycle. Can be described as 1-SOC. This parameter is used to study how much of the capacity in the battery is used, and different DOD lead to different degradation. Typically, the more of the total capacity that is discharged, the faster the degradation of the battery are, but this is not as prominent in all batteries. The need for a battery that can handle a large DOD is important for BESS, as it means that the entire capacity of the battery can be used, and the smallest capacity of the battery can be purchased (instead of a battery that can only handle, say, 50% DOD, which would need to have twice the capacity of a battery that can handle 100% DOD to deliver the same usable capacity)

[29]Conversations with Finn Helge Tolpinrud, 6. and 27. February 2024
[30]Conversations with Finn Helge Tolpinrud, 6. and 27. February 2024

- C-rate: this is the time the battery uses to charge or discharge. A C-rate of 1C means that the entire battery is charged or discharged in one hour, while a c-rate of C/2 means it uses two hours, and a C-rate of 2C means it uses half an hour. The time it takes for the battery to charge or discharge plays a role on the lifetime and degradation of the battery, and typically slower c-rates tend to be better for the battery health. But different batteries are also built to handle different c-rates, so a c-rate of 3 (which means full charge in 20 min) could be possible with a NMC battery made for this application, while other batteries are only rated to handle c-rates of 1C or C/2. In a BESS situation (in SSA and elsewhere), both charge and discharge will happen over the span of several hours, and high C-rates will not be reached during normal operation, meaning degradation will be low, and is not so important to think about in that situation

- Equivalent full cycle (EFC): this is a way to generalize battery charging and discharging by saying that one equivalent full cycle is the sum of charge/discharging events, meaning a battery can be charged and discharged from 80% to 30% twice to get one EFC, or charge and discharge from 100% to 0% once. This metric is used in battery testing to compare batteries even though the cycle regime might be different. For a real application in SSA, this is not a metric that will be studied specifically, but the general "cycle life" is used, but only to describe an estimated number of charges the battery should be able to do or have done already

- State of health (SOH): this is the % of initial capacity that is left in the battery after some times use. This gives an idea that there has been degradation of some sort of the battery, which makes it unable to have the same maximum capacity as when it was made. This is influenced by several factors such as how it is stored, SOC, DOD, C-rate and operating temperature. It does not give any information of what degradation mechanisms that have happened. For an EV battery, a rule of thumb is that a battery should be changed at 80% SOH, but for BESS, this is not as important, as the operation conditions of the battery is not as challenging (lower C-rates), but the battery usually begin to degrade faster over time and with lower SOH, so batteries need to be replaced at some point. For this thesis, a SOH of 70% are used as a guideline to when the battery should be replaced. In a real application in SSA, this number is not as important as long as the capacity in the battery is enough to meet the household demand

- End of life (EOL): this is when the battery has reached its end of service, for instance when the EV battery has degraded to more than 80% SOH. Then the battery should either be disposed of and recycled, or used in less demanding operating conditions, such as BESS

- Cycle life: this refers to the expected amount of charges and discharges, or EFC the battery is expected to last. For a car battery, there are margins which say that the battery has reached its end of life (EOL) when capacity retention is at 80% of the initial capacity (SOH), meaning that if a battery has a cycle life of 1000 cycles, it is expected to have at least 80% capacity retention after all these cycles are done. Cycle life gives information about how long a battery can be expected to last/the lifetime of the battery, but deviations from the expected cycle life is to be expected if the operating conditions are worse than the test conditions. For instance, if a battery is to be operated for 20 years, charged and discharged every day for that period, the battery will need a cycle life of 20*365=7300 cycles. For BESS, there are typically no need to swap the battery at 80%, however degradation tend to increase with decreasing SOH and the battery would need to meet the demand, so for this thesis, a 70% SOH before the need to exchange the battery is used as a guideline

- Operating temperature: Batteries tend to like to operate in a temperature window, where it has best performance. Batteries with liquid electrolytes cannot get too cold, because this will stop the movement of ions through the electrolyte. On warmer side, the batteries cannot operate above a certain temperature, as this could lead to thermal runaway, a process where the battery enters a self-heating state caused by the high temperature and the stored energy in the battery. The thermal runaway can end in a fire or explosion, or seriously damage the performance of the battery. This is an important metric in SSA both when choosing a battery and when operating the battery. A battery with optimal operating temperature around 25 to 35 ^{o}C should be chosen, and the battery should be operated as close to this optimal operating temperature as possible

These general metrics are important to know, now that the theoretical background for the different battery technologies is explained.

Lithium-ion technologies

Lithium-ion batteries are a mature, but ever-evolving technology with high performance. It can be divided further between different chemistries, and is typically named from their cathode materials, such as LFP ($LiFePO_4$), NMC ($LiNiMnCoO_2$) and NCA ($LiNiCoAlO_2$). The anode material is typically graphite, but can be others, such as LTO (Li_2TiO_3), which gives higher C-rates, or graphite with a fraction of silicon to increase energy density. All the technologies have slightly different properties and performance characteristics tweaked towards a specific need. NMC has a large market share in high-end EVs, as it has high gravimetric energy density, while LFP often are seen in markets where performance is not as needed, and price and lifetime are more important. LFP is a polyanionic compound, which is known to have high cycle life due to its high structural and thermal stability[59].

Lithium-ion batteries in general uses several critical raw materials, which means that there are materials that are scarce, either economically, geopolitically or ethical and environmentally. Several measures are done to reduce this issue, such as reducing the amount of that battery that are critical raw materials, recycling and securing supply chains, but with the recent explosion in lithium-ion battery demand, the critical raw material still pose a risk of constraining production[31]. Luckily, LFP batteries does not use as much critical raw materials as NMC for instance, but with Lithium in itself being critical, it is still a problem.

For stationary storage, it usually comes down to cost, cycle life and safety metrics, and within the sphere of lithium ion, LFP are the type of chemistry that can be seen to match the wanted metrics of stationary storage. The cathode is a polyanionic compound, which is known for its good cycling stability[32]. It has lower gravimetric and volumetric energy density, which again also makes it more stable and safer, and the cycle life is some of the better of the lithium-ion chemistries, as can be seen in fig 2.11. The cost is also lower, at around 100 $/kWh compared to 120 $/kWh[6], and it uses less expensive and less critical raw materials. Because of these factors, LFP are the chosen battery type used to compare in this study.
For LFP, typical operating temperatures range around 0 to 40 ^oC for a more optimal use, and -20 to 60 ^oC as the extremes, varying for the different manufacturers. Expected gravimetric energy densities are typically between 120 to 160 Wh/kg, and for normal operating conditions and depending on the depth of discharge, the expected cycle life is between 3000 and 4500 cycles, which means around 10 years of service if discharged once every day. In the case of an off-grid energy system, the expected lifetime of solar cells is between 20 and 25 years, meaning that the battery in this case will have to be swapped once if the assumed lifetime of the energy system is going to be 20 years. The cycle life will of course vary with operating conditions, and an analysis of this will be discussed later in chapter 3.3.2.

[31]In 2022, Lithium carbonate prices skyrocketed as a reaction to increased demand and supply chain disruptions, however this has later stabilized, but shows the risks critical raw materials can pose: https://www.statista.com/chart lithium-carbonate-price-timeline//28037/

[32]https://www.researchgate.net/publication/255749039_Recent_advances_in_the_research_of_polyanion-type_cathode_materials_for_Li-ion_batteries

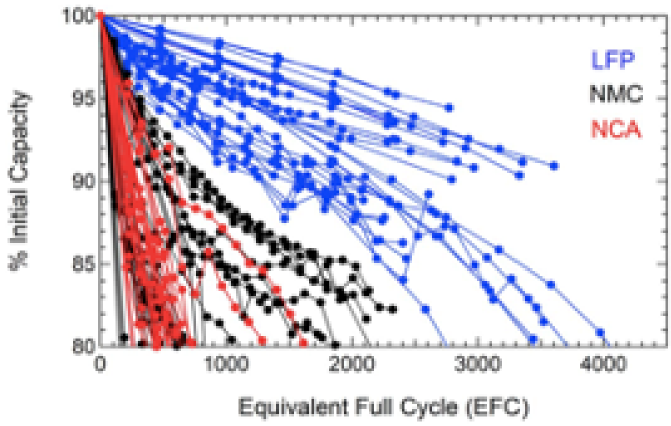

Figure 2.11: Comparison of degradation of commercial LFP, NMC and NCA. From the chart, it can be seen that LFP generally have the largest capacity retention of the three [1]

Sodium-ion technologies

In recent years, major advancements towards commercialization of the sodium-ion batteries have been made. The sodium-ion battery technology is similar to lithium-ion, as sodium and lithium are in the same group in the periodic table, make them operate on the same principles[17]. Because of the electrochemical similarities, there are quite a lot of transferability, which has led to the rapid development seen lately, and we have got commercial sodium ion batteries in record time. The same lithium technology can often be compatible and comparable to its sodium counterpart, leading to a higher success rate in new chemistries and faster research and development. Sodium-ion battery technology was in fact introduced several decades ago, and was researched alongside lithium-ion technology in the 1970's, but this declined after the successful commercialization of lithium-ion batteries. However new research has been gaining traction in recent years due to the increasing market demand of batteries, where it is possible lower cost and great raw material availability makes it lucrative, as these are some of the main challenges with the lithium-ion technology.

To understand the sodium ion battery technologies, there are some background information that needs to be known. For cathode materials, there are three main cathode material groups: Layered oxides, Prussian blue analogues and polyanionic compounds. There are different benefits and drawbacks of them all, and the choice of cathode material is related to performance, lifetime and ease of manufacturing.

Layered oxides have simple structure and is easy to manufacture, but are limited by lower conductivity and performance, and the list of different layered oxides are limited by the fact that the ionic radius of sodium ions are larger than lithium ions, so some materials can have issues with volume expansion during intercalation if they cannot accompany the large sodium ion[17].

Prussian blue analogues have an open frame structure and has large enough interstitial states to accommodate the sodium ions in its structure, making it a great choice for reversible insertion and removal of ions on paper. However, some problems with stability and columbic efficiency have been hurdles to overcome. Also, the use of cyanide compounds can be a challenge. This is not toxic by itself, but if the battery starts to produce cyanide gas, it can be dangerous. This will only happen if there is a fire or explosion in the battery[17][18].

Polyanionic compounds uses anionic tetrahedral units and transition metal polyhedral units. This combination gives a higher operating voltage and stability, but lower energy density and ionic conductivity. Vanadium, which is used in some of the polyanionic compounds for SIB is also toxic[18].

For the anode side, carbon-based materials are usually the choice, either soft or hard carbon. Graphite cannot be used, as the Na ions are too large, meaning it will not intercalate properly, leading to volume expansion or plating. Some use of titanium can also be observed. The choice of anode will influence operating voltage, energy density and cycle performance, and carbon-based anodes are often chosen as they fulfill these requirements, while at the same time being cheap. It also has the added benefit that it can be made from trees, contributing to low CO_2 footprint[38].

When it comes to performance, sodium-ion batteries generally have operating temperatures of -40 to 80 ^{o}C, giving high safety and low chance of thermal runaway due to higher internal resistance[17]. It has especially good performance in the more extreme parts of the temperature range compared to LIB, as can be seen in fig 2.12[33], which is what makes it so interesting for SSA. They have energy density comparable to LFP at 120-160 Wh/kg, with goals of being over 200 Wh/kg soon[18]. These characteristics makes SIB well suited for storage in harsh climates, and would require less cooling to operate in hot climates, such as SSA[34].
The batteries are said to be non-toxic and can have very low carbon footprints, at 10-20 kg CO_2 per kWh compared to 100-150 kg CO2 per

[33] https://www.ailepupower.com/sodium-ion-battery/
[34] Video from Northvolt CEO

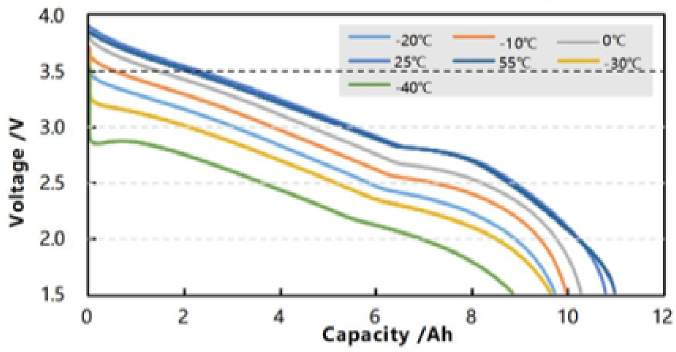

Figure 2.12: Temperature dependency of SIB (ref: footnote 33)

kWh for comparable batteries, due to the choice of materials, and compete or outperform LIB on cost, lifetime and energy density[35]. As of now, with the technology not being as mature as LIB and comparable in cost and performance, LIB would still be favorable, because it is more mature. One of the main challenges before cost reductions can be seen for SIB is in the supply chain. Once these supply chains are well established, cost of SIB can further decrease[51], with claims of future prices being as low as 45 $/kWh by 2030[18].

Because of the newly commercialization of the sodium ion battery technology, for this study, generally sodium ion batteries will be compared with LFP batteries. This is due to the short time that data have been available, and that not all numbers are given for every commercial battery yet. However, from the research side, performance testing of different chemistries, temperature dependency and even lifetime testing is starting to be readily available information, so this will give fairness to the comparison of the different technologies. Lastly, it is important to point out that both technologies are moving and developing as we speak, and this analysis will only reflect what we know and expect today.

2.2.3 BOS

Balance of system is a term used in solar systems to describe all the other components of the system than the PV modules itself[36]. This includes all the supporting components of the system such as wires, inverter, solar controller and mounting system. It usually does also include the battery, but in this case, this is studied as a separate part. How the balance of system performs is of great importance for the overall performance of the

[35]Video from Northvolt CEO, Peter Carlsson: https://northvolt.com/articles/insights-from-cop28/

[36]TEK5330 Solar energy systems

system, but it is considered out of the scope of this thesis. Faulty BOS can result in overall lower production or utilization as well as lower lifespan of the system. Here, it is assumed that the BOS functions through the lifespan of the system, 20 years. The inverter in this case is also expected to last 20 years, as it is a small home system, however, bigger inverters for larger scale typically have a lifetime of 10-25 years, so one replacement in that case should be expected[37].

For the systems in this thesis, they will all be AC, with inverters from the DC parts of the PV and batteries. Opinions on this is divided, but the reasoning for doing it this way is that it is easier to compare the different scenrios with focus on other parts, and that it allows all users to buy regular appliances instead of special DC appliances.

Knowing the BOS and cost of the PV and batteries is important to know to be able to estimate the cost of the system and ensure a system that performs well. In the next section, theoretical background of cost is presented, and gives insight to how analysis and projections of costs are conducted in this thesis[38].

2.3 Cost

Calculation of cost for an energy system is important to study the affordability of the system and making decisions on choice of system. The cost of electricity can be described in several ways, and the different approaches gives their own valuable information. Before we go into detail, two metrics are important to know: CAPEX and OPEX. This refers to the capital expenditure and the operational expenditure for a system, and means the upfront cost of the system, such as the components and the operational expenditure, such as fuel[39]. Different systems will have different sizes of CAPEX and OPEX. For instance, a car has a sales price, which will be the CAPEX, but it also needs fuel and maintenance, which is the OPEX. For an off-grid PV-battery system on the other hand, it is mainly CAPEX, as it uses no fuel, and require very little maintenance[40].

Because the systems are different, a tool to compare them are needed. An extensively used method used to compare different solutions are LCOE – Levelized cost of electricity. However, this method has its drawback when comparing energy systems that are intermittent and continuous, as it does

[37]TEK5330 Solar energy systems
[38]Conversations with Finn Helge Tolpinrud, 8. and 27. February 2024
[39]TEK5340 – Energy system analysis: modelling, methods and scenarios
[40]TEK5330 – Solar energy systems

not account for intermittency[41]. It is also almost impossible to use such a tool to compare the systems presented in this thesis to for instance grid connection, as calculation of the cost of grid extension would be needed, which is highly location dependent[43], and considered out of the scope of this thesis. Another example of why such a comparison tool cannot be used here is, once again, because it does not consider intermittency. From an LCOE standpoint, a system including only PV would be considered more feasible than a system with PV+battery, as the battery would increase the cost. However, a PV+battery solution would ensure that demand is met continuously, while the only PV system would only be able to provide electricity during daytime.

Instead, a simplified method of this is used to compare different sizes of PV+battery systems for three scenarios. Because the systems are the same, only with size difference, this is possible. The systems are assumed to only have CAPEX costs. A cost pr kWh for an expected lifetime of 20 years is made, and a cost pr day.

Lastly, it is expected that the low-income rural households of SSA does not have money saved up to pay for the CAPEX upfront. Instead, they will need to fund their new energy system. There are several ways this can be done, and this thesis will discuss some of these.

Loans are a familiar solution if someone wants to buy something, but does not have all the money to pay upfront. A loan is usually constructed with an interest rate, meaning you pay "rent" on the money that you have borrowed[42]. Usually, the maximum size of the loan is determined by how much the loaner is able to pay back, and a widely used method to ensure that they are "good for it" is to use collateral. This is a valuable possession, for instance a house, that the one that loans out money can take if the loaner is not able to repay the loan. The collateral is often a barrier for low-income rural households in SSA, as they possess little of high value that can be used for collateral. Combined with quite high interest rates, as seen in fig 2.13[43], it is nearly impossible for these people to take a regular loan, yet again repay it. In some countries, the interest rate can reach as high as 30%[44].
This means that some other way of financing such systems are needed. A widely used solution is called PayGo, which is sort of like a subscription. A company pays for the system, and then the household has down payments

[41] TEK5340 – Energy system analysis: modelling, methods and scenarios
[42] TEK5340 - Energy system analysis: modelling, methods and scenarios
[43] https://tradingeconomics.com/country-list/interest-rate?continent=africa
[44] https://tradingeconomics.com/country-list/interest-rate?continent=africa

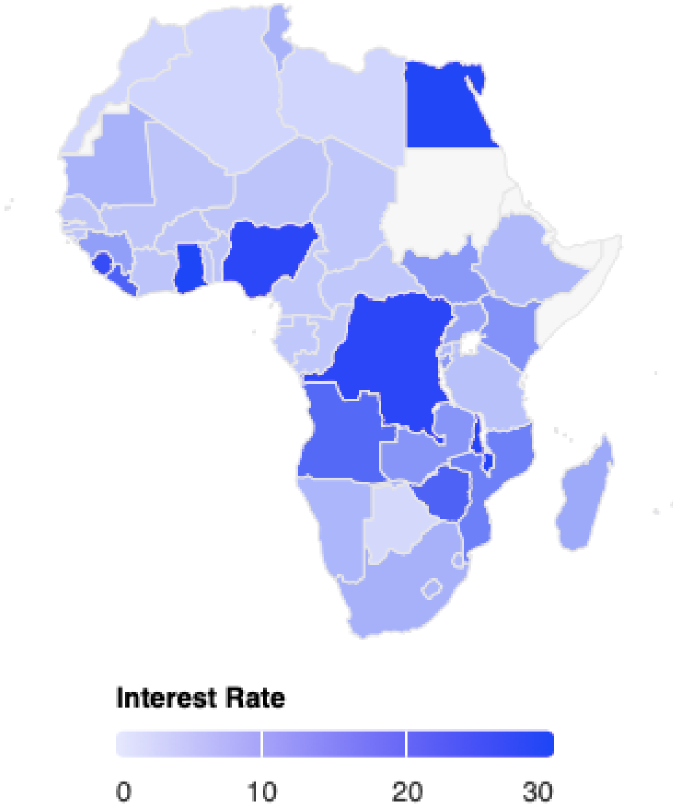

Figure 2.13: Interest rates in African countries in 2024, showing the issue with high interest rates especially in some countries (ref: footnote 43)

followed by a recurring installment to the company[45]. Currently, 40% of all solar off-grid products are paid using the PayGo method[46]. This makes it possible for "unbanked" people to buy energy systems, as a company with assets and collateral can rent out the system instead of the homeowner owning it.

It is also possible for governments to subsidise such systems, or for governments or organisations to fund them, but this is not considered in this thesis. However, some policies, like removing the need to apply for permits if the system is under a certain size or take away the tax is discussed in chapter 5 discussion, as helpful tools for more adaption of such

[45]https://www.lightingglobal.org/paygo/

[46]https://www.powerforall.org/application/files/6316/4986/8168/Fact_Sheet_Off-grid_PayGo_Unlocking_Affordable_Energy_Access_and_Financial_Inclusion_in_SSA.pdf

systems.

Chapter 3

Analysis of energy systems for Africa

Here, the performance data, demands and the findings from literature and expert interviews are presented. Later, in 4 results, choices of technology and calculations of estimated system cost is done to study the affordability and performance of such system for rural households in SSA.

It is assumed that the system lifetime is 20 years. This means that the components should be able to withstand normal operation through the entire lifetime, or added cost of replacement needs to be included. For the PV and inverters[1], this should not be an issue, but the main challenge here falls on the battery. If an expected normal temperature between 30 and $35^{o}C$ is assumed, the battery would need to handle 7300 cycles in these conditions, in order to have a lifetime of 20 years (one cycle each day for 20 years).

Before the analysis begins, the main challenges to the technologies and affordability are presented:

- Only high quality LFP batteries are rated from 6000 cycles to 10000 cycles, but this is at 25 ^{o}C[2], and any higher temperatures will negatively affect this cycle life. This means that batteries will have to be replaced at least once during the lifetime.
- Consumers are not thought how to use and maintain their system properly, resulting in sub-optimal use, which again can negatively impact

[1]From TEK5330: PV have warranty of 20-25 years and inverters for small household systems are expected to have a lifetime of 20 years

[2]Conversation with Finn Helge Tolpinrud, 14. May 2024: Regarding cycle life of LFP batteries. Battery data sheet from Pylontech used as example

the performance and lifetime of the system[3].
- LFP batteries are costly, have sub-optimal performance in higher temperatures and with sub-optimal use.
- SIB struggle with being in its infancy of commercialization, and lack validation, performance history and maturity.
- There is a lack of data, meaning synthetic load profiles and estimations on demand has to be made[4].
- PV loose efficiency if not properly installed, however this is easily overcome by building competence.
- The price of batteries is still too expensive, even though prices in LIBs has dropped 82% in the last decade[6].
- The overall system cost including PV and batteries are costly compared to what low-income families can afford.

The underlying challenges with low access to electricity in the area and low affordability of grid extension to rural areas are also still present, as mentioned earlier in the 2 theoretical background chapter.

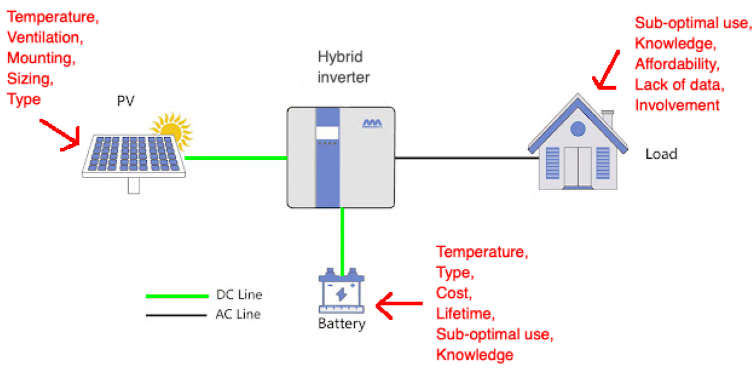

Figure 3.1: Energy system with challenges highlighted. Edited by the author using picture from http://solars-inverter.com/off-grid-energy-storage-solution.html

3.1 Specific challenges

There are several different challenges that are presented when installing an off-grid energy system in SSA. For this thesis, which are focusing on low to middle income rural households, the challenge of affordability is always there, and it first of all needs to be competitive with other systems. This means that challenges connected to performance, cost, lifetime, proximity

[3]Conversations with Albert Awopone, 9-11. October 2023 and 8. March 2024
[4]Conversation with Finn Helge Tolpinrud, 6. and 27. February 2024

to the grid and fuel price of alternative solutions will influence whether or not the system is of interest. Lack of data is also an issue, which is addressed in the coming sub-chapter.

Also, for the challenges connected to the technology itself, it is the performance and lifetime, as well as if it is able to meet the demand that are important challenges to study. How it handles elevated temperatures and if there are anything that can be done to optimize performance when installing is important. Choosing the right components and technologies are also important here.

For the more social and political challenges, the issues lie mostly in non-optimal or improper use of the system, low local knowledge, systems that are not scaled right, cost and that there are actors that are not transparent in what they do. For instance, several projects have ended in early death, under-performance or unnecessary costs because of lack of transparency from commercial actors[5]. Getting loans and other political issues, such as having to apply for installing a small system can be other hurdles.

3.2 Data

In this subchapter, the collected performance and demand data are presented. An energy system with several components can be quite complex, and therefore a systematic approach is used to look at each component and their performance, challenges and demands. Then, the system can be evaluated as a whole, and the system that have the best combination of performance, qualities, lifetime and cost will be clearer.

To be able to know how big an energy system should be, it is important that it somehow is able to meet the demand of the user. This can be done by calculating the needed electricity over time. If data is available from an already installed system, a load profile can be extracted, but this is often not the case in rural Africa, as such data usually exists only for urban, grid-connected households[46]. This is a major hurdle today, simply because there are not enough data and very few studies on this topic[21][11][57], and rough estimations that might not reflect the actual use are often used instead.

Another way of estimating demand, in a so-called bottom-up approach, is to find out how much W each appliance is drawing, and for how many hours of the day the appliance is expected to be used. Because of the lack

[5] Conversations with Albert Awopone, 8. March 2024

of data in many cases, it is also possible to use a combination of the two approaches, and for this thesis, this is what is being done. That is partly because the thesis is not studying a specific user case, but a more a general estimation and exploration. The other reason is because the load profiles here are used more to scale an energy system, and to be able to estimate a cost of such a system and make it comprehensible. However, the goal with the load profiles is still to estimate load sizes and patterns.

3.2.1 Overview of electricity demand

Several studies has been conducted to find load profiles for rural off-grid households, villages and communities in Sub-Saharan Africa[28][11][30][57][34][46][33][21]. Some have been made to create load profiles of a specific project, while others have been made to create realistic hourly reference load profiles. They are made with several different approaches, such as holistic, data driven studies, synthetic load profiles, simulated clusters, bottom up and electricity consumption measurements. Demand profiles from Finn Helge Tolpinrud have also been studied[6]. Together, they form the basis for the synthetic load profiles generated for this thesis.

Typically, what can be taken from the electricity load profiles is that the demand is quite low, at least compared to European standards, and the main use of electricity is for lighting, charging phones and entertainment or information (TV or radio). See Table 3.1 in subchapter 3.2.3. Cooking and heating are mainly covered by firewood and other inefficient biomass[10], and low income households can nevertheless usually not afford a system with the size to cover all of that. Both the World Bank and IEA have developed benchmarks for minimum levels of electricity[21], as seen in 3.2, and these have been used for sizing the different scenarios presented in subchapter 3.2.3.

3.2.2 Demand profiles from literature

The information that can be drawn from the demand profiles from the literature is that there are several patterns that can be recognized. There are load variations throughout the day, and depending on if it is a household, commercial building or a whole village, the load peaks happen at certain times of the day (see fig 3.3, 3.4, 3.5). For a household, the load picks up at early in the morning and in the afternoon/evening during dinner time and when people are home in the evening. For whole villages, load peaks also happen through the normal working hours of the day, typically around noon, when the heat is highest, and lunchtime takes place.

[6]Conversations with Finn Helge Tolpinrud, 27. February 2024

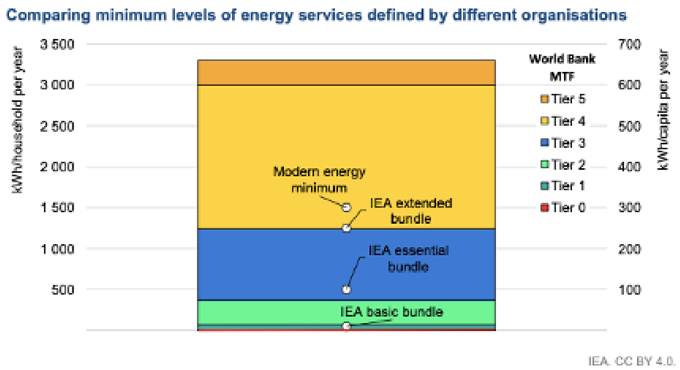

Figure 3.2: Minimum levels of energy services defined by different organisations[21]

A thing to notice is that the typical baseload that are familiar in households in Europe, typically is very low or non-existing for rural SSA. This indicates that there are few household appliances such as fridges and water heaters in use, as these are typical appliances that are always on, using electricity every hour. To highlight some of the learnings from the literature, some of the load profiles are presented:

Middle-income households in Tsumkwe, Namibia[28]: Synthetic load profiles of different sized middle-income families that have day jobs and electric cooking. Electric cooking creates quite a large spike in load during peak load hours. However, it can clearly be seen here that general baseloads are typically very low or non-existing, which comes from that very few appliances that draw electricity continuously are utilized.

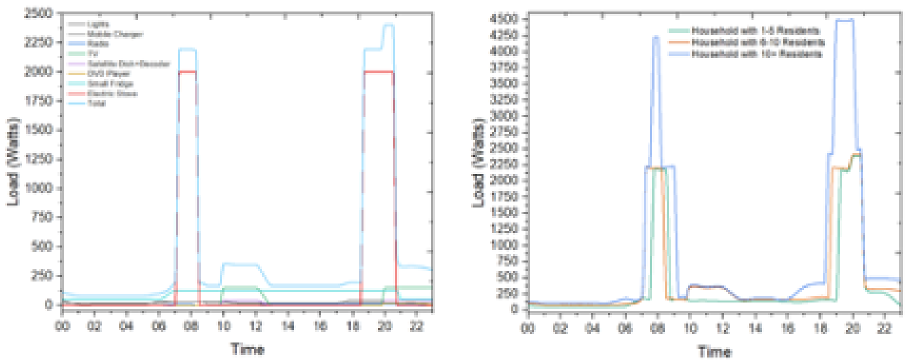

Figure 3.3: Load profiles for a medium sized (6-10 person) middle-income household pr appliance (left), and different load profiles of different sized middle income households (right) in Tsumkwe, Namibia[28]

Reference electricity load profile for a typical rural African village (from 2015)[46]: a reference load profile for a micro CHP (Combined heat and power) system. The profile is modelled from rural consumption data from both Africa and other parts of the world, and takes into consideration hot water use, biomass use, cooking activity and electricity use. The early peak at 3:00 at night is due to it being a CHP, so that the energy needed to heat water are drawn a few hours prior to the use time in the morning at 6:00-7:00. This could also be said for the evening peak, being shifted slightly to the left, compared to other electricity load profiles that are not CHP.

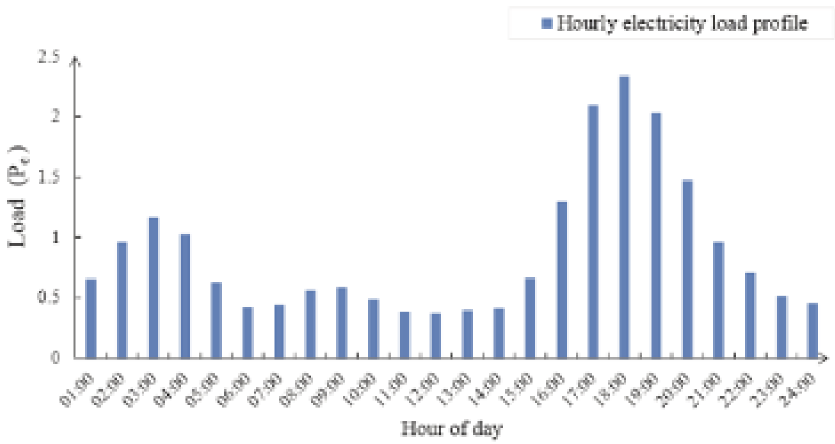

Figure 3.4: Reference electricity load profile for a typical rural African village[46]

Hourly mean load and power generation of the mini-grids in villages of Omorate and Tum, Ethiopia[57]: Load and generation profiles generated as an hourly mean based on 2 years of data. Two villages with different load profiles. Note that the village of Omorate has around 13 hours pr day without electricity, due to growing demand, that has led to insufficient power supply, that are not able to meet the demand. At Tum, however, the consumption is smaller than the generation, leading to consumption throughout the day.
For our thesis, we will now establish load profiles of low, mean and medium demand, which is featured by the amount of appliances, expected loads and expected consumption, based on the literature profiles already described.

3.2.3 Synthetic demand profiles generated for this thesis

To create quantifiable results and do calculations based on system sizes, some scenarios consisting of different demand profiles are created, based on

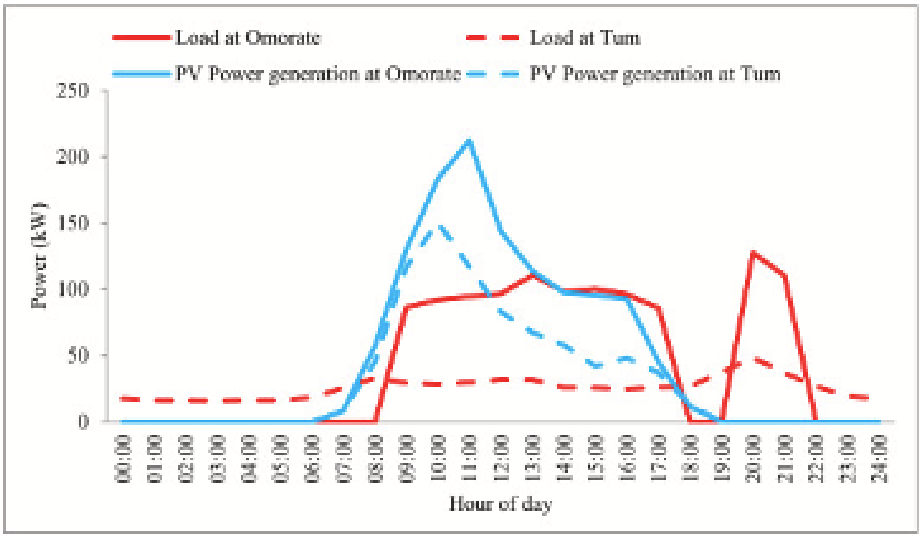

Figure 3.5: Hourly mean load and power generation of the villages of Omorate and Tum, Ethiopia[57]

data gathered from the literature load profiles and insights from experts. They are generated with a holistic approach, by combining what appliances are needed in each scenario, expected time the appliances will be used throughout the day and total energy consumption so that the scenarios are in line with the findings of the earlier studies together with expected use from the literature data. This then builds the basis for the energy system and gives information about the needed PV and battery capacity. This again creates a basis for the initial cost estimations of such a system.

Different consumers will have different load profiles, and to generalize, three scenarios are generated: baseline scenario (1,5 kWh/24h), "half" scenario (300 Wh/24h) and "double" scenario (3,5-4 kWh/24h). These are made from which appliances might be present in a household and how much they are used, and is supposed to create a picture of consumers in different social, economic and life situations. Note that the actual size of the system and energy demand might not be directly multipliable, but the names "half" and "double" is created simply to easily differentiate the scenarios.

It is assumed that they live with an expected daily income represented by the World Bank poverty lines. These are 2,15$ (international poverty line), 3,65$ (lower-middle-income line) and 6,85$ (upper-middle income line)[7].

[7] https://www.worldbank.org/en/news/factsheet/2022/05/02/fact-sheet-an-adjustment-to-global-poverty-lines#12

The two latter ones are used to measure poverty in less poor countries, and can help give an idea of affordability in the different scenarios. With 556 million people living in multidimensional poverty in SSA, which of 82% lives in rural areas[55], these income assumptions should be acceptable.

8

Baseline demand (3,65 $/day)	Half demand (2,15 $/day)	Double demand (6,85 $/day)
Lighting (50 W) Tv (75 W) Radio (30 W) Phone charger (20 W) Household appliances (75 W) Fan (15 W)	Lighting (15 W) Phone charger (10 W) Radio (20 W)	Lighting (80 W) Tv (100 W) Radio (40 W) Phone charger (30 W) Household appliances (75 W) Small fridge (100 W) Cooking (75 W) Fan (40 W)

Table 3.1: Typical appliances and their maximum W drawn at a time used in households with energy demand represented by the baseline, half and double demand scenarios

From the appliances and assumed W drawn, expected time used and the earlier studies conducted on electricity demand in rural Sub-Saharan Africa, the load profiles for the three scenarios are created:

Load profile "baseline" represents a household that has an off-grid PV and battery system installed. As seen in 3.6, the demand is around 1,5 kWh for every 24 hours. This is what the literature has been shown to be the typical usage of a low income household, and is for instance what is referred to as the "essential bundle" from the Guidebook for Improved Electricity Access Statistics[21], where appliances such as lights, radio, TV, fan and phone charging are the type of demand that the system is able to cover.

There will be demand peaks in the morning and afternoon/evening, with little to no baseload through the night, as there are only appliances that are physically switched off after use. TV is limited to 3 hours of use pr day, as this is one of the main electricity consumers in the system. Access to

[8] Appliance sizes and use have been found from the work of Finn Helge Tolpinrud and from literature

information and entertainment is maintained by having a radio on for most of the day.

Even though the largest demand happens in the morning and evening when there are not peak hours for solar production, some consumption also happens through the day, meaning this demand can be covered directly from the solar production. This means that as long as there is a sufficient amount of PV panels, and the inverter is big enough, there are no need to install a bigger battery, even though demand increases, as long at it is during the day. So there are for example possibilities to have a barber shop or similar during the day, without changing the energy system. This creates flexibility, and means that the system can be used in several situations.

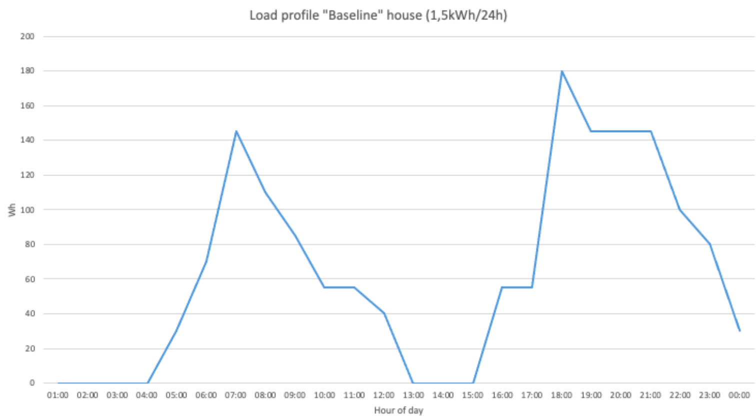

Figure 3.6: Load profile baseline scenario. Generated by the author

Following the same path as before, by estimating load profiles from appliance acquisition and how much they are used, two more scenarios with load profiles are created, see fig 3.7 and 3.8. For the "half" house, the size of the system is quite small, around 300 Wh for every 24 hours, and only the essential electrical needs are covered, such as lighting, phone charging and radio[21]. However, as shown in several studies, these are all some of the most important and needed things that electricity can bring to rural Africa[37][14][16]. Even though the system is small, and the electrical needs seem minimal, getting electricity access are still transformational[5][26]. These are all factors that attract customers, and are factors that will lead to social and economic development over time[36].

For the "double" household scenario, one can see a difference from the other two scenarios presented in that there is a baseline power consumption of 50-75W. This is mainly due to the implementation of a small fridge, which will be continuously running. The demand of around 3,5 kWh is substantially higher, and the system size will therefore be larger. There are also a larger chance of demand increasing over time, as a household that can install a system of this size will likely have a higher and stable income. Several studies points to demand growth and new appliance acquisition as to be expected, except for in situations where households have very low income[56][5][26][9]. Because of this possibility of demand growth, it is especially important to build the system so that it does not constrain the household. Large enough margins and flexibility, as well as expansion should be done where possible in these situations[39].

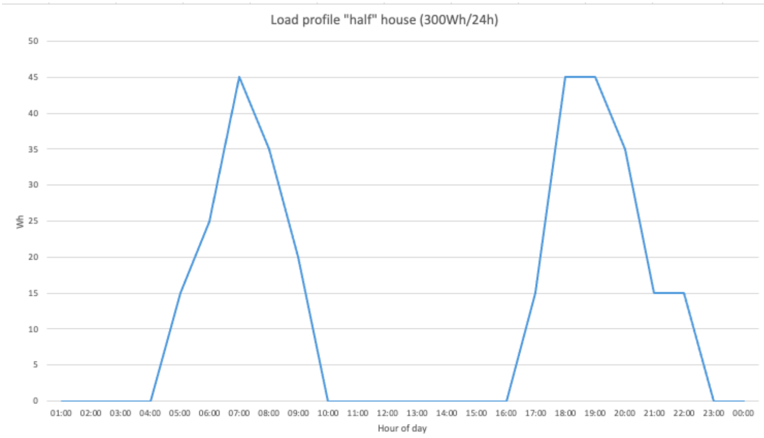

Figure 3.7: Load profile half scenario. Generated by the author

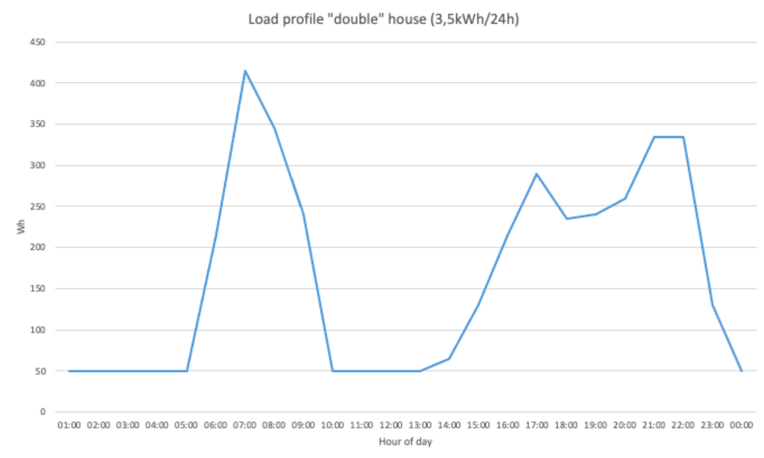

Figure 3.8: Load profile double scenario. Generated by the author

The load profiles give an average daily consumption of approximately 1,5 kWh, 300 Wh (0,3 kWh) and 3,5-4 kWh for the baseline, "half" and "double" scenarios respectively. This will be used to size the needed energy systems to meet the demand. Note that for a system with a daily demand of 1,5 kWh, there might not be need for battery storage of 1,5 kWh, as some of the electricity will probably be used during the day, at the time of electricity generation from PV, however, when developing the scenarios further, the battery size will cover the daily demand of 1,5 kWh. This means that there are less confusion and less numbers to think about, as well as it leaves room for flexibility, higher demand over time and degradation. However, this means that the overall cost could be a little higher, but it rules out several uncertainties, and for the sake of this thesis, this approximation is within reason.

3.3 Technology

3.3.1 PV

For the PV part of the system, the main challenge is with the high temperatures the modules are facing, that have effects on the power output[22]. There have also been several other challenges that have come up through the research both from literature and from the expert interviews. For example, in some cases, theft is an issue, and to avoid this, some people choose to bring their PV modules inside their house for safekeeping at night[9]. Others point to challenges with poor quality of the systems and that the system is not built flexible enough to allow for changes in demand[39][48][25].

However, as previously mentioned, PV can be a great way of gaining first electricity access, especially for rural areas[10]. From the course TEK5330 – Solar energy systems, it was also said that off grid solar is competitive when you are far from grid, have unreliable grid, expensive grid/electricity and if you have low power demand. There is also a need for reliable solar resource[10]. These are all the factors that correlates with the situation in many African cases. Grid access is low, and many people live far away from the grid. The grid can be both expensive and unreliable, and Africa have one of the best solar resources in the world, low seasonal variability, and the scenarios studied in this thesis also have low power demand.

To overcome the technological challenge of the elevated operating temperature of the modules, several studies have conducted tests and calculations of how to improve performance[12][22][50][40][2][15]. The findings from these studies are that free-standing modules or active cooling give the best results in regard to lowering the operating temperature. But

[9]Conversations with Finn Helge Tolpinrud, 6. and 27. February 2024
[10]Lectures in TEK5330 – Solar energy systems

active water cooling or other forced cooling strategies complicates the system and introduces moving parts as well as consuming electricity, so if the modules are to be mounted on a roof, the simplest and easiest approach would be to allow for airflow behind the panels, relying on convection. The importance of sufficient space behind the module, so that proper ventilation can happen, however, the needed space is not stated specifically. In all, free-standing modules is able to lower the operating temperature the most, and if the panels need to be roof-mounted, sufficient space behind the panels are needed to allow airflow, as this is the best solution that does not complicate the system, and is the cheapest method. For many cases, the roof-mounting option will be chosen because of other factors such as theft or land ownership, and the importance of module mounting with sufficient space from the roof is therefore once again highlighted.

When it comes to what type of modules to choose, there are many types on the market. However, what have been noted when working on this thesis is that the technology available in Africa is not generally up to date, and newer technologies might not be available for a household. A South African company that specializes in selling PV systems both with and without batteries have been used to find costs as well as available technologies[11]. They mainly sell silicon based PV, monocrystalline and polycrystalline. The main choice in regard to performance is to choose monocrystalline solar cells over polycrystalline. The price is usually 10-20% higher for the monocrystalline panels on comparable models with same wattage, but the most influential choice on cost is the power output (W), with panels of 400-500W costing only approximately double that of 100-120W panels. See more detail in subchapter 3.4 costs.

3.3.2 Battery performance under different conditions

For the battery part of the system, the main challenges are related to enhanced degradation at elevated temperatures and with non-optimal utilization, resulting in reduced lifetime and increased cost[27]. These issues will be discussed in depth for both LFP Li-ion batteries and SIBs in the coming subchapters.

There were also several environmental concerns in the studies, especially about what will happen if the battery is disposed of wrongly[7][8]. This is most concerning for the LIBs, with fears of toxic chemicals leaking into the environment. For lead acid batteries, recycling is high, and as long as the battery is disposed of the right way, it has better recovery rates than LIB and are considered better than LIBs[8]. For SIBs, being made of less toxic

[11] https://www.sustainable.co.za currency used are South African Rand, with exchange rate to USD at 100R=5,3 USD in March 2024

compounds than LIBs, as well as having lower environmental impact in total, as shown in several life cycle assessments[45][38], this concern is also lower.

LFP

The depth of discharge (DOD) is influential on the cycle life of a battery, however LFP cells are good at handling different degrees of this. The 0-100% DOD is considered to be hardest on the batteries, however, as can be seen in fig 3.9, the battery still has 90% capacity retention compared to initial capacity after 3000 cycles for all DOD windows[1].

What can be drawn from this is that this is probably not the main cause of elevated degradation and early death of the batteries in SSA. The temperature dependency on the other hand, which can be seen in fig 3.10, have a much greater influence. Having an ambient temperature of 15 to 25 ^oC gives substantially longer cycle life, and the difference to the tests conducted at 35 ^oC shows about 5% difference in SOH compared to initial capacity at 2000 EFC, being at around 95% and 90% respectively. For a battery in a stationary storage system, the SOH is not as crucial as for an electric car, but with increasing capacity loss, the battery will eventually not be able to meet demand either, and the battery will have to be swapped.

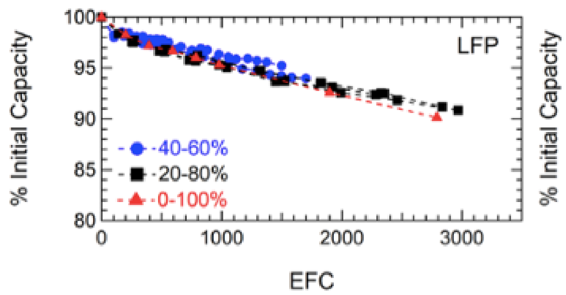

Figure 3.9: Degradation based on DOD for LFP cells at 25 ^oC [1]

For a lifetime of 20 years, with one discharge each day, a battery will need to withstand 7300 cycles, and from these tests, assuming the batteries have insufficient capacity to meet the demand after 70% SOH, it will have to be swapped at least once in all temperature cases. Typical expected lifetime for commercial LFP batteries is 3000 to 4500 cycles[17], with claims of up to 6000 to 10000 cycles under optimal conditions[12]. In fig 3.10, the measurement stops after approximately 2300 cycles, but a linear

[12]Conversation with Finn Helge Tolpinrud, 14. May 2024

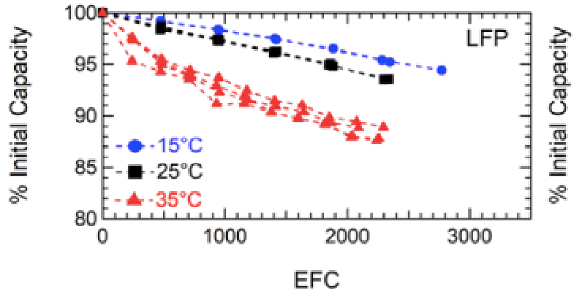

Figure 3.10: Degradation based on temperature for LFP cells [1]

extrapolation would give around 3500 cycles before 80% SOH for the 35 ^oC case. However, degradation tend to increase with ageing, and at the higher temperature of 35 ^oC, with non-optimal utilization, there is a possibility that it could degrade even faster[13]. Anyway, with an assumption that the battery can be used until 70% SOH, at least 4000 cycles are expected at 35 ^oC. In this case, it would mean that the battery for the energy system would have to be changed at least once through the service period, but the possibility that the battery may have to be swapped twice is present. This all adds to the cost of the system, and the lifetime of the battery is therefore crucial on the overall cost[14].

From the talks with the experts contributing to this thesis, they all agree that it is common for batteries to degrade faster in real life applications than these laboratory measurements, and that they must be expected to be replaced after 7-10 years[15][16].

As have been shown for the current "state of the art" LFP battery, there are several areas of improvement. LFP batteries are superior to lead acid batteries in that it is better at dealing with non-optimal use in regard to DOD and has overall longer lifetime, but is still costly and degrades faster at the higher temperatures that are found in SSA, which once again adds to the costs. In the next subchapter, the SIB are compared to see if it is able to provide better performance for the different challenges, and a study of cost for both batteries and the system are done in subchapter 3.4 costs.

[13] TEK5440 Batteries: Technology and systems
[14] Conversations with Albert Awopone, 9-11. October 2023 and 25. April 2024
[15] Conversations with Albert Awopone, 9-11. October 2023 and 25. April 2024
[16] Conversations with Charles Ogalu, 9-11. October 2023

SIB

From the studies of both lab-scale SIB cells and commercial cells, a picture of the performance of SIB can be created. As already stated, because of the recent commercialization of SIB, specific sodium-ion battery chemistries cannot be compared to LFP LIBs. For lab-cells, data is usually available, but for the commercial cells, the different performance data and cost is not always clearly stated, and sometimes can only be found in fragments in the company press releases and announcements. The situation is the same when talking directly with people in the industry.

To give an overview of different commercial SIB manufacturers and their cells, the information found from the manufacturers shared data, research, websites and tests are presented here[41][53][18][52][31][17][18]:

	Energy density	Cycle life	Anode material	Cathode material	Commercial level
CATL	160 Wh/kg	Comparable to LFP	-	Layered oxide (?)	Commercial from 2022
Faradion	155 Wh/kg	3000	Hard carbon	Layered oxide	GWh production in 2024
Northvolt	160 Wh/kg	"comparable to LFP"[19], 4000	Hard carbon	Prussian white	Near commercial
Altris	160 Wh/kg	approx. 4000	Hard carbon	Prussian white	Technology developer
HiNa	125 Wh/kg	4500	Soft carbon	Layered oxide	Commercial from 2022

Table 3.2: overview of different commercial SIB manufacturers and their cells

What can be drawn from this overview is that energy density and which general chemistry is used in the different batteries is certain, while lifetime and specific chemical composition is not usually clearly stated or shared, however the general material type is stated and lifetimes seems to be around 4000 for most types. What is interesting to see, is that none of the commercial SIBs mentioned uses polyanionic compounds, which is the category LFP falls into. This has to do with more complicated synthesis and issues with conductivity[23], but when this type of SIB emerges more,

[17]https://faradion.co.uk/technology-benefits/strong-performance/
[18]https://www.catl.com/en/news/6201.html
[19]Mail from Northvolt

it is believable that more of the good properties that LFP has towards BESS, such as cycle life, can be increased even more. $Na_3V_2(PO_4)_3$ is a promising Sodium cathode that has this polyanionic structure[59].

When it comes to cost, specific prices for a cell or battery type is not to be found, just a technology average price of production of approximately 100 $/kWh[18], or comparable to LFP[20].

When studying the research of the SIB technology, it shows promising results and good performance when facing the challenges of stationary storage in rural SSA. The temperature range is larger than LFP, at -40 to 80 ^oC (LFP at -20 to 60 ^oC), and also performing better at the extremes in the temperature range[17]. This means that there is less need for cooling of the batteries. For lifetime, the technology still needs more time, data and real life applications before cycle life of specific cells can be validated and determined. For now, only accelerated age testing and other lab tests can give indication of expected lifetime, and just recently have studies where commercial SIB compared to LIB become available[21]. However, these recent studies seem to validate the claims and announcements of the manufacturers about performance and lifetime.

This means that the expected overall lifetime for commercial SIB on the market today is between 3000 and 4500 cycles before the SOH is below 80% in normal operation. Because of the SIB technology SOH being less affected by running in the extreme parts of their temperature range, as well as having a larger temperature range than LFP to begin with, this shows its possibility to be well adapted for the rural SSA application. It also has the same added benefit as LFP of not being affected as much by larger DOD, at least down to 80% DOD. Another perk of the SIB is that it can also be shipped out being 100% discharged and survive being discharged all the way down to 0V[22]. This adds benefits both if suboptimal use happens and ensures higher safety during shipment and installing.

The commercial SIB manufacturers also all have goals and projections that the cycle life will do major leaps in the coming years[31][18][41]. As can be seen in fig 3.11, the SIBs of Altris have over 4000 cycles before 70% SOH at C/3, with goals of doubling this in the coming year[31]. Others seem to aim towards 10000 cycles, and China even has goals set for the industry that by 2030, for the same cycle life[18]. If these goals are reached, then the

[20]Mail from Northvolt

[21]https://battery-power.eu/en/poster2/4858/

[22]https://www.linkedin.com/pulse/comparision-sodium-ion-batteries-lithium-ion-current-status-tharad-7zshe/

batteries would be able to be operational over the entire operating time of 20 years, at 7300 cycles, under normal conditions. However, these are only goals and estimates, but the chances of such major improvements are definitely there, as the technology still is in its infancy, compared to LIB, which are closer to its theoretical limitations[23].

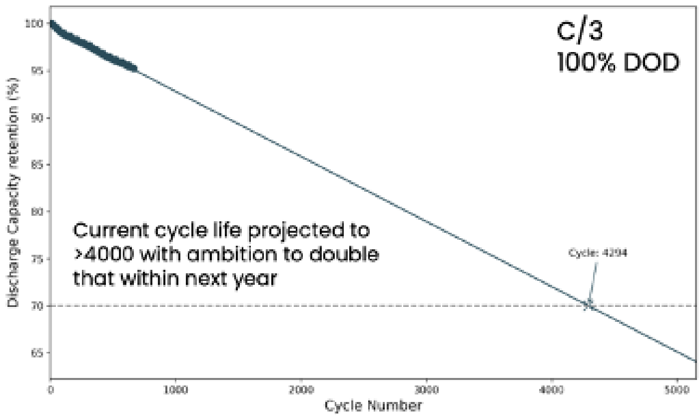

Figure 3.11: Altris prototype cell showing 4300 cycles before 70% SOH at C/3 at 100% DOD[31]

Regarding temperature, for the LFP battery type, it was able to function without major increase in degradation at temperatures up to 25 ^oC, but started to see elevated degradation at the 35^oC measurement. This indicate that it is not made for the higher temperatures of SSA, and a shorter cycle life is to be expected. The commercial SIB of Faradion has been tested for 30^oC, as seen in fig 3.12[24], and shows comparable, if not better performance than the LFP for higher temperature, and this is also backed by independent research on other commercial and early stage SIBs[58][4]. This means that the batteries need less cooling and can operate in higher temperature situations, which is an advancement in hotter climates such as the SSA.
There are also studies that have been focusing on making batteries with materials specifically designed to have optimal operating conditions at higher temperatures, like 55 or 60^oC[60][13], but this is only on lab scale(fig 3.13 and 3.14). As seen in fig 3.14, the increased temperature actually makes the degradation slower and more consistent than if the battery is operated in room temperature[29]. This is an even more influential approach, where the batteries can be designed for specific temperatures, instead of having large temperature operating ranges, but are still in its infancy for SIBs[29].

[23]https://www.koreaherald.com/view.php?ud=20200624000708
[24]https://faradion.co.uk/technology-benefits/strong-performance/

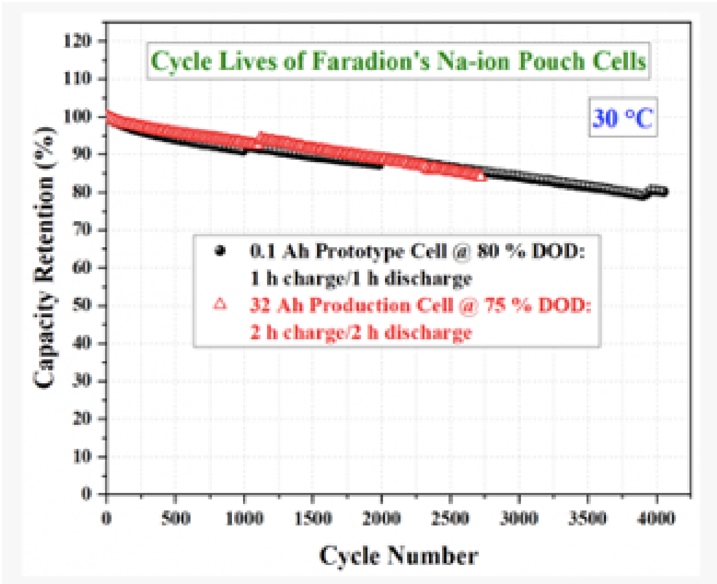

Figure 3.12: Faradion cells showing at least 4000 cycles before 70% SOH at C/2, 75% DOD (ref: footnote 24)

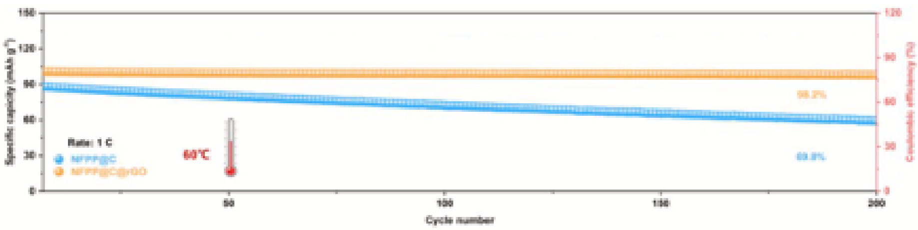

Figure 3.13: NASICON high temperature SIB, with 98,2% coulombic efficiency/capacity retention after 200 cycles at 1 C at 60^oC[13]

To sum up, commercial sodium batteries are comparable to LFP batteries in regard to cycle life and energy density, if not a little better in higher temperature lab environments. However, because the technology is not mature yet, validation of this and real-life testing is needed to approve that this is the case in the field. The promised increase in performance in the next few years is also promising regarding high temperature performance and increased lifetime. But as of today, SIB technology is comparable to LFP, but lacks the maturity. From a performance perspective, this means that a LIB system would make more sense to choose, as this has more maturity and better lifetime projections. However, both from a safety and environmental perspective, choosing SIB for the system could be better, as there are lower risk of thermal runaway, a larger operating temperature range, and less toxic materials than in an LIB, as well as having low carbon

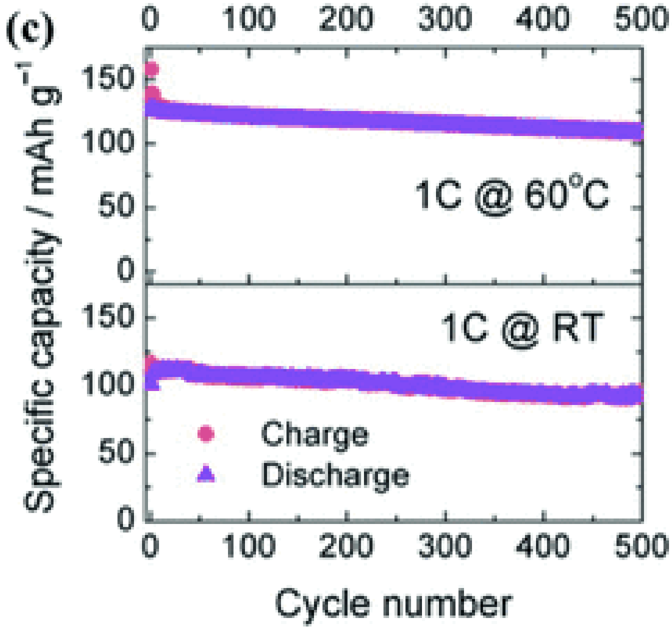

Figure 3.14: A research SIB technology for high performance at 60 ^oC[29]

footprints[45][38]. If the LIB is of LFP type, the toxicity is also lower than other types of LIBs.

Anyway, to be able to say that SIB are superior to LFP for a rural SSA BESS application, more knowledge and testing is needed to conclude. But all numbers are pointing in this direction, and with more maturity it seems that this would be the obvious choice in the near future. Pilot projects and more specific testing of the commercial SIBs at elevated temperatures should be conducted to study the results. It is definitely an interesting technology to follow, and with more validation, this could be a large market player in the BESS market, especially in countries with higher overall temperatures and with the average global temperatures rising.

But there are other factors that will influence the choice of battery technology in the system, such as general acceptance, ease of use, local knowledge and costs. These factors are analyzed in the coming subchapters of 3.3.4 Local knowledge and understanding and 3.4 Costs.

3.3.3 BOS

The PV and battery are a large part of the system but will not be working without complimentary components. Cabling, mounting and especially inverters are important parts. As seen in fig 3.1, a schematic of the system can be seen. The PV needs an inverter, or an MPPT tracker, that can ensure that the right combination of I and V gives the highest output W, and there are several types of inverters that do this a little differently, which will not be looked into further here. The battery also needs an inverter, which have to be bidirectional, as it will both be charged and discharged. The system will be AC, as previously discussed in 2.2.3, and the inverters will have to convert the DC power from the PV and battery to AC to provide power to the system.

For a small system, the different inverters are usually two separate devices, simply because this is often the cheapest option. It also adds the benefit that if one of the devices breaks, we only need to change that part. However, inverters that includes both exists. Such a solution could help the system seem less complicated and for the user to feel that they need to handle and maintain less components. It is usually a little more advanced, with the added benefit of having a SOC display for the battery and a BMS as well. Some also allow to be used more like a fuse box, where grid could be connected, which could make sense and promote to invest in the system, if grid is not too far away, and the possibility of future connection is big.

The choice of inverters and other components will have to be dependent of the specific project. The cheapest and easiest with two separate inverters would probably still be the favorable choice in many cases, but then, a SOC display should be prioritized to be invested in. There are several advantages of choosing a more advanced inverter, because it has BMS and SOC included, as well as it usually being better quality inverters, which provides better systems in terms of efficiency, lifetime and quality.

3.3.4 Local knowledge and understanding of the energy system

An off-grid energy system built for a rural low income household need to be easy to use for the people living there. If the system operates optimally, this should generally not be an issue, but such operation is not common in real life applications. The main issue today is with having advanced equipment that the locals are unable to fix[25]. Local knowledge and

[25]Conversations with Albert Awopone, 9-11. October 2023 and 8. March 2024, he have seen several examples of this, and showed the author one of them at a school in Ghana, where solar cells and lead acid batteries were installed, but no education on use were given, and no information about the lifetime of the components were given other than the overall expected lifetime of 20 years. After 4-5 years, the batteries were dead, and the system ended up not being used, as there were not budgeted for a battery change from the school, as they thought the batteries would last the entire expected lifetime of 20 years

involvement are crucial for good operation of the system, and several measures should be done to ensure this.

Local knowledge: One of the main reasons for battery degradation is suboptimal use or overuse. If this is explained and the users are trained, the issue can be handled in a good way[27]. There are several tools for this already, such as the SESA Toolbox[26]. However, this might not be widely known and still has a quite technical level compared to the knowledge of a rural user.

What could be done is to always provide a short, basic guide for the users at their level that they can follow to ensure proper use and maintenance. This should only include the basics, such as washing the PV modules and keeping vegetation away, look for abnormalities, not put load on the modules, and how to not overuse the battery. In regard to the battery, the right battery should be chosen, but installers should also always include a way of monitoring the battery SOC through a display as a minimum, and preferably include BMS systems and SOH monitoring as well. If the user is then instructed that use under 10% SOC can drastically decrease the lifetime of the battery, such information and display with SOC would aid users to ensure that their use of the system is as good as possible. Also being transparent with the expected lifetime of the battery can ensure that the users are aware of an upcoming cost of having to replace the battery, and monitoring of the SOH could also provide stability and the possibility to plan ahead[27]. The education on increased degradation if used wrong would also motivate for more optimal use.

Local involvement: This includes several aspects. First of all, it is important to have dialogue with the locals to ensure that they get what they need, and not just what outsiders assume they need[39]. This ensures proper sizing, as well as local trust and involvement, which is important to reach the project goals[44]. Secondly, working with local entrepreneurs increases local knowledge and expertise as well as establishing local component suppliers[24]. Such local involvement has also shown higher diffusion of systems in Kenya[27].

By working together with the users and the locals, proper use, maintenance and knowledge are ensured, which can increase lifetime, performance and reduce cost. Having local entrepreneurs involved could also reduce cost and increase quality.

[26] https://toolbox.sesa-euafrica.eu

[27] Conversations with Albert Awopone, 8. March 2024

3.4 Costs

This analysis studies both the overall costs, as well as the cost of the different battery technologies, as this has been a main focus in this study. This chapter presents costs of today, and is used to present the scenarios in the 4 results chapter, and is further used in the 5 discussion chapter, where a “what if” approach is used, with how different situations and future outcomes might affect the cost.

For the cost analysis in this thesis, the analysis is divided into two focus areas: the overall system cost and the battery production cost and its influences. The overall cost covers all parts from PV, battery, inverters and other BOS, installing and permitting. The battery production cost analysis is done for the different battery technologies, as this has been one of the main focuses in this thesis. This does not reflect a battery purchase price, and actual purchase prices for batteries will be found from providers in the overall system cost. The overall system cost is what in the end matters for the consumer, as this will decide if they can afford the system.

3.4.1 Battery costs

To start, the battery cost of LFP batteries and SIBs are compared. For sodium ion batteries, the price is not confirmed with a specific number from the whole industry, but the different manufacturers price it in the same price area as LFP batteries, if not a little less[20]. This means that the cost of commercial SIB is around 87 $/kWh today, as calculated by IDTechEx[52].
The general average cost for an LFP battery in $/kWh is around 95 $/kWh on cell level in 2023[6], which is a little under the average for LIB batteries at around 110 $/kWh. This increases to 130 and 139 $/kWh on pack level, respectively. These numbers are presented as the total cost for the manufacturers to produce the batteries, and does not reflect the price of a battery system that can be bought in the store. But this is the best way to compare the average price of the different technologies without introducing more specifics than needed. The historic price development of LIB is shown in fig 3.15, and will be discussed further.
This means that commercial SIB are substantially cheaper than the general LIB, but that comparison is not really fair, as it should be compared to LFP, which as already discussed, is the “competing” type of LIB in the BESS segment. The SIB raw material cost is still for most sodium-ion chemistries lower than that of LFP, but this is unlikely to contribute to the SIB being significantly cheaper than LFP in the coming years[18]. This is hindered by that the supply chain is not as established, and that lithium carbonate prices has stabilized after the 2022 spike[51][6]. A further decline

in LIB price is also to be expected, but can be slowed down by pressure on supply chain and production being moved to Europe and US, which has higher costs of production than for instance Asia. So towards 2030, it is expected that both technologies reduce their cost, but that the reduction will be higher for SIB[52][6]. This can happen because the SIB technology is taking a larger share of the demand and higher technology learning, as well as a more established production[51][53]. Estimates from IDTechEx estimate SIB costs to be under 40 $/kWh at cell level and 50 $/kWh on pack level by the end of the decade in a forecast[52]. Others claim the same either by 2030 or by the next “generation” of SIB[20][28]. For LIB, it is estimated a pack cost of around 80 $/kWh by 2030[6].

These trends are in line with the historical development of LIB batteries, as will be presented now, as well as many other technologies, such as PV and semiconductors. The technologies follow a "learning curve", generally referred to as Wrights law [29]. Lithium-ion batteries have decreased 97% in cost since they were introduced by Sony (1991) 33 years ago (adjusted for inflation)[61]. In the last decade, there have been an 82% decrease, and a 34% decrease in the last 5 years[6], as can be seen in fig 3.15.

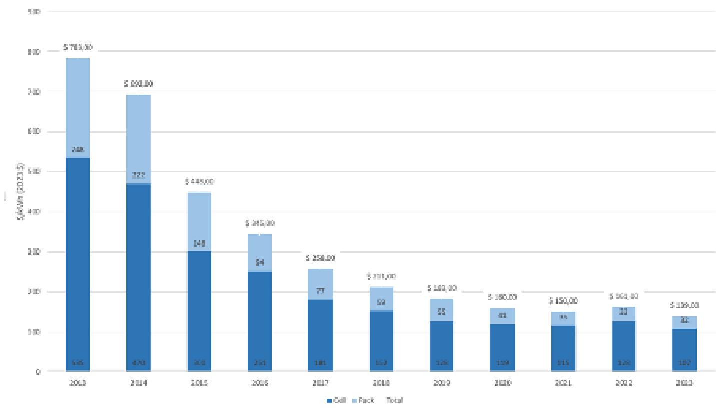

Figure 3.15: Historical LIB cost for the last decade (adjusted to 2023 $). Chart created by the author with the information from BNEF price study[6]

The effect of the empirical Wright’s law is observed because of several reasons, such as standardization, establishing of supply-chains, method improvements, product redesign and shared experience. Summarized, it states that “for every cumulative doubling of units produced, cost will fall by a constant percentage” [30]. This is also likely to be the case for SIB, and

[28] 47 $/kWh on pack level for gen 2 SIB: https://www.nextbigfuture.com/2023/09/future-sodium-ion-batteries-could-be-ten-times-cheaper-for-energy-storage.html
[29] https://en.wikipedia.org/wiki/Experience_curve_effects
[30] https://ark-invest.com/wrights-law/

as the market today is still small compared to LIB (100 GWh operating, planned or under construction for SIB vs 1500 GWh operating LIB), the expected growth will be large in the coming years[6]. Sodium-ion batteries have also been able to get a kick-start, because of the electrochemical similarities to Lithium-ion technology, so this is definitely a factor that can help with reducing costs, as well as SIB supply-chains being more established[51]. This possibility will be discussed further in the 5 discussion.

3.4.2 Overall system costs

For the overall system cost to be calculated, which includes the costs from components, installing, delivery and permitting, this thesis bases its assumptions on expected prices based on a National Renewable Energy Laboratory (NREL) report (2022) which benchmarks cost of off-grid energy systems in the US[49], and the prices for available components from sustainable.co.za, which is a South African company that sells renewable energy systems.

From the NREL report, it clearly shows that the PV and battery component cost is only a fraction of the total cost[49]. Note that this is for a larger sized system and in the US, so cost of labor or administrative costs can be different than that of other countries. However, it shows that with the system components, which includes the PV, battery, inverters and BOS is only around 50% of the total system cost. Even though the system calculated in the report is of 7,9 kW PV and 12,5 kWh Li-battery, it is assumed that this is scalable down to the system sizes studied in this thesis. The NREL study concludes that a system of this size would cost between 33858 $ and 38295 $ based on either a lowest sustainable cost calculation (MSP) and a modelled market price calculation (MMP), see fig 3.16[49].

When finding components that can work for the scenarios generated earlier in the 3 analysis of this thesis, a South African website that sells energy systems is used to find the market cost. Prices for PV, battery and inverters are presented, and it is assumed that an additional 40% needs to be added to cover structural and electrical BOS. Then, the price of the system is doubled, to account for all other costs. This is what is used when calculating the costs in the different scenarios.

As previously discussed, mono crystalline PV should be chosen for performance benefits in elevated temperatures, and as can be seen in table 3.3, it can also make sense in a cost matter as well. The other thing to note is that there are substantial savings to be made by buying larger capacity panels. A 410 W panel costs a little over twice as much as a 100 W panel, but in return you get 4 times the capacity, making this a great way of

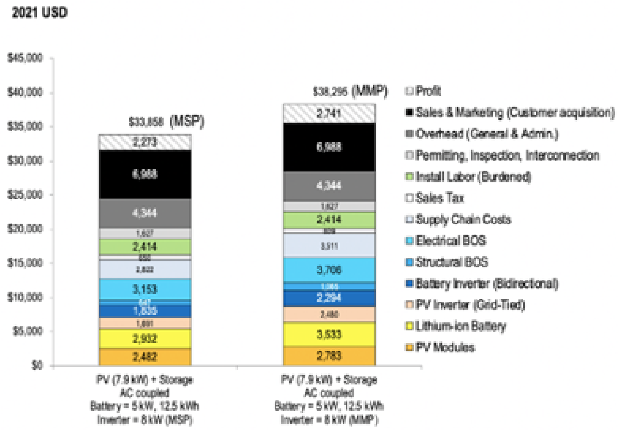

Figure 3.16: US benchmark of an off-grid energy system with 7,9 kW PV and 12,5 kWh Li-battery, with its system cost sectioned by type of cost. MSP=Minimum sustainable price, MMP=modelled market price. Note that around 50% of the total cost are other costs than the actual component costs[49]

reducing the PV component cost. There could also be savings to be made if buying in bulk or buying an entire system.

	Cost R	Cost $	Cost $/100 W	Link
Poly 150 W	1259	67	44,7	[31]
Mono 100W	776	41	41	[32]
Mono 410W	1864	99	24,1	[33]

Table 3.3: Table to show cost of different PV

For LFP batteries from sustainable.co.za, it goes the same with the price being reduced pr kWh for larger batteries. Using the different sizes of LFP batteries that they provide from the company BlueNova, the battery cost ranges from 800 R/100 Wh to 550 R/100 Wh, if you choose a battery size of 104 Wh or 1400 Wh respectively[34] [35]. In $, this is around 42,5 $/100

[31] https://www.sustainable.co.za/collections/rigid-solar-panels/products/enersol-150w-mono-crystalline-solar-panel

[32] https://www.sustainable.co.za/collections/rigid-solar-panels/products/enersol-100w-mono-crystalline-solar-panel

[33] https://www.sustainable.co.za/collections/rigid-solar-panels/products/canadian-solar-410w-high-power-mono-perc-hiku6-solar-panel-with-black-frame-with-mc4-evo2

[34] 104 Wh LFP battery: https://www.sustainable.co.za/collections/lithium-batteries/products/bluenova-bn13v-8-104wh-mps-lifepo4-battery

[35] 1400 Wh LFP battery: https://www.sustainable.co.za/collections/lithium-

Wh to 30 $/100 Wh[36]. Once again, the economies of scale, which shows that larger scale gives cost advantage, is prominent [37].

For inverters, one for each scenario is chosen, that covers the demand from the system. They are all with a display to show SOC of the battery and other parameters, so the users more easily can use it more optimally. The inverters and their cost are as follows:

Baseline: 1,5 kWh battery and 800 W PV, using a 1 kWp hybrid inverter costing 5389 R, 286$:
https://www.sustainable.co.za/collections/off-grid-inverters/products/rct-axpert-vm1-1k12-1kva-1kw-12v-hybrid-inverter

Half: 300 Wh battery and 200 W PV, using a 800 Wp hybrid inverter costing 3999 R, 212 $:
https://www.sustainable.co.za/collections/bi-directional-inverters/products/homaya-850va-12v-hybrid-inverter?_pos=2&_fid=a59d573ce&_ss=c
This inverter is a little large, but is the smallest available, and would allow for later expansion.

Double: 3,5 kWh battery and 2000 W PV, using a 2 kWp hybrid inverter costing 14194 R, 752$:
https://www.sustainable.co.za/collections/inverter-chargers/products/rct-axpert-vm3-3k24-3kva-3kw-24v-hybrid-inverter

These products are all used to create cost estimates presented in the 4 results chapter. This will then be used in 5 discussion to see what can be done to lower the price and find better solutions.

batteries/products/bluenova-bn13v-108-1-4k-mps-lifepo4-battery

[36] 100R=5,3 USD in march 2024

[37] https://en.wikipedia.org/wiki/Economies_of_scale

Chapter 4

Results

From the analysis, several user scenarios, performance and cost estimates were presented, and the basis for the following results were set. In the subchapter 4.2, the actual situation today of the different user scenarios are presented, and what such a system might cost. But before this, the subchapter 4.1 is presented, showing the ideal situation of today for the PV and battery part of the system. This gives information about what can be done to optimize performance, but is often limited by the extra cost of implementing or the added complexity of the system. The pointers can still be valuable and is important to understand what can be done to optimize performance, if the situation allows for it.

4.1 Ideal situation regarding technology choices

The analysis chapter (3) gave valuable information about the challenges, opportunities and solutions for an energy system in rural SSA. To sum it up, subsections on ideal battery and PV are presented here with what an ideal battery and PV for the situation would be, and what the state-of-the-art solution is today.

4.1.1 Ideal battery

An ideal battery for rural SSA would be a battery that would be able to operate at temperatures in the range of 30-40 ^oC and withstand large DOD and sub-optimal use, as well as more than 7300 cycles, to cover the entire operating time of 20 years of the system. A swap of battery would be acceptable as well, as this would allow for newer technology and resizing of the storage capacity if the demand have changed over time, however, this is not the most cost-effective solution.

An ideal battery could also overcome the issues related to heightened temperatures by implementing active cooling or by having a climate-controlled room, however this is not recommended for low income rural households and was not studied further in this thesis, as it complicates the system, adds upfront cost and uses some of the generated electricity to cool down the batteries.

However, with cheap PV, adding more capacity than needed and utilizing this excess electricity to cool down the batteries should be studied in a future project. This will utilize the fact that peak electricity production happens in the middle of the day, when the temperature usually is highest and the batteries are charging, and a simple active cooling system could be implemented, without increasing the cost substantially.

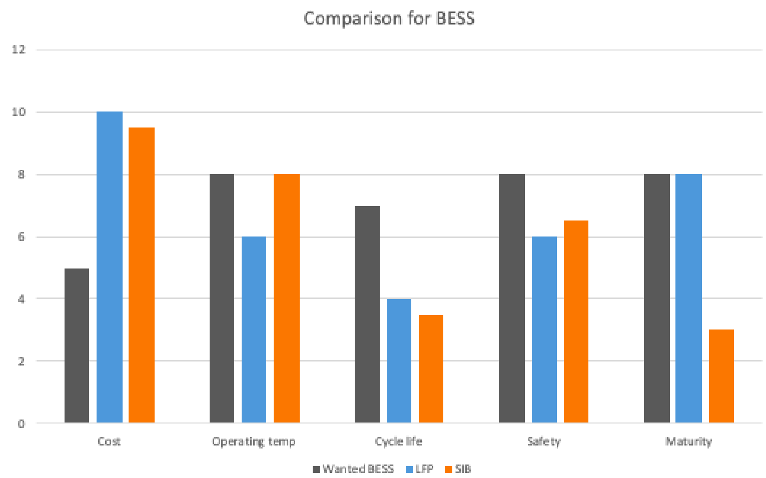

Figure 4.1: Comparison of SIB and LIB in regards to wanted paramenters of BESS in SSA. Figure created by the author

As seen from the performance data for the sodium ion batteries, the possibility for the utilization of the technology for the climatic conditions of SSA is promising. To better see the comparison between the LFP and the sodium ion batteries, the data is summarized in 4.1. This shows that the performance of both technologies is very comparable. The more mature technology of LFP would still be the choice as of today, and in the first coming years, except in some pilot cases where SIB are selected. Even though SIB have been shown to be competitive, it is still in its infancy of commercialization, lacking validation, performance history and maturity.

Even though SIB allows for lower carbon footprint and less toxicity at

EOL, the maturity of the LFP batteries will still be the over-weighing reason that will lead to this still being the choice today. For coming development and generations of SIB, this is likely to change, as long as the operation in elevated temperatures and cycle life is validated through testing and implementation in early projects. BESS[1] and EV utilization of SIB are already in pilot projects in China[2], which will help develop the sodium-ion technology to more maturity.

4.1.2 Ideal PV

An ideal PV for rural SSA should be a monocrystalline silicon PV, as it has better performance at higher temperatures than its polycrystalline counterpart, and is a mature technology. Choosing monocrystalline PV, together with choosing larger capacity panels (higher W) is also the most affordable. In an energy system, considering adding a little more PV than is calculated to be needed should be done. Especially if the inverter can handle it, as this will create flexibility for less sunny days and allow for flexibility for the future, if the energy consumption increases over time. PV is considered to be a low cost solution to generate electricity, and increasing the size of this part of the system is more affordable than increasing the storage capacity in batteries.

Proper ventilation is also of huge importance to allow for better PV performance and durability. The ideal situation would have the PV as a free-standing structure, for instance like a pergola or free standing roof out from the side of the house, as this will both provide maximum passive ventilation and shade for the users at the same time. Active ventilation is in this thesis found to complicate the system and introducing moving parts, which can lead to more maintenance or early death of the system if some of the parts fail. However, this has shown to provide the largest reduction in operating temperature.

If choosing to mount the panels on the roof, enough space between the panels and the roof is needed to allow for airflow and proper ventilation of the backside of the panels. This will all lead to lower operating temperatures, which again can increase lifetime.

[1] https://www.energy-storage.news/sodium-ion-100mwh-bess-project-to-be-built-in-chinas-hubei-province-in-2024/

[2] https://www.electrive.com/2024/01/02/first-sodium-ion-battery-evs-go-into-serial-production-in-china/

4.2 User scenario

The resulting cost calculation for each of the scenarios presented in the 3 analysis is given for each scenario here. It uses the cost of PV, battery and inverter, and then adds 40% for the cost for BOS, and is then doubled to allow for all other costs, as have been discussed in 3.4.2. Then, a cost pr kWh for a lifetime of 20 years is presented and compared to the set expected income. Examples including one and two battery swaps is also presented, assuming only todays cost of the battery, to show how this affects the cost.

4.2.1 Baseline

Using the components listed in subchapter 3.4.2, the system cost for the baseline scenario will look like this:

Battery 1,5 kWh: 403 $
PV 800 W: 198 $
Inverter: 286 $
Total components: 887 $

Total with 40% added for BOS: 1242 $
Total for overall system cost (doubled to account for all other costs): 2483 $

Cost pr kWh over 20 year lifetime:
$2483\$/1,5kWh * 365 * 20 = 2483\$/10950kWh = 0,227\$/kWh$

With one battery replacement:
$2886\$/10950kWh = 0,263\$/kWh$

With two battery replacements:
$3289\$/10950kWh = 0,300\$/kWh$

With utilizing the full 1,5kWh each day, these numbers will result in 0,341 $/day, 0,395 $/day and 0,450 $/day.

The assumed daily income of the baseline scenario was set to the 3,65$/day (1330$/year), meaning these costs will take up 9,3%, 10,8% and 12,3% of the daily income depending on number of battery replacements.

4.2.2 Half scenario

Using the components listed in subchapter 3.4.2, the system cost for the half scenario will look like this:

Battery 3,5 kWh: 129 $
PV 2000 W: 82 $
Inverter: 212 $
Total components: 423 $

Total with 40% added for BOS: 592 $
Total for overall system cost (doubled to account for all other costs): 1184 $

Cost pr kWh over 20 year lifetime:
$1184\$/0,3kWh*365*20 = 1184\$/2190kWh = 0,541\$/kWh$

With one battery replacement:
$1313\$/2190kWh = 0,600\$/kWh$

With two battery replacements:
$1442\$/2190kWh = 0,658\$/kWh$

With utilizing the full 300 Wh each day, these numbers will result in 0,162 day, 0,18 $/day and 0,197 $/day.

The assumed daily income of the half scenario was set to the 2,15$/day (785$/year), meaning these costs will take up 7,5%, 8,4% and 9,2% of the daily income depending on number of battery replacements.

4.2.3 Double scenario

Using the components listed in subchapter 3.4.2, the system cost for the double scenario will look like this:

Battery 3,5 kWh: 1008 $
PV 2000 W: 495 $
Inverter: 752 $
Total components: 2255 $

Total with 40% added for BOS: 3157 $
Total for overall system cost (doubled to account for all other costs): 6314 $

Cost pr kWh over 20 year lifetime:
$6314\$/3,5kWh * 365 * 20 = 6314\$/25550kWh = 0,247\$/kWh$

With one battery replacement:
$7322\$/25550kWh = 0,287\$/kWh$

With two battery replacements:
$8330\$/25550kWh = 0,326\$/kWh$

With utilizing the full 3,5kWh each day, these numbers will result in 0,865 $/day, 1,005 $/day and 1,141 $/day.

The assumed daily income of the double scenario was set to the 6,85$/day (2500 $/year), meaning these costs will take up 12,6%, 14,7% and 16,7% of the daily income depending on number of battery replacements.

4.2.4 Comments

A positive thing to note is that the installed PV is quite large in all three scenarios compared to the battery size. This is because it is allowed by the low cost of PV, as long as the inverter does not have to be upgraded as well, and it ensures that the batteries are charging up also on days with lower PV production. It also allows for flexibility to have more electricity demand during the day, when the sun is shining, as there will be surplus electricity produced, especially on good production days.

These results show that the overall cost is quite high, at least compared to Norwegian grid electricity[3], but possible, as the total daily cost is low because of the low consumption. Compared to other fuels for energy, such as kerosene for lighting, this is a competitive solution[32]. For all three scenarios, the daily cost of such a system is al under 15% (except for the double scenario with two battery replacements) of their expected daily income, which should be possible. However, this is assuming that the households are able to pay for the system upfront. This will probably not be the case in real situations, as the overall upfront costs are so large compared to the income.

The situation would instead be funded either by a loan, a PayGo model or with some sort of subsidy from an organization or government. These have all already been described in 2.3 cost. A loan or PayGo both adds additional costs, as they have interest and fees. However, for the poorest

[3]https://www.ssb.no/energi-og-industri/energi/statistikk/elektrisitetspriser/artikler/lavere-strompris-for-husholdningene-i-2023

people, the issue with loans is that they sometimes lack collateral to guarantee for the loan, and they may not be eligible. The other option of PayGo is then often the only option, but here the users pay a monthly fee or pr kWh used, which is usually higher than the calculated costs here, and the users end up with not owning the system themselves[32]. This will anyway allow low-income families to overcome the high upfront costs, and give access to renewable energy.

Loans in Africa, especially in some countries, have high interest rates (see 2.13), which have substantial consequences on the overall cost. In some countries, it can reach as high as 30%[4]. This is a barrier to making investments, and for the poorer people, lacking collateral, this is usually out of the question, together with paying for the system upfront.

4.3 Solutions with SIB today

There are actually also SIB solutions coming to the market that could be implemented in the energy system. A French company, called Perma batteries sells a product called "BIWATT PowerNest", which includes both 3,6 kWh of HiNa Sodium-ion batteries and a hybrid inverter (managing both batteries and PV)[5]. From email correspondence, they quoted 2500 €[6], which is approx. 2700 $[7]. The focus of the seller is on the battery's high performance in low temperatures, down to -20 ^oC, but is also rated for use up to 60 ^oC, meaning it has promising possibility for high performance in both extreme cold and hot temperatures, which is in line with the findings of this thesis.

The size of the battery is at the scale of the double scenario, and because it includes both the batteries and hybrid inverter, the system is only missing PV. From the resulting cost of the scenario, 2000W of PV, costing 495 $, added together with the Perma battery, the total cost comes to 3195 $. This is 940 $ more than the parts used in the LIB system solution. However, being an all-in-one integrated system, it claims to lower installation costs by 30%[8], and a higher quality and optimal system is to be expected from this, and also has the added possibility to be connected to a future grid. But again, with such an integrated system, the replacement of batteries would probably be more complicated, and rated

[4] https://tradingeconomics.com/country-list/interest-rate?continent=africa

[5] https://www.perma-batteries.com/en/product/sodium-battery/

[6] E-mail correspondence with the director of Perma batteries, Julien Allera, dated 6. May 2024

[7] 1 euro=1,08 USD in May 2024

[8] https://www.biwattpower.com/powernest-w

with 3000 cycles at 90% DOD, this is something that will have to be done over the 20 year system lifetime set in this thesis.

What is interesting to see is that even though the cost of the components of the system, with SIB, is still higher than the one using LIB, it is only 42% higher. With the claim of having 30% lower installation costs, this system could in fact be competitive with the LFP solution in this scenario. Also, giving the short time the SIB have been on the commercial market, and with expected higher quality and better price for the batteries, it is not impossible that this can become the cheaper option in a few years. Competing with the LIB system in the double scenario probably also makes this a possible solution, as the household with such a "large" demand and appliances are expected to have a somewhat larger income than the other scenarios, and can therefore choose the better solution instead of the cheapest.

Regarding the baseline and half scenarios, it seems like there are no ready and available SIB systems available to purchase, only cells, which will have to be assembled, and makes such a system not recommended at this stage.

Chapter 5

Discussion

From the 4 results, it can be seen that the overall system costs are 1184$, 2483$ and 6314 $, for the half, baseline and double scenarios respectively. If this is within affordability depend on the income of the household. How to estimate this can be hard, as it can be done by using mean or median income pr capita for the region or selected countries, using the GDP or by assuming salaries. In this thesis, the latter has been done, as the region is large, and the overall incomes might not paint the picture for rural SSA households. This is nevertheless a shortcoming, as doing calculations without actual data for income becomes highly theoretical.

From the assumed incomes of the households, the cost to energy production ratio ranged from around 7 to 16% of the daily income. If this is compared to calculations from US [1] and UK [2], which have anywhere from 2 to 12 % of income used for electricity, this can be said to be somewhat affordable. However, it is a large difference between buying a whole off-grid system to use grid connected electricity in US or UK. As already mentioned, the system will probably need a loan, PayGo model or funding, which will change the calculations on cost and affordability. This should be done in a cost analysis if a system were to be implemented, and will not be calculated any further in this thesis, as the high uncertainty with assumptions and estimates would make it difficult to get any results of value.

Instead, using the cost of systems and components, several possible solutions to lower the system cost and price development projections for the energy system and its components are presented. The overall system cost compared to the expected income has quite a large mismatch if the system is to be paid upfront in its entirety. The households will need at

[1] https://www.electricchoice.com/blog/percentage-income-electricity/

[2] https://www.electricradiatorsdirect.co.uk/news/how-much-of-your-salary-are-you-spending-on-energy-bills/

least (no battery swap) between 1,5 and 3 years salaries saved up to be able to pay for their system upfront. For low income households, this seems unlikely to be the case. So to close the mismatch, we have to find ways to make the overall costs of the system more affordable in the future.

There are several ways to close the mismatch of the energy system cost and the income of poor rural families in SSA. The obvious being either getting the price down or the income up. However, how this is done can vary. Generally, the families are in a situation where they are not able to earn very much more than they already are, as they are limited both in possibilities, time and resources. They are still dependent of a development around them, so that they can climb the ladder, and getting electricity is often one of the ways they can do this. This means that it will probably be expected a development and income increase over time, but as this is dependent on that they gain electricity access, this will not help combat the mismatch to the upfront costs today.

5.1 Decreased system cost

A possibility lies in a decrease of system price. As previously shown, the system consists of several components, and cost reduction could be possible by improving the different parts, and is expected in some form, following the technology learning curves discussed in 3.4.1 battery costs. There are several potential parts of the system that can improve and develop in cost, but a large potential still lies in the SIB, as the technology is expected to scale up and mature in the next few years[53]. Both with performance increase, and supply chain cost reductions, once it is more established would allow for rapid reduction in price[51]. The cost estimates lies in the range between 40 to 60$ pr kWh by 2030[52][20][3].

From this, and the price development of LIB over the past 10 years, three trend lines are created and presented in 5.1. The first line shows the development with a 50% price reduction over 10 years, the second line shows the development with a 50% price reduction over 5 years, and the third line shows the development with a 70% price reduction over 5 years. Compared to the LIB development and the mentioned cost estimates, the second trend line of 50% price reduction in 5 years seems the most probable. Such a development would substantially reduce the battery and system cost.
There are also expected performance improvements, and this will also influence the overall price. Especially lifetime improvement could lead to

[3] 47 $/kWh on pack level for gen 2 SIB: https://www.nextbigfuture.com/2023/09/future-sodium-ion-batteries-could-be-ten-times-cheaper-for-energy-storage.html

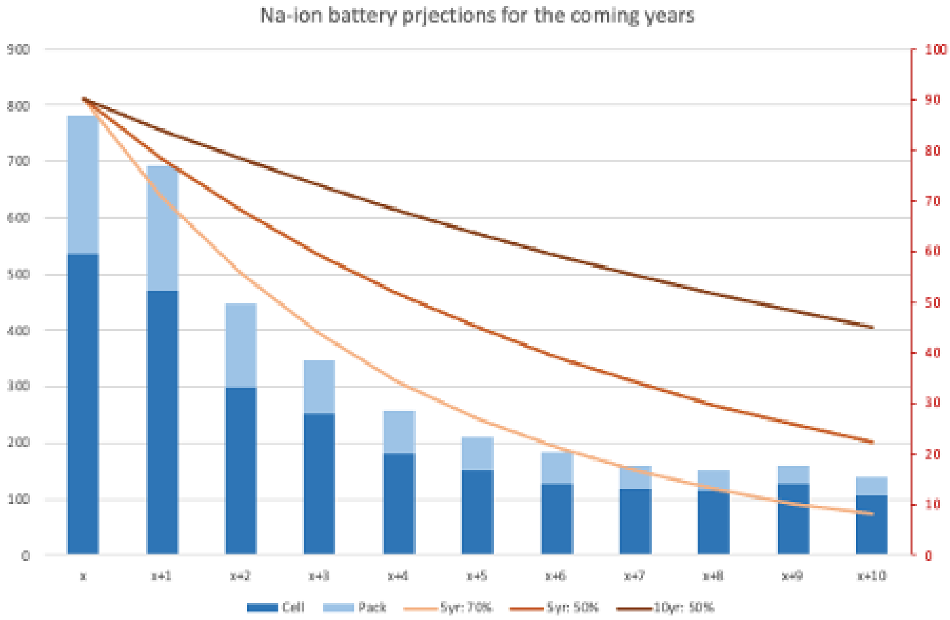

Figure 5.1: LIB price for the last 10 years in blue (left y-axis showing price pr kWh in 2023 USD) and proposed price development of SIB (right axis with USD), showing possible future cost reductions. The middle line, proposing a 50% price reduction in 5 years are in line with the cost estimates from IDTech and IEA, and seems the most probable outcome. Figure generated by the author

improved system cost. If a battery is able to last the entire lifetime of the system of 20 years, that would be a major advancement and a huge cost reduction.

5.2 Thinking outside the box

There is also a possibility to solve the scenarios and demand levels different from one another. There is quite a large difference between the scenarios with appliances and also expected user demand and preferences. To choose a design that works in all situations and sizes is not optimal, and other possibilities may be explored. From the system cost calculations in 4 results, the lowest cost/kWh was for the baseline scenario, meaning this is probably where the proposed system has lowest production to cost ratio. The others have higher production to cost ratios, and in the following subsections, discussions on how to improve the solutions for these scenarios are presented.

5.2.1 Double scenario

In the double demand scenario, it is assumed that the household is already more well off than in the other scenarios. It is possible to assume that they have already climbed the ladder and secured a stable income. In this case, it could be possible to go for a flexible system that could allow for expansion over time. If an assumption is made that the electricity access would make the household more efficient, income could increase fast in a short amount of time. Savings in food wastage and time spent buying food could also be possible with a fridge. If this would be the case, it is also possible that more people in the household can spend more time working, increasing the income.

If the system is built to allow expansion, for instance enough capacity in the inverters to allow for additional batteries and PV to be installed after a few years, the system could be small to begin with, costing less and being affordable at the time, and then develop and expand as the household increase their income. This would also allow for future price decrease for components to be utilized, and because of the economies of scale, this price reduction could also have a higher effect.

5.2.2 Half scenario

If we look at a scenario with half/basic demand, the costs of implementing such a small system with PV, inverters, batteries and all that comes with it, makes the cost pr kWh substantially larger than that for the other two scenarios. The small scale makes the production to cost ratio very unbalanced compared to the household income, as you still need all the components, and it becomes way off due to the economies of scale. If we think of the consumer that only have the basic needs of lighting, phone charging and radio covered, this is probably a low-income household that does not have the ability to pay for an energy system, especially not the high upfront capital expenditure (CAPEX). In the case of SSA, a large share of the rural population could be in this category, and solutions are needed to help them gain access to electricity.

A solution here could be to move the upfront costs over to an investor, and instead have a PayGo business model, as previously mentioned. But in this case, because the size of the system is so small, other solutions than installing all components in the home can be used, as this can help reduce the cost as much as possible.

Think of it as a "wireless microgrid" where a rich neighbor can invest in a large solar system on a central building, or even a small solar park. Then, they should also invest in a battery charging system consisting of many battery packs of for example 150 Wh and 300 Wh. These battery packs can then be charged in the central “hub” building, preferably in a climate-controlled room. This would allow more optimal charging situations for the batteries, which often have smaller operating temperature for the charge than the discharge[4]. Then, the degradation would be limited to only the discharge, which typically have larger operating temperature windows, and in general would mean less harsh environment for the battery overall.

Then, a business model can be made, where the operator can install systems in user's household, being the low-income households of the half scenario. Such a system should only include a battery pack connector with a DC/AC converter/inverter to power AC appliances such as light, radio and phone charging. Having only a battery connector and a one-way inverter would reduce the system cost to a minimum. A DC/AC inverter from sustainable.co.za have been found as an example, costing only 2344 R, or 125 $, being only around 10% of the system cost calculated in the results[5], Then, the people in the household can walk from their home to the hub and rent batteries as they need. Renting of the batteries could be done with NFC tags or with a mobile app, and the batteries could have a GPS tracker to ensure that the batteries will be returned. There should also be a “pant”(such as we have on plastic bottles in Norway) to incentivize that the battery will be returned.

Then, the operator can rent out a battery to whoever has the system installed in their house. The things that differentiate this from a regular microgrid is that there is no connection between the hub and the users. So, there are no expensive or complicated grid infrastructure, and there is no risk that someone will be able to illegally connect to a microgrid power line. It also means that there is no need for a monitoring system to see how much electricity each user has used. They will also pay for the rent of the battery upfront, meaning that situations where users are billed at a later time, but are unable to pay, are avoided. If for instance the rural people go to the market to buy food and necessities each day, they could also take with them a battery enroute from the charging hub.

The batteries should be enough to cover a day or two worth of electricity need, and with the different battery capacity sizes, it would also be possible to scale to more users, and also in situations where demand increases over time. There could also be an agreement between the provider and user that

[4]TEK5440 Batteries: technology and systems course

[5]https://www.sustainable.co.za/products/victron-phoenix-ve-direct-250va-200w-12v-24v-inverter?_pos=53&_sid=3e5afe2f2&_ss=r&variant=40898453635265

the user pay more for the first x batteries, to cover installment of the system, and then it becomes cheaper when that is paid down and you only pay for the rent of the battery and the electricity in the battery[6].

This kind of solution would be very good in an area where there are small villages far from grid. The rich neighbor is just an example of who could have such a business, but organizations or governments could be other good candidates. This makes sense as it does not push all the costs over on the "rich neighbor", such as the government, but makes the ones that are able to take up a loan or afford the CAPEX to get a return on their investment over time, while distributing the benefits to the users. This business model could also be expanded to include e-mobility for instance, where bikes use the same batteries as the homes. A variant of this is for instance done at WeTu[7] in Kenya.

The overall benefits are that it removes the CAPEX cost from the low-income households, and giving return on investment for a provider, and eliminating high interest loans. It benefits both from the economies of scale, having a larger central hub, while minimizing system cost in the household (and eliminates the need of having many "full" small systems with PV, inverters and batteries), as the entire system is smaller and less complicated. It would be cheaper for the low-income household than taking up a loan or other forms of PayGo, and is more in line with what we observe are the preference in Africa (to buy what you need right now[8]). It would also create a natural demand side management, as the pay as you go model would motivate users to not waste electricity.

If a household at a later stage would want to have a proper system with PV, inverters and battery installed, the already installed system could just be dismounted, as it does not cost much in the first place, and the operator could also move and install it in a new household. This would allow for the new system to be properly sized after the users have had experience with having electricity for some time, and maybe they also have been able to increase their income over time because of the electricity.

Having many small batteries would also allow for the ones that would reach an early EOL being replaced at a low cost. For the investors, it would also be a lot easier, as they can invest a larger sum of money in only one place, instead of granting small sums for each house. This will lower the overall

[6] Conversations with Finn Helge Tolpinrud, 6. and 27. February 2024: this is a strategy Finn Helge Tolpinrud presented for the author, incentivizing more use, as it will motivate people to rent the battery more so it becomes cheaper

[7] https://wetu.co.ke/about-us/

[8] Conversations with Josef Noll

cost of permitting and planning, and allow it to be more profitable, meaning for instance governments would not have to take the whole bill.

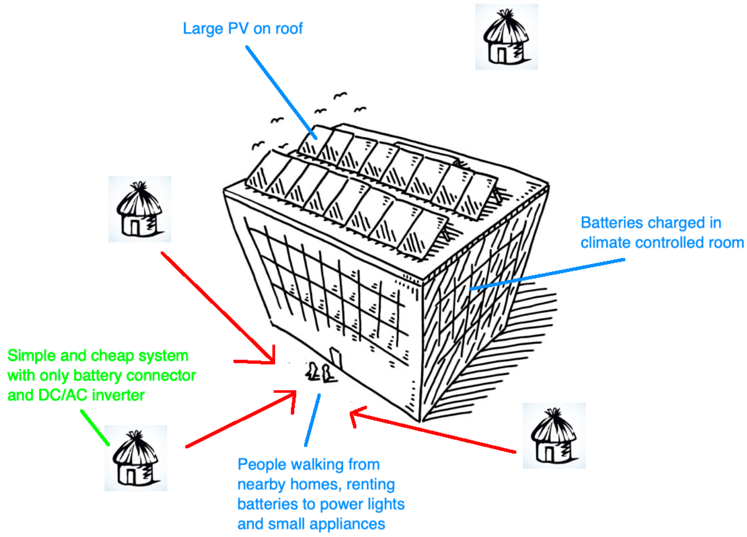

Figure 5.2: Proposed business solution for the half scenario with one central hub, renting out small batteries to households who have a cheap and simple system. Figure created by the author by putting together figures found on the web

5.3 Eliminating other costs than the components

The last proposed solution is one that has emerged in Germany lately, called "Balkonkraftwerk". It is designed to be a ready-to-go package that require no skilled workers to install it. You can simply connect it through an existing socket in the wall. The system is scalable and comes both as a PV system and with battery storage. Being mass produced, the price can be lowered, and it would cut the cost of installation, planning and permit, meaning the overall cost could be lowered. A bundle with two batteries, two inverters and 12 PV modules, resulting in a 5280 Wp and 10 kWh system costs 7336 €[9], or 7922 $ [10]. This system is more than twice the size of the double scenario, but for the sake of easiness, if we were to buy such a balkonkraftwerk, and divide it and install in two houses, the total cost for one household would be under 4000 $, which compared to the overall cost

[9]https://www.maxxisun.de/product-page/maxxicharge-komplettset-5280wp-10-kwh-speicher

[10]1 euro=1,08 USD in May 2024

calculated in the results for double demand (6314 $) is less than two third the cost, for a bigger system.

If governments would allow for installing of such plug and play systems up to a certain size without having to get a permit, and if households could do it themselves, the savings from this would allow for higher penetration, as it is more affordable and easy to install, while ensuring a system of high quality. It should also be considered if it is possible to subsidise such systems or at least deduct tax for these, as this will lower the overall cost.

Chapter 6

Conclusion

To conclude this thesis, we revisit the research question:

- What are the challenges of performance, durability and affordability for decentralized energy systems in Sub-Saharan Africa, and how can they be overcome?

This thesis was an exploratory study to see the possibility to use SIB in off-grid energy systems for low-income rural households in SSA, challenges tied to such systems and affordability.

Regarding performance and durability, LFP batteries and SIB were studied. The main challenge lies in the sub-optimal use of the batteries both in terms of operating temperature, but also that knowledge on how to use the battery is minimal. A 100% DOD should be avoided, and this can be ensured by using simple battery monitoring, as well as teaching proper use. If the user can cut unnecessary consumption when the battery reaches for instance 80% DOD, this can prolong the lifetime of the battery and stop increased degradation.

While SIB shows great potential for having high performance and durability for the use in SSA, this needs more validation and is probably something that can become a reality in the next coming years. It is not ready for adoption as of today. Regarding affordability, it is on the same level as LFP, with the possibility of future price reduction. A system today, should still include LFP batteries over SIB, as this is a battery with enough performance history.

The scenarios presented in 4 results show the situation of what can be bought right now and for what price. As of today, there are quite a large mismatch between the upfront cost of such a system and the income of poor rural families in SSA, but this can to some extent be overcome using methods such as PayGo. The daily cost of such a system is affordable compared to assumed incomes, assuming that the system is paid for upfront or with no interest, and is between around 7 to 16% of the daily income of the households depending on scenario and number of battery swaps needed. The reality is that the added cost of loans or PayGo can alter this affordability, making it too expensive again.

The future expected price decline of such systems, following experience curves, also indicates that systems will be more affordable in the next couple of years, closing the gap between the cost and the income of households. Policies stimulating the choice of such systems, and incentives such as tax deduction would also aid quicker adoption.

For PV, the challenges consist of several different issues. Overheating because of the high temperatures is the main issue here as well, but other, such as improper sizing, theft and low level of knowledge on how to use it is also important. Overheating can be avoided or reduced by choosing monocrystalline silicone PV over polycrystalline, as this has lower temperature dependency and the performance is better at higher temperatures. Ensuring proper ventilation behind the panels is also very important. If possible, free-standing PV, used to provide shade outdoors, like a pergola, should be done. In cases where this is not possible, it is important to have enough space between the panels and the roof. The potential to use PV to provide access to electricity rural households in SSA is large, and should be utilized more.

Lastly, to end the conclusion, I would like to include some wise words from one of my experts in the field, Dr Albert Awopone:

"It is a fact that adoption of new technology comes with some reservations. Therefore it is essential that when introducing new technology, a lot of effort should be done to ensure its effectiveness in order to build confidence and promote adoption" [1]

[1] Conversation with Albert Awopone, 8. March 2024

Chapter 7

Future work

As the work in this thesis is only exploratory, several steps are needed before such scenarios presented here, using SIB, can be done. The challenges of such systems are solved in varying degree, and some solutions is easy to implement right away, such as monitoring and basic usage education, and using moncrystalline PV with enough ventilation. But for SIB to become part of such a system, some questions are need to be solved before it can be rolled out.

A future thesis should study SIB battery cycle life testing, especially at elevated temperatures. Some studies are already done on this topic, but a specific research on SIB for rural energy systems in SSA would be a huge step towards it being a solution, if the study finds the same results as other studies is already indicating.

A pilot project, or several should also be done, where real life issues can be studied and solved before rolling the technology out in large scale.

Studies looking into active cooling of the batteries by oversizing PV and see the cost and benefits of such a solution can also help decision makers invest in the right system.

Also, more studies on the business related side of such a system could be conducted. It should emphasize that the system would need to be affordable. Maybe solutions based on the discussion on the 5.2.2 half scenario can find its way into a viable business solution one day.

Lastly, the interconnection between small off-grid systems to form mini-grids should be studied. How to share the electricity and cost becomes questions in this situation, but the sharing of system can lead to fewer components and more flexibility, more optimal use and higher utilization, as well as overall lower cost, so more studies on this is highly relevant.

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