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Distributed Renewable Energy based DC-Microgrids as Means of Sustainable Energy Solutions for Rural Areas in Sub-Saharan Africa

PhD Thesis in Sustainable Energy Systems, Supervised by Prof. Aníbal T. de Almeida
and Prof. Pedro Moura, submitted to the Department of Mechanical Engineering,
Faculty of Science and Technology, University of Coimbra

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by

Yohannes Biru Aemro

PhD Thesis in Sustainable Energy Systems

in the framework of the Energy for Sustainability Initiative of the University of Coimbra
and MIT Portugal Program, submitted to the Department of Mechanical Engineering,
Faculty of Sciences and Technology of the University of Coimbra

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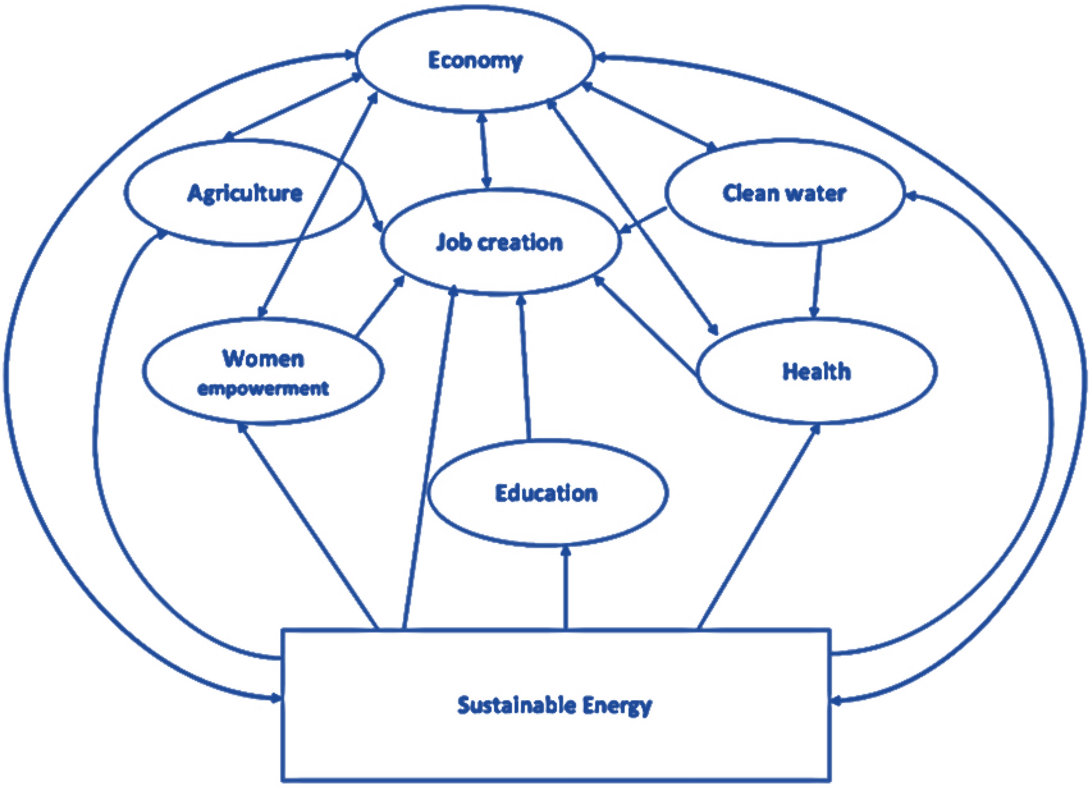
Economy
Agriculture
Clean water
Job creation
Women empowerment
Health
Education
Sustainable Energy

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Dedication

To my Father, (Late) Biru Aemro Tessema and to my brother, (Late) Sefinew Biru Aemro.

For all civilians who are affected (who have nothing to do with the tribal and toxic politics) by the war in my beloved country Ethiopia.

Abstract

This PhD thesis was focused on investigating inclusive sustainable energy access means for remote and rural locations of sub-Saharan Africa with the main objective of designing and modeling DC-microgrids and to assess how distributed renewable energy generation-based DC microgrids can be a solution for rural areas in providing inclusive sustainable energy services. In this research, there are two main aspects that are addressed. One is analyzing and defining the best option of hybrid renewable energy systems for applications in a rural primary school, household, health center and village. The second is the matching between energy demand and supply by incorporating super-efficient appliances and using energy storage systems.

To evaluate the current status of energy-efficient appliances and their impact to improve sustainable energy access in rural areas of sub-Saharan Africa, a study was conducted on different clean cooking technologies with their associated fuels. The study assessed the energy consumption, energy costs, efficiency, energy outputs/inputs, Net Present Costs (NPCs), and heat transfer behaviors of two electric resistance cookstoves, induction stoves, and pressure cooker. The results indicated that pressure cookers provide a lower energy difference between the output and input, higher water boiling efficiency, and lower energy costs, whereas locally manufactured products resulted in higher energy consumption, lower water boiling efficiency, and higher energy costs. Concerning NPCs, the Single Hot Plate presented a better cost-benefit ratio compared with the other cookstoves options. Additionally, the work highlighted the policy and strategies that should be followed for the promotion of cost-effective electric clean cooking technologies.

Designing and modeling optimized and cost-effective off-grid solutions for inclusive energy access in rural areas is a key concern, where most of the available studies are focused on addressing issues such as only electrification or only clean water supply. This dissertation developed the design and model of different configurations including PV with battery storage system, hybrid systems with PV and wind power, and battery storage systems with the use of energy-efficient appliances for different applications. The analysis carried out showed that DC microgrids are a viable option to electrify rural primary schools, health centers, households, and villages. For the case studies, different load estimation scenarios, based on the sensitivity variables (inflation rate, discount rate, constraints related to components like derating factor and lifetime of PV, minimum and maximum state of charge of batteries) were analyzed.

Overall, the results obtained in this dissertation are multi-dimensional and are major results to promote large-scale energy access in rural areas of Sub-Saharan Africa, a region with very low energy access rates and abundant renewable energy sources. The results also enable to improve the socio-economic well-being of the underserved people who lacks the multiple benefits of modern energy services, giving a large contribution to achieve the United Nations Sustainable Development Goals, including Good Health and Well-being (SDG 3), Quality Education (SDG 4), Gender Equality (SDG 5), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG7) and Decent Work and Economic Growth (SDG 8).

Keywords: energy access; DC microgrids; renewable energy sources; off-grid efficient appliances; UN2030 agenda for sustainable development; cooking systems; rural electrification.

Resumo

Esta tese foi focada em meios de acesso a energia inclusivos e sustentáveis para locais remotos e rurais da África Subsaariana, com o objetivo principal de projetar e modelar microredes DC e avaliar como as microredes baseadas em geração de energia renovável distribuída podem ser uma solução para o fornecimento de serviços de energia sustentável inclusivos nas áreas rurais e para alcançar os objetivos dos planos de acesso a energia sustentável para todos. Nesta pesquisa, há dois aspetos principais que são abordados. Um consistem em analisar e definir a melhor opção de sistemas híbridos de energia renovável para aplicações em escolas primárias rurais, domicílios, centros de saúde e aldeias. A segunda é o ajuste entre a procura de energia e a disponibilidade de geração renovável, incorporando equipamentos de elevada eficiência e usando sistemas de armazenamento de energia.

Para avaliar a situação atual dos equipamentos de elevada eficiência energética e o seu impacto para melhorar o acesso a energia sustentável em áreas rurais da África Subsaariana, foi realizado um estudo sobre diferentes tecnologias de cozinha limpa e dos combustíveis que lhe estão associados. O estudo avaliou o consumo de energia, custos de energia, eficiência energética, valores atualizados líquidos (VAL) e comportamentos de transferência de calor de dois fogões de cozinha de resistência elétrica, fogões de indução e panela de pressão. Os resultados indicaram que as panelas de pressão fornecem uma menor diferença de energia entre a saída e a entrada, maior eficiência de ebulição da água e menores custos de energia, enquanto os produtos fabricados localmente resultaram em maior consumo de energia, menor eficiência de ebulição da água e maiores custos de energia. Em relação aos VAL, o sistema de placa única apresentou uma melhor relação custo-benefício em comparação com as outras opções de fogões. Além disso, o trabalho destacou as políticas e as estratégias que devem ser seguidas para a promoção de tecnologias de cozinha elétrica limpa.

Uma preocupação fundamental foi projetar e modelar soluções fora da rede otimizadas e económicas para o acesso inclusivo a energia em áreas rurais, onde a maioria dos estudos disponíveis se concentra em abordar questões como apenas eletrificação ou apenas abastecimento de água limpa. Assim, esta dissertação desenvolveu o projeto e o modelo de diferentes configurações, incluindo PV com sistema de armazenamento em bateria, sistemas híbridos PV e eólicos, com sistemas de armazenamento em baterias com o uso de equipamentos de eficiência energética elevada. A análise realizada mostrou que as microredes DC são uma opção viável para eletrificar escolas primárias rurais, centros de saúde, domicílios e aldeias. Para os estudos de caso, foram analisados diferentes cenários de estimativa de carga, com base nas variáveis de sensibilidade (taxa de inflação, taxa de desconto, restrições relacionadas a componentes como fator de redução e vida útil de PV, estado mínimo e máximo de carga das baterias).

No geral, os resultados obtidos nesta dissertação são multidimensionais e são resultados importantes para promover o acesso a energia em grande escala nas áreas rurais da África Subsaariana, uma região com taxas de acesso a energia muito baixas, mas com fontes de energia renováveis abundantes. Os resultados também permitem melhorar o bem-estar socioeconómico das pessoas que carecem dos múltiplos benefícios dos serviços modernos de energia, dando uma grande contribuição para alcançar os Objetivos de Desenvolvimento

Sustentável das Nações Unidas, incluindo Saúde e Bem-estar (ODS 3), Educação de Qualidade (ODS 4), Igualdade de Gênero (ODS 5), Água Limpa e Saneamento (ODS 6), Energia Limpa e Acessível (ODS 7) e Trabalho Decente e Crescimento Económico (ODS 8).

Palavras-Chave: acesso a energia; microrede DC; fontes de energia renováveis; equipamentos de elevada eficiência; Agenda UN2030 para o desenvolvimento sustentável; sistemas de cozinha; eletrificação rural.

Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

AC	Alternative Current
ALRI	Acute lower respiratory disease
A_{pv}	Area of the PV module
BTU	British Thermal Unit
COE	Cost of Electricity
COPD	Chronic obstructive pulmonary disease
DC	Direct Current
DG	diesel generator
EJ	exajoules
GDP	Gross Domestic Product
GHG	Greenhouse gases
GOGLA	Global association for the off-grid solar energy sector
GW	Gegawatts
h	hour
HAP	Household Air Pollution
HOMER	Hybrid Optimization of Multiple Energy Resources
ICT	Information Communication Technology
IHD	Ischaemic heart disease
IPPC	Instant Pot Duo 7-in-1 Electric Pressure Cooker
kW	Kilo Watt
kWh	Kilo Watt Hour
LCOE	Levelized Cost of Electricity
LED	Light emitting diode
Li-ion	Lithium-ion
LMEC	Locally Manufactured Electric Cookstove
LPG	Liquified Petroleum Gas
N_{pv}	Number of PV panels
NPC	Net Present Cost
NPV	Net Present Value
PV	Photovoltaic

SDGs	Sustainable Development Goals
SHP	Antlion Single Hot Plate
SHS	Solar Home Systems
SoC	State of Charge
TEIH	Tefal Everyday Induction Hob
TVs	Televisions
η_{pv}	efficiency of the PV system

CHAPTER ONE

INTRODUCTION

1.1. Motivation

The socio-economic development of any nation and its inhabitants depends on the availability of cost-effective energy supply systems to ensure the required energy demand (Islam, 2017). However, the access to energy services in the developing world presents a low rate (IEA, 2020), which is aggravated by high transmission and distribution costs, weak infrastructure, poor operating and maintenance performance (G. Prinsloo, 2017), high greenhouse gas emissions and their associated environmental and health impacts, as well as lack of capital (United Nations, 2015). The impact of these problems on the balance between energy supply and demand in developing countries is huge, leading to poor living standards and a lack of human development (Roy & Kabir, 2012).

Worldwide, millions of people do not have access to electricity, being the majority of them concentrated in rural areas of developing countries such as Sub-Saharan Africa (IEA, 2020). Access to electricity provides many benefits to communities in the developing world, including replacing hazardous methods of lighting and cooking (such as solid biomass, kerosene), promoting education and healthcare services, women empowerment, job creation, increasing productivity and manufacturing small and micro industries and economic development. The former Secretary-General of the United Nations Ban Ki-moon stressed the importance of energy as follows which precisely describes the link between energy access and human development, as well as the benefits of access to energy services:

> "*Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive. Access to energy is a necessary precondition to achieving many development goals that extend far beyond the energy sector eradicating poverty, increasing food production, providing clean water, improving public health, enhancing education, creating economic opportunity, and empowering women. The transition to sustainable energy systems also presents one of the greatest investment opportunities of the 21st century. In short, development is not possible without energy, and sustainable development is not possible without sustainable energy"* (Ki-moon, 2011).

On the other hand, energy demand globally and specifically in Sub-Saharan African countries is increasing due to rapid economic growth, industrialization, urbanization, population growth, and improved energy access. Therefore, addressing the required energy demand using the traditional way, i.e., providing new electrical connections to communities through the expansion of centralized grids, is crucial, but it is also too slow, economically unsustainable and too expensive, since most of the population living without modern energy access is located in rural and remote areas of Sub-Saharan African Countries. The rural and remote areas are too far from the grid, and considering the economic situation of the countries, the cost of installing transmission and distribution lines is too high (IRENA, 2017). Therefore, distributed renewable energy generation systems based on off-grid (stand-alone, mini-grid/micro-grid) systems are promising options to provide sustainable energy access in rural and remote areas (APP, 2017).

Lack of energy access in developing countries is not only limited to electrification, but also billions of people around the globe are living without access to clean cooking. Globally, more than 2.6 billion people use solid fuels, namely wood, charcoal, coal, animal dung and crop wastes for cooking and heating. Most of the people who do not have access to clean cooking are also living in rural and remote locations of developing countries particularly in sub-Saharan Africa and developing Asia (IEA, 2020; Wolde-Rufael, 2005; Fiona Lambe, 2015). The solid fuels used in inefficient traditional cookstoves, specifically three-stone open fire, charcoal stoves and mud stoves, resulting in indoor air pollution (Kar & Zerriffi, 2018). Cooking using three-stone open fire or other very inefficient cookstoves has large negative impacts by causing diseases, injuries, pollution, excess time spent for gathering fuel, deforestation, and high fuel costs relative to income for people living in low-income countries (Johnson & Bryden, 2015).

The use of such cookstoves which result in the release of health-damaging pollutants, including particulate matter (small soot particles) are factors for the death of about 4 million people every year. Among the total premature deaths attributed to household air pollution, women and children are the most affected with about 54% of the total deaths (WHO, 2018). Furthermore, due to the high levels of pollutant emissions, the use of low efficiency cookstoves and solid fuels has a significant impact on the climate. Greenhouse gases (GHGs) including carbon dioxide, methane and nitrous oxide (Wilson, Talancon, Winslow, Linares, & Gadgil, 2016), which results from the biomass combustion process, and other types of pollutants, like black carbon, also have high-risk potential to increase global warming (Dinesha, Kumar, & Rosen, 2019).

On the other hand, the basic needs of human life such as health services, housing, education, production and preparation of food, as well as clothing, are linked with the lack of access to energy services. As a result, access to clean energy is critical for sustainable socioeconomic development at every level such as household, regional, national and global levels (Mbaka, Gikonyo, & Kisaka, 2019). Therefore, the Sustainable Development Goals, in particular, SDG3 (Good health well-being), SDG7 (Affordable and Clean Energy) and SDG 13 (Climate Action), are not ensured through the use of low efficiency cooking technologies, leading to dangerous household air pollution, and destructive solid fuel harvesting (Mehetre, Panwar, Sharma, & Kumar, 2017). Although there is an agreement among different stakeholders on the development and promotion of clean and efficient clean cooking technologies and fuels, there are still challenges due to key technology and market barriers, such as the lack of policy and regulation, lack of cookstoves quality standards, low consumer education level, low access to finance, lack of business development support and lack of sustainable fuel supply (ESMAP, 2018).

Furthermore, in many developing countries the traditional way of addressing energy access problems has been mainly focused on increasing energy supply to improve energy access. However, the promotion of energy efficiency measures and energy-efficient appliances can greatly contribute to increasing modern cost-effective energy services access (Cana, Pudleiner, & Pielli, 2018). Even if the benefits of energy efficiency are well presented in different sectors including residential, commercial, industrial and transportation in developed countries that consider energy efficiency as a key energy resource, practically it is not yet fully exploited. Energy efficiency measures and use of energy efficient appliances could minimize the need for additional investments in energy supply and storage by improving system reliability and performance, as well as saving energy costs and mitigating the social and environmental impact of energy supply systems (Jordan, Corry, & Jaques, 2017; IEA, 2019), but there still are gaps on the linkage between energy access and energy efficiency in developing countries (Cana, Pudleiner, & Pielli, 2018). As a result, the potential contribution of energy efficiency towards energy access is immense, but the developing countries are lagging to address it mainly due to economic and social development. In developing countries, since there is a lack of access to modern energy services, the impact on socio-economic and human development is much higher in rural locations than in urban locations, being, therefore, the problem more alarming in rural and remote locations. On the other hand, the economic level of developing countries cannot afford to cover expenses for services such as energy, clean water, health and other basic services. In addition, there is a lack of awareness and accessibility of different energy-efficient appliances, including different lighting appliances, refrigerators, cooking options, and fans.

The sum of all the problems in rural and remote locations of Sub-Saharan Africa hinders the problem of selecting the type of efficient, cost-effective and reliable energy system which could supply the energy demands for rural communities undeservedly suffering from the lack of access to modern energy services. With this regard, a sustainable solution that can balance the demand and supply is needed, being off-grid systems composed of locally available energy resources integrated with energy efficiency measures and appliances an important option to ensure reliable power at a lower cost.

Based on the number of energy sources and consumers, off-grid systems can be divided into decentralized and distributed systems. Decentralized systems can be classified as stand-alone (single household) or microgrids (multiple customers) and distributed systems are usually classified as microgrids, which consist of different energy sources for multiple consumers. A microgrid is a discrete energy system consisting of distributed energy sources (including demand-side management, storage, and generation) and loads capable of operating in parallel with, or independently from, the main power grid. These microgrids can be AC-microgrids or DC-microgrids. The focus of this work will be on DC-microgrids, which have more advantages in terms of reducing the investments needs in the power system infrastructure, reduction of conversion steps, reduction of losses and voltage drops, absence of reactive power in DC distribution lines, as well as easy to integrate with DC loads, which planning, implementation and operation can be simpler and cheaper over AC-microgrids (Estefanía Planas, 2015).

1.2. Objectives and Research Questions

Although there is progress in energy access in sub-Saharan Africa, there are still gaps that should be addressed in relation to off-grid systems to supply inclusive modern energy services. The research and the practical solutions are usually focused on specific energy services like only lighting and entertainment. This thesis work pursues by selecting different locations in Sub-Saharan African countries, like Ethiopia, as case studies, analyzing the potential of different renewable energy sources and assessing the best combination of renewable energy sources complemented with energy efficiency options and energy-efficient appliances. The thesis thoroughly investigated different cooking options in the lab by testing and measuring the energy performance of different clean cooking technologies, since cooking is the main energy demand activity in households of sub-Saharan African countries. Such a task was developed with the aim of selecting efficient and cost-effective clean cooking options. Additionally, recently developed energy-efficient off-grid appliances, including lighting, TVs, and fans are considered in the study, with the aim of minimizing the load demand without compromising the comfort of users. Then, renewable energy systems (PV with storage, and hybrid PV -wind-with storage) were designed, developed and assessed for different applications such as for primary schools, households and community-level energy demands with the aim of answering the following research questions. Therefore, this thesis work formulates the following research questions to address the gaps in the off-grid energy solutions:

1. What are the available renewable energy sources in the selected locations and their potential?

Aim: To know the available resources and choose the best combination of renewable sources in the selected locations.

2. What are the best available off-grid energy-efficient appliances? How could the efficiency of the available technologies/appliances (different cooking technologies) be evaluated?

Aim: To evaluate and test different cooking options to know the best available cooking technology among the available technologies including traditional and modern (clean) technologies. And to know the best available energy-efficient off-grid appliances and choose the best combination of appliances that can be integrated with the proposed DC microgrid.

3. How can the supply and demand be matched in remote locations?

Aim: There are different options (e.g. solar lanterns, solar home systems) to have access to electricity in rural areas, but there is the need for energy services like cooking, heating, cooling, food preservations, etc in hours of low availability of generation. Therefore, in this research question, the mismatch between supply and demand were addressed in order to find a solution to have sustainable energy access for different energy services.

4. What is the best possible microgrid design to supply inclusive modern energy services in rural areas?

Aim: Based on the locally available renewable energy sources and the load demand different kinds of configurations of microgrids could be proposed to supply the energy demand. However, the proposed configuration might not be viable technically and economically. Therefore, in this research question, the techno-economic feasibility of different configurations of hybrid renewable energy systems configurations will be investigated.

By addressing the above-mentioned research questions, the thesis aims to achieve the following general and specific objectives. The general objective of this thesis work is to design and model DC-microgrids and to assess their contribution to rural development by providing sustainable energy access in rural and remote areas of sub-Saharan African, using Ethiopia as a case study.

The specific objectives include:

- To assess the current energy trend and the energy needs of the rural community.
- To determine the potential of renewable energy sources in specific locations.
- To investigate the benefits of energy-efficient appliances, such as different cooking technologies.
- To model and design DC-microgrids.
- To assess the technical and economic viability of DC-microgrid systems.
- To develop, design and integrate clean energy systems into the rural community.

1.3. Major Original Contributions

This thesis addresses the modeling and design of DC microgrids for different applications to improve sustainable energy in rural and remote areas of sub-Saharan Africa. Previous studies have been focused on AC microgrids for such applications. There are two main contributions of this dissertation. The first one is analyzing and defining the best hybrid renewable energy system (DC microgrid) option to improve access to sustainable energy for people still living without access to modern energy services which will assure sustainability and sustainable development. In this regard, the thesis work analyzed different configurations of microgrids in different locations of Sub-Saharan Africa with different scenarios. The second is as demand increases to provide new services the usual solution is increasing generation to fill the request from the consumers. However, this practice needs high investment for generation and infrastructure. This will not ensure sustainability and sustainable development from an economic, environmental and social perspective. To increase generation, there is a need for space (land that may force people to displace from their property and create some kind of social crisis) and also from an environmental perspective, which has a significant impact. In relation to this, this research addressed the issue by balancing the demand and supply by incorporating super-efficient appliances and energy storage. Addressing these issues will provide a new perspective for sustainability research and it will have a significant impact in shifting sustainable research in developing countries to another level.

With these aims, the original research work carried out supported the preparation of the following international Journal published and conference papers to research communities.

Journal Papers:

1. Aemro, Y.B.; Moura, P.; de Almeida, A.T. Design and Modeling of a Standalone DC-Microgrid for Off-Grid Schools in Rural Areas of Developing Countries. *Energies* 2020, *13*, 6379. doi.org/10.3390/en13236379
2. Aemro, Y.B.; Moura, P.; de Almeida, A.T. Experimental Evaluation of Electric Clean Cooking Options for Rural Areas of Developing Countries. Sustainable Energy Technologies and Assessments 2021, 43(100954). https://doi.org/10.1016/j.seta.2020.100954
3. Aemro, Y.B., Moura, P. & de Almeida, A.T. Inefficient cooking systems a challenge for sustainable development: a case of rural areas of Sub-Saharan Africa. Environ Dev Sustain (2021). https://doi.org/10.1007/s10668-021-01266-7
4. Yohannes Biru Aemro, Pedro Moura, Aníbal T. de Almeida. Energy access during and post-COVID-19 Pandemic in sub-Saharan African countries: The case of Ethiopia. Environment, Development and Sustainability Journal. *Accepted for publication*

Conference papers:

1. Aemro, Y.B.; Moura, P.; de Almeida, A.T. DC-Microgrids as a means of Rural Development in East African Countries. Proceedings of the ASME 2018 Power Conference, POWER2018, June 24-28, 2018, Lake Buena Vista, FL, USA
2. Y. Biru Aemro, P. Moura, A. de Almeida, Impact of Cooking Technologies for a Sustainable Future: A Case Study for Ethiopia and Rwanda, in 4th Energy for Sustainability International Conference “Designing a Sustainable Future” (EfS 2019), Turin (Italy), 2019

Projects:

Aníbal T. de Almeida, Nuno Quaresma, Yohannes Biru Aemro, Luís Ferreira, Evandro Garcia. Design and Development of Super-Efficient Refrigerator with Phase Change Materials (PCMs). https://efficiencyforaccess.org/updates/r-d-cooling-call-winners

1.4. Thesis Outline

This thesis is structured in six chapters including the introduction chapter. The content of each chapter is outlined below.

Chapter 2 presents the status of global energy access, as well as specifically in sub-Saharan Africa, from electricity and clean cooking access perspectives. Further, it details the different technologies used for cooking and lighting services in sub-Saharan Africa, as well as their impacts on health, environmental and socio-economic aspects. In this chapter, the major gaps and the innovation required to tackle the challenges with respect to energy access in rural areas of sub-Sahara Africa were presented, where off-grid solutions and energy efficient appliances are considered as emerging technologies and cost-effective solutions to address the issue of energy access in rural areas of developing countries. Furthermore, the different options of off-grid solutions including AC microgrids, DC microgrids, pico solar systems and emerging energy efficient appliances were discussed in detail.

Chapter 3 presents one of the case studies of this thesis work, which is the evaluation and experimental analysis of different types of cooking technologies. In this part of the thesis, the background of different cookstove options used in developing countries and the cookstove technologies selected for the case study were presented. Followed by the experimental methodologies used in the study, including the input data for the selected technologies, the food ingredients and the testing procedures. Moreover, the results of the analysis related to the energy consumption, heat transfer behaviors, cooking efficiency and life cycle costs are presented and discussed.

Chapter 4, another case study is presented, which is the design and modeling of DC microgrids. In this chapter, a rural primary school located in rural Ethiopia was considered for the design and model of the proposed DC microgrid. The chapter presents the details about microgrids and the differences between AC and DC, as well as the bases for the classification of microgrids. Further, the design and model of the proposed DC microgrid for the primary school is presented by analyzing the available renewable energy sources in the selected site including the PV generation potential, PV and battery sizing, as well as the model of the proposed system using MATLAB/Simulink. Moreover, the model was validated, and the main results are presented.

Chapter 5 discusses the techno-economic feasibility studies of different hybrid renewable energy systems for household, health center and village applications. This chapter is related to chapter 4, but the followed methodologies, as well as the case studies in terms of location, application, software used and analyzed techno-economic issues, are different. In this chapter, the data of each case study is presented, namely, the location, load demand, and available renewable energy resources. The design and simulation analysis of four microgrids (three DC and one AC-DC) were discussed in detail.

Chapter 6 presents the concluding remarks of the thesis and discusses critical reflections for future work.

CHAPTER TWO

ENERGY ACCESS AND OFF-GRID SOLUTIONS

2.1. Energy Access-Global Status

The World population is expected to grow to nearly 9 billion by 2035 (BP, 2017; GEA, 2012) and the GDP is expected to increase by 3.4% in the next 20 years (BP, 2017), which will increase the energy demand from 549 quadrillions BTU in 2012 globally to 815 quadrillions BTU in 2040 (EIA, 2016). In particular, in developing countries, the energy demand is increasing due to economic growth, rapid industrialization, improved energy access and urbanization (IRENA, 2017). However, the estimation of energy demand and GDP growth is highly impacted by the unprecedented global COVID-19 pandemic which the world is facing since the end of 2019. Based on the IMF's longer outbreak scenario indicates the World's GDP will decrease by 6% in 2020, and this impact will last for many years and is expected to reduce the World's GPD by 9% in 2050.

On the other hand, the global energy demand was predicted to be 456 exajoules (EJ) in 2050 and based on the latest figures the demand was 424 EJ in 2018. According to the DNV modeling, the global energy demand in 2050 will be the same as the demand in 2018, implying an 8% reduction compared with estimation before the COVID-19 pandemic (Alvik & Irvine, 2020). This further impact sustainable development plans globally, as well as in every nation. Figure 1 presents the global energy demand projection before and with COVID-19, as well as the historical energy demand levels.

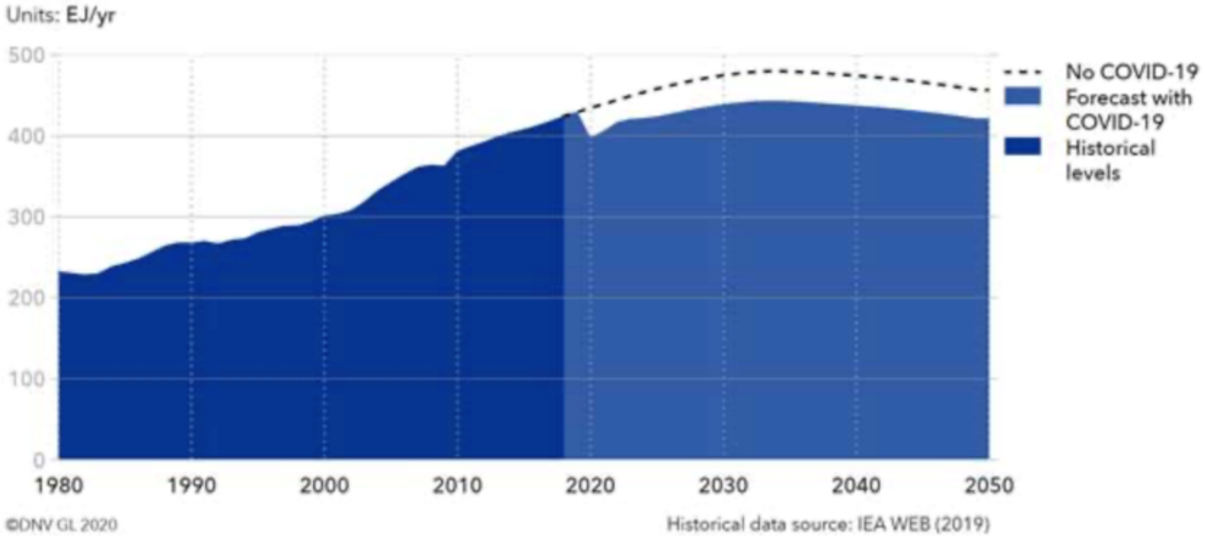


Figure 1 World final energy demand-with and without COVID-19: source (Alvik & Irvine, 2020)

Together with increasing GHG emissions, global warming and depletion of fossil fuels (IPCC, 2014) are some of the major challenges that hinder the achievement of sustainable development. The Sustainable Development Goals developed by the UN, including the accessibility of affordable and clean energy (SDG7) for all by 2030, are also fundamental to achieve other SDGs (IRENA, 2017) such as: no poverty, zero hunger, good health well-being, clean water and sanitation, climate action, gender equality, etc. To tackle these challenges, achieve sustainable development goals and address the demand of the users: countries, policymakers, governmental and non-governmental organizations, and research institutions are focusing on the increasing use of renewable energy.

Renewable energy ensures a carbon-free economy and environment, sustainable development and energy security, being also the most cost-effective option to increase energy access in developing countries. Due to its market growth, technological development and policies towards mitigating climate change (REN21, 2020) renewable energy systems show tremendous progress in the last couple of decades, being fundamental to achieving sustainable development targets. The use of renewable energy has increased not only in the electrical grid level, but also in buildings, industry, and transportation, ensuring new markets and the creation of jobs (IRENA, 2019).

The share of renewable energy sources in the global energy mix has been increasing in the power sector. In 2019, an increment of 176 GW of renewable power generation capacity was recorded, which represented a 7.4% increase compared with the previous year. As shown in Figure 2, the major additions were in solar photovoltaic (PV), wind, hydropower, bioenergy and geothermal with capacities of 98 GW, 59 GW, 12 GW, 6 GW and 0.7 GW, respectively. The share of renewables in the total energy consumption is expected to increase in the next couple of decades as well, in particular in sub-Saharan Africa where there is a high potential for renewable energy resources (IRENA, 2020).

Furthermore, renewables are expected to have a major impact on the global energy share and to impact economic development, as well as to contribute to recovery from the impact of the COVID-19 pandemic in many aspects including social and economic aspects. According to the International Energy Agency, due to the contraction of oil, coal and gas markets, renewable energies are the only energy sources set for a growth in demand in the coming years and are the most resilient to COVID-19 lockdowns (Farand, 2020). However, recent market trends and reports indicate that renewables are also affected by the pandemic's overall impact. In China, the impact of COVID-19 on renewables was evident mainly due to the delay in delivering equipment necessary for power plant construction. China is one of the countries which delivers most of the renewable power plant components including solar panels, wind turbines and batteries for the whole world. Nevertheless, since the spread of the COVID-19, orders have been delayed. As a result, renewable energy companies and distributors could not achieve the deadlines for the construction and installation of equipment (TETIANA MYLENKA, 2020). For example, in India, the delay of equipment supplies, and workforce availability resulted in about 63% of solar power plant projects being on hold because of the pandemic during the first three months of the year (GUPTA, 2020).

On the other hand, a survey made by the global association for the off-grid solar energy sector (GOGLA) in March 2020 among its members found that due to the COVID-19 pandemic most of the members already faced serious challenges to operation and disruptions in sales as well as after-sales support. The study found that about 50% of off-grid companies could be in serious financial trouble if the pandemic lasts for more than three to four months, whereas about 11% of the GOGLA member off-grid companies found themselves in an immediate financial crisis (GOGLA, 2020).

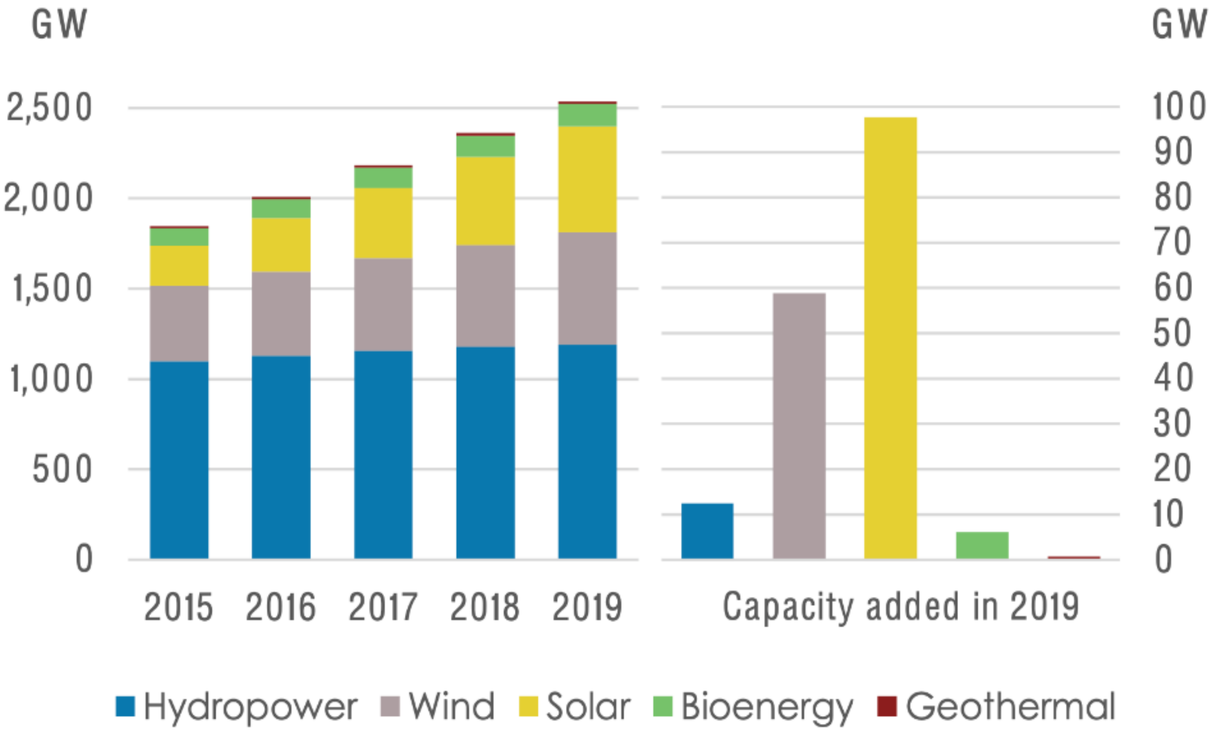


Figure 2 Renewable power capacity growth (IRENA, 2020)

Although there is progress in energy generation and technological development towards using renewable energy resources, about 0.8 billion people are still without electricity access and about 2.6 billion people rely on the traditional use of biomass for cooking, heating, and other energy services. Most people who do not have access to electricity and other energy services are living in rural and remote areas of developing regions and countries, like Africa and Asia, in particular Sub-Saharan African countries and India (IEA I. U., 2021). Figure 3 presents the global electricity access rate progress and the population living without access to electricity between 1990 and 2018. As can be seen, there is a decreasing number of populations living without electricity access from 1.5 billion in 1990 to about 0.8 billion in 2018. Concerning the electricity access rate, in rural areas, there is still about 20% of the global population located in rural areas without access to electricity, whereas in urban areas more than 97% of the global population have access to electricity.

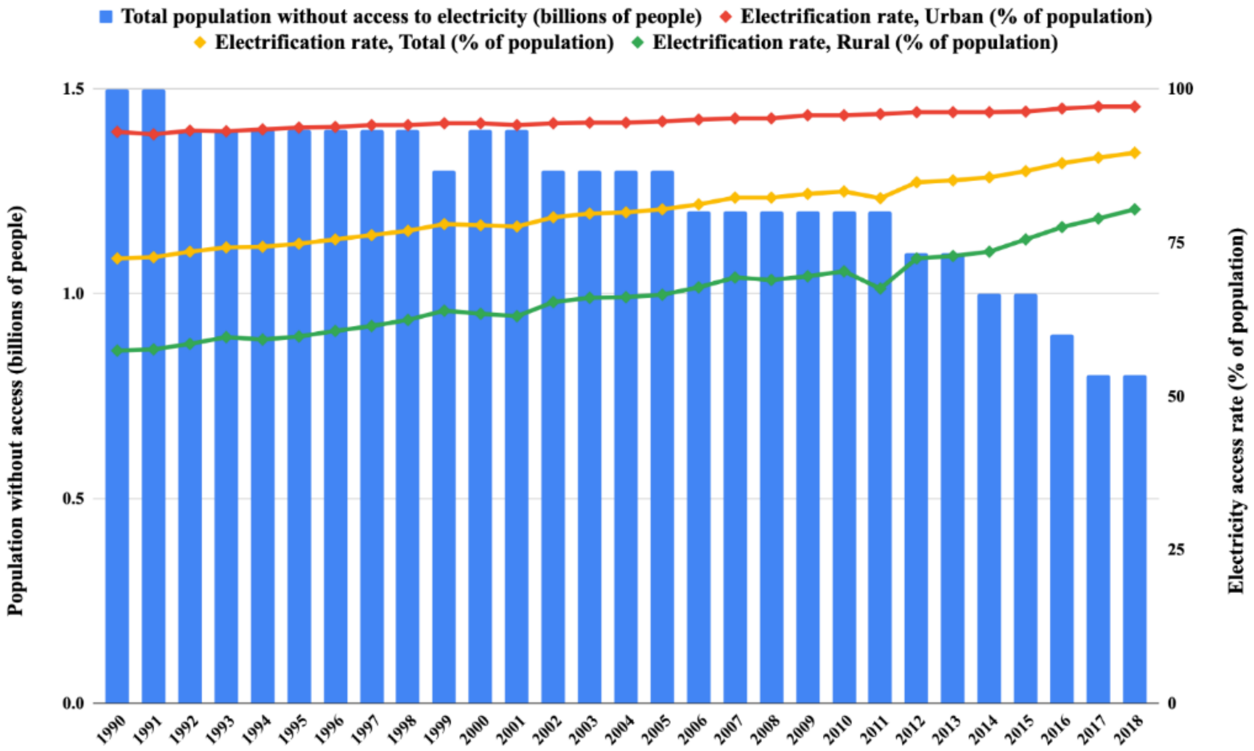


Figure 3 Progress in electricity access from 1990 to 2018 (billions of people and share of the population (%) with access to electricity) (ESMAP, 2020)

Figure 4 presents the clean cooking access progress in terms of billions of people with access and without access, as well as the access rate for the last two decades. There is progress in clean cooking access from 2000 to 2018. For instance, the number of people with clean access was 3 billion in 2000 and 5 billion in the year 2018. However, regarding the number of people living without access to cleaning cooking, there is no significant change. The number of people living without access in 2000 was 3 billion and the number of people that are living without access to clean cooking in 2018 is also almost the same with 2000. Worldwide, in 2018 about 37% of the World population do not have access to clean cooking.

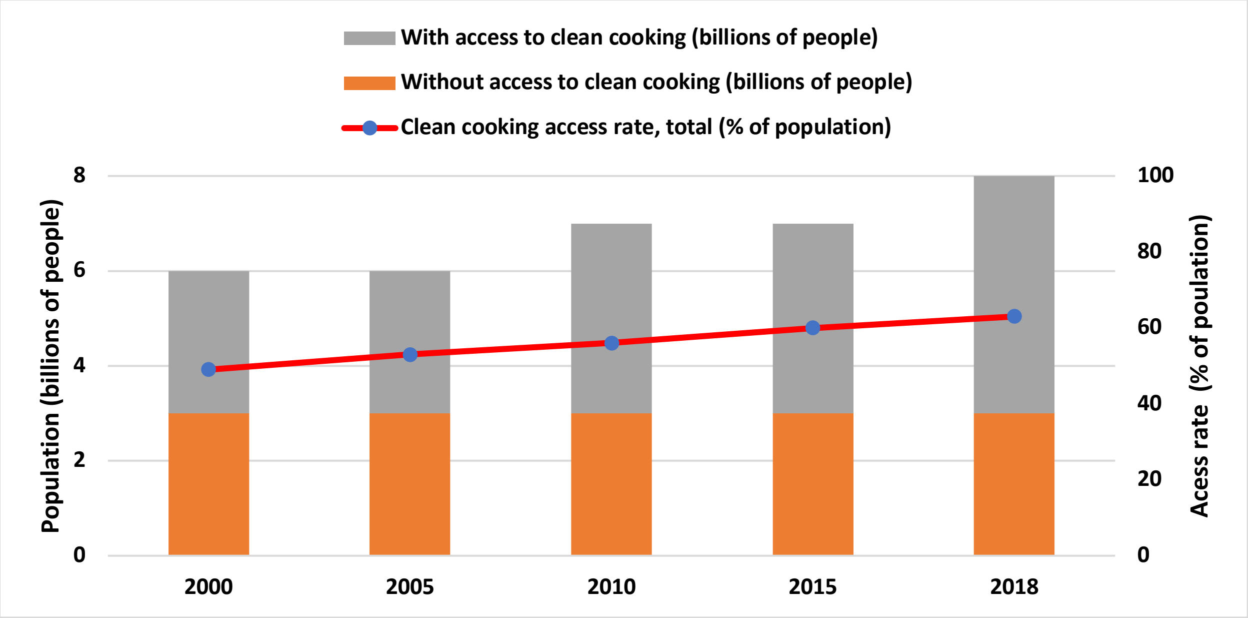


Figure 4 Progress in clean cooking access from 2000 to 2018 (billions of people and share of the population with access to clean cooking) (ESMAP, 2020)

2.2. Energy Access in Sub-Saharan Africa

Access to modern energy services is a pillar for human development, environmental protection, and countries' economic development, as well as it connects economic growth, increased social equity, and an environment that allows the planet to thrive (IEA, 2019; UN, 2012). However, in sub-Saharan Africa, human service areas such as health care, nutrition, education, and income present a low level which is impacted by the lack of modern electricity and other energy services, compared with developed countries. Additionally, poor urban and rural consumers relied on wood, coal, and kerosene for their daily energy service needs (H. Rudnick, 2014), and due to the indoor air pollution from traditional cooking and heating systems (open fire) about million people die prematurely (IEA, 2016).

Even if energy access has been increasing slowly in the region, only 47% of the population in sub-Saharan Africa had access to electricity in 2018. In numbers, about 600 million people do not have electricity, around 900 million people are living without access to clean cooking that depends on using traditional biomass (wood, crop wastes and animal dung) for cooking and heating their homes (IEA, 2020). Figure 5 presents the worldwide electricity access rate for different regions in 2018. It clearly presents that sub-Saharan Africa has a lower access rate compared with other regions followed by Oceania. On the other hand, average electricity consumption per capita in sub-Saharan Africa is more than 100-fold lower compared with other developing nations. For instance, by the year 2014, the average electricity consumption in the USA was about 13,000 kWh/year, which is more than 100-fold compared with the average electricity consumption per capita in Tanzania, Ethiopia and Niger which all consumed below 100 kWh/year (Ritchie, 2019).

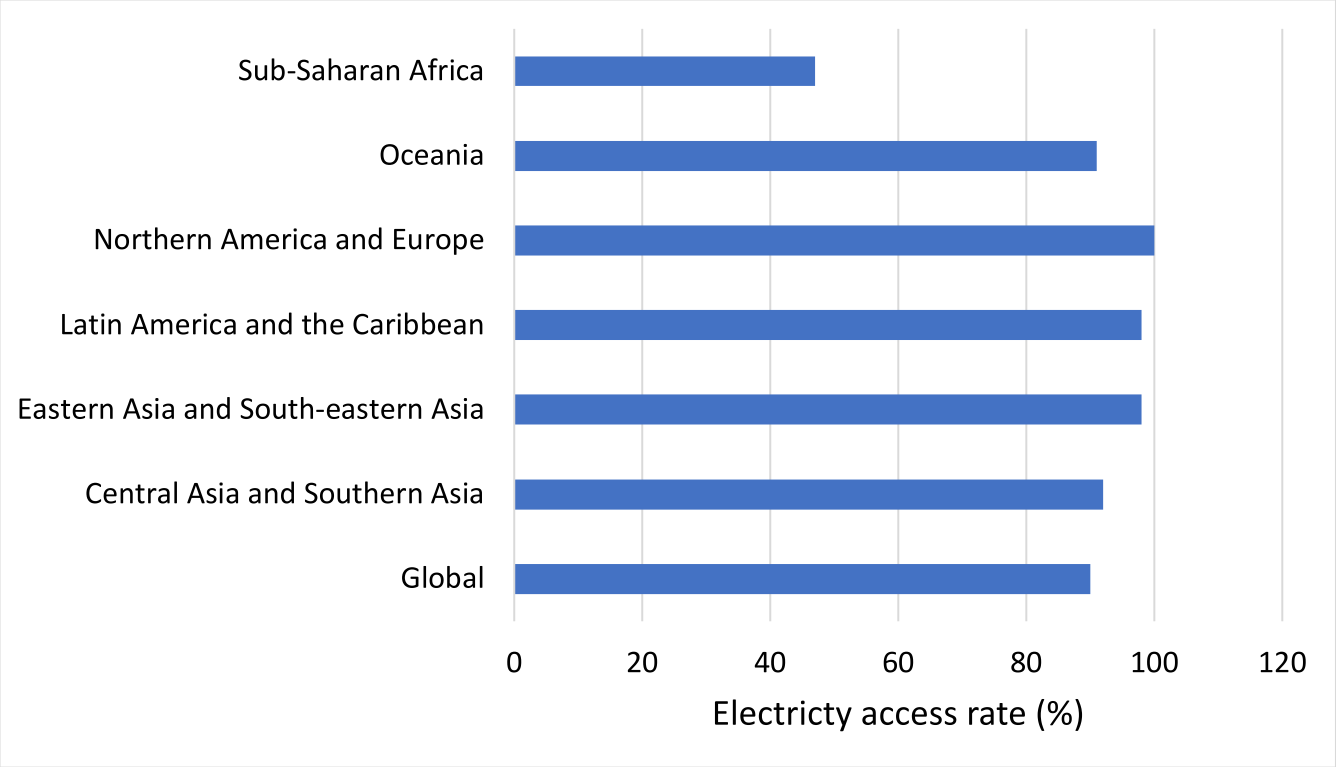


Figure 5 Worldwide electricity access rate in 2018 (ESMAP, 2020)

2.2.1. Electricity Access and Recent Developments

Among the total population living without access to electricity more than 60% of the population is located in sub-Saharan Africa. As presented in Figure 5, the rate of electrification in the region is at a lower rate compared with the electrification rates of other countries in the developing world like Central and Southern Asia (which the access rate is about 92% on average). Despite the low rate of access in the region, there was tremendous progress of electrification across each nation of the region in the last couple of years. From 2014 to 2018 about 20 million people get access to electricity, which is double compared with the number of people gaining electricity access from 2000 to 2013 i.e., 9 million people. However, there are still about 600 million people living without access to electricity which increases every year due to the high birth rate in the region. Therefore, the region is facing a huge challenge of delivering affordable, clean, and safe electricity for millions of people born every year and for the 600 million people living without access today.

Figure 6 presents the millions of people living without access to electricity in Africa. Countries including Nigeria, Ethiopia, the Democratic Republic of the Congo, Tanzania and Uganda have a higher population without access to electricity, which is nearly half of the population without access to electricity in sub-Saharan Africa. On the contrary, among all countries in the region Ethiopia, Kenya and Tanzania connected the majority of the population gaining electricity access in the last 5 years that accounting for about 50% of the total population gained electricity from 2014 to 2018 (IEA, 2020).

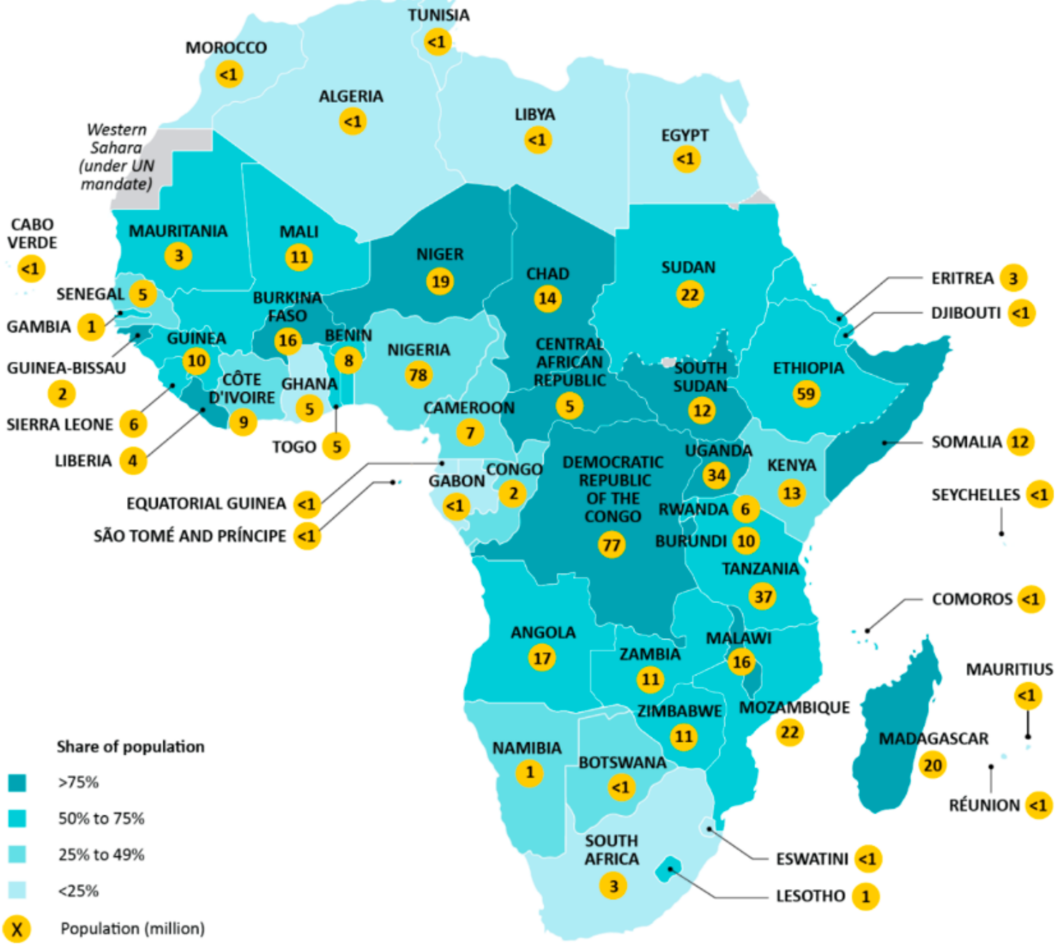


Figure 6 Population without access to electricity by country in Africa, 2018

On the other hand, the majority of the population in the region is located in rural areas, implying that most populations located in the region do not have access to electricity. Figure 7 shows the urban and rural electricity access rates in sub-Saharan Africa. It indicates that in rural areas about 73% of the total population do not have access, compared with urban areas the electricity access is lower than by about 50%. Furthermore, the average electricity consumption is in the range of 50 to 100 kWh per year and simultaneously about 80% of the people who do not have access to electricity are living in rural areas, which require effective and efficient solutions to ensure balanced economic growth in the sub-Saharan African countries, as well as Worldwide sustainable development (IEA, 2014).

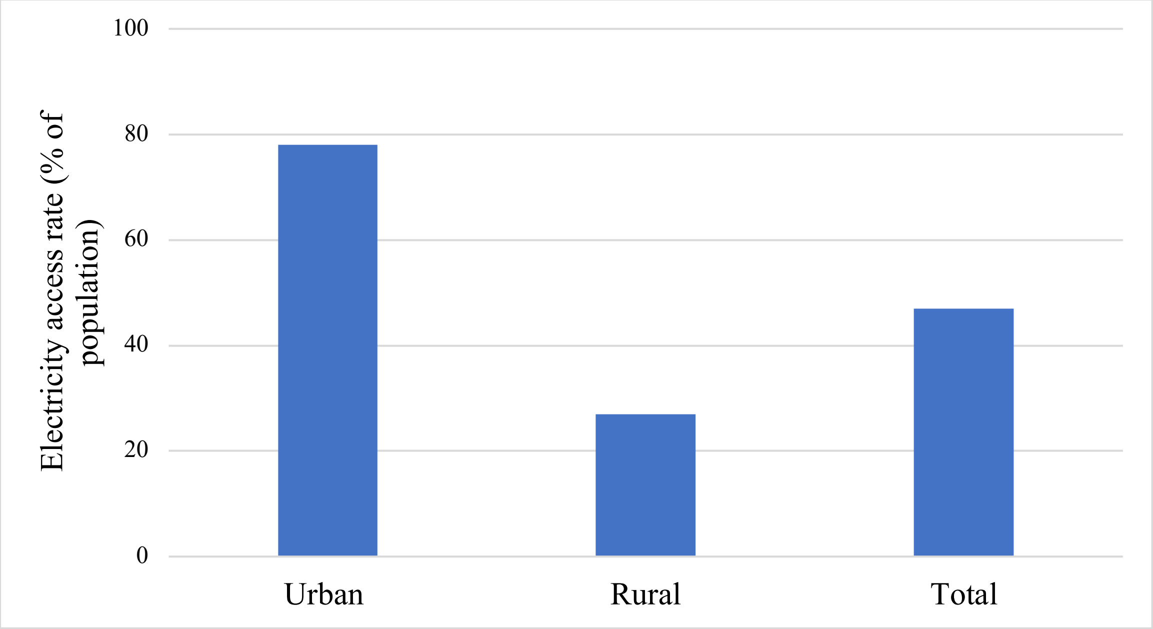


Figure 7 Urban and rural electricity access rate in sub-Saharan Africa (% of the population)

Access to electricity is important for households, small businesses, farming and lifting a country and its inhabitants out of poverty. The benefit of electricity is also depending on the use and availability of appliances, equipment and materials that work using electricity. Figure 8 shows the link between electricity and its benefits concerning education, knowledge dissemination and entertainment, comfort and productivity improvement, and business creation. In rural areas of sub-Saharan Africa where electricity access is at a low rate, increasing affordable and reliable electricity is crucial to promote quality education by allowing the students to study more time at night as well as to use education supplementary appliances including computers, radio, TVs.

Additionally, delivering electricity in rural areas means creating jobs, increasing productivity, increasing small and microbusinesses, creating flexible working areas and time, as well as saving time for cooking foods in a short period of time and preserving it (Douglas F. Barnes, 2018). In many of the countries of sub-Saharan Africa, such services are not available due to the lack of access to electricity, rather the population is forced to use solid biomass, crop wastes, animal dung and kerosene fuels for any energy service required at the household level. Such fuels have greater economic, social, environmental and health impacts. Therefore, it is necessary to find reliable, efficient and cost-effective solutions to improve electricity access in rural and remote areas, as well as to improve the quality and standards of living of millions of people located in such areas of sub-Saharan African countries.

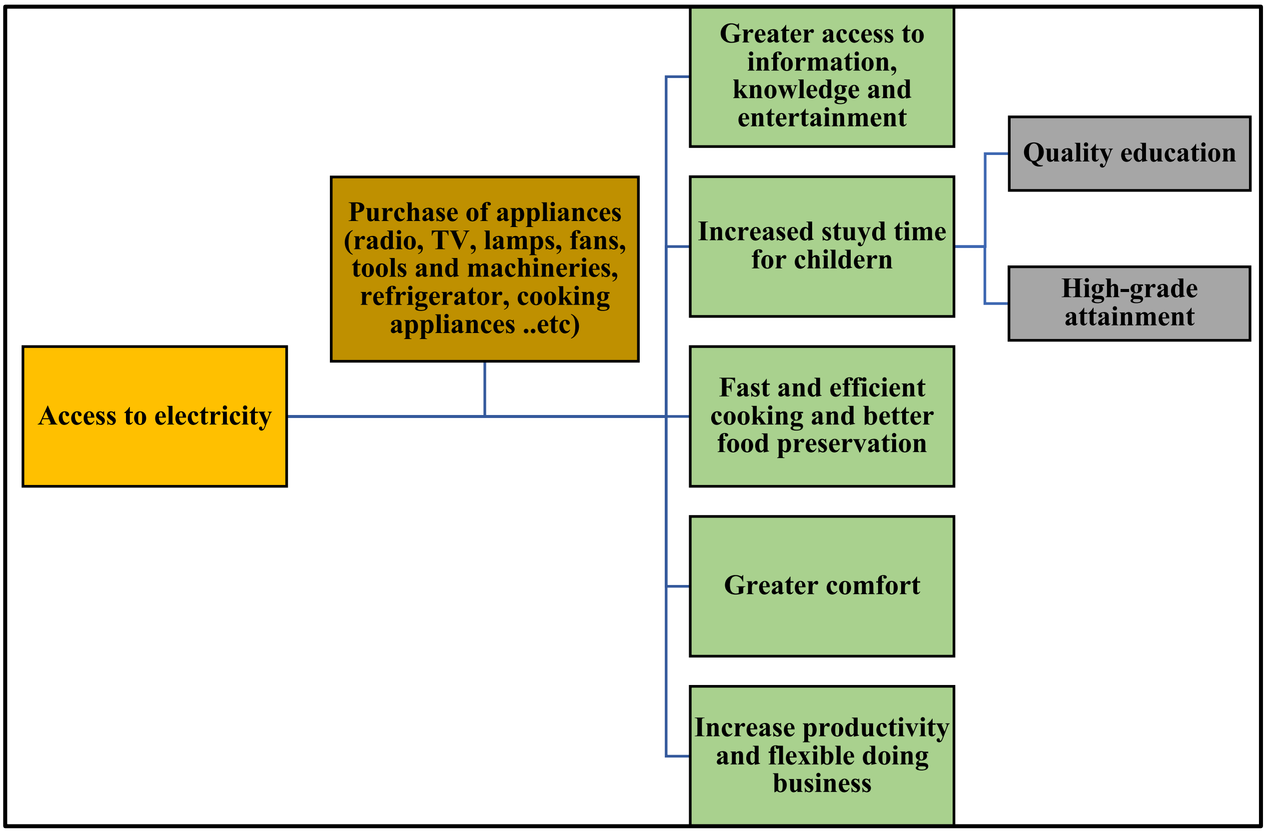


Figure 8 Benefits of access to electricity (adapted from (Douglas F. Barnes, 2018))

2.2.2. Clean Cooking Access and Recent Developments

Sub-Saharan Africa is the region with the highest rate of people relying on traditional biomass and low efficiency cookstoves (J. Morrissey, 2017), with more than 900 million people in the region (above 80% of the total population) depending on solid biomass for cooking. More than 90% of the population relying on biomass for cooking lives in rural and remote areas (IEA, 2020). Figure 9 presents the population (in millions) that relies on solid biomass, in more than 25 countries in sub- Saharan Africa. For instance, in 2018, in Uganda, about 42 million inhabitants relied on solid biomass for cooking, which represents more than 98% of the total population. On the other hand, it was estimated that around 823 million people will be forced to depend on solid biomass and low efficiency cookstoves by 2030 in the region (J. Morrissey, 2017; IEA 2017), due to the fast population growth rate (about 2.5 %) and slow penetration of modern cooking systems.

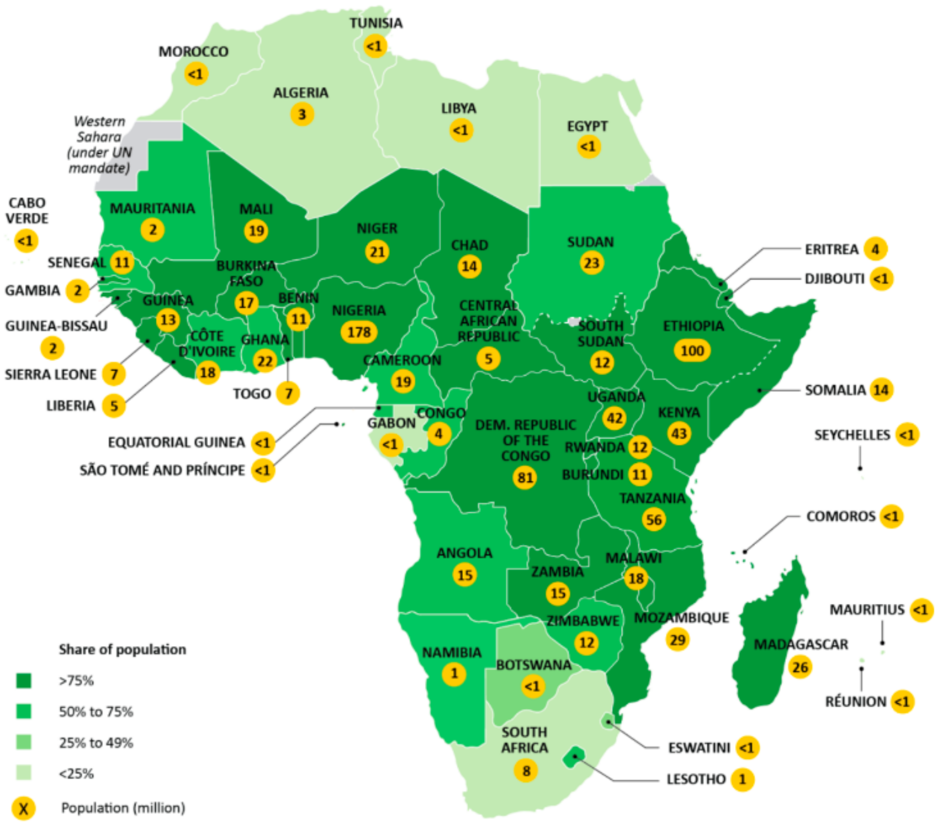


Figure 9 Population without access to clean cooking in Africa, 2018 (IEA, 2020)

Although there are different cleaner cooking options available in the region, about 7% of urban and 2% of rural households in the region use Liquified Petroleum Gas (LPG), about 6% of the population (urban and rural) uses kerosene and the rest of the population relies on solid biomass. More specifically in South Africa, only 8% of the population depends on wood fuels, 83% uses electricity, and the remaining uses other kinds of fuels including charcoal or kerosene. In Nigeria, more than 40 million people located in urban areas rely on kerosene (IEA 2017). In countries such as Burundi, Central African Republic, Chad, Liberia, Gambia and Sierra Leone more than 95% of the population relies on wood-based solid biomass for cooking (Wolde-Rufael, 2005). Figure 10 presents the type of fuels currently being used for cooking in urban and rural households in some sub-Saharan African countries. In all of the countries listed in Figure 10, fuelwood, straw and other wastes are the dominant fuels used in rural areas. Whereas in urban areas, with the exception of Nigeria and Ethiopia, charcoal is the dominant fuel. The share of electricity consumption for cooking is very low in all countries in urban and rural areas with the exception of Ethiopia, where electricity has a significant share in urban areas.

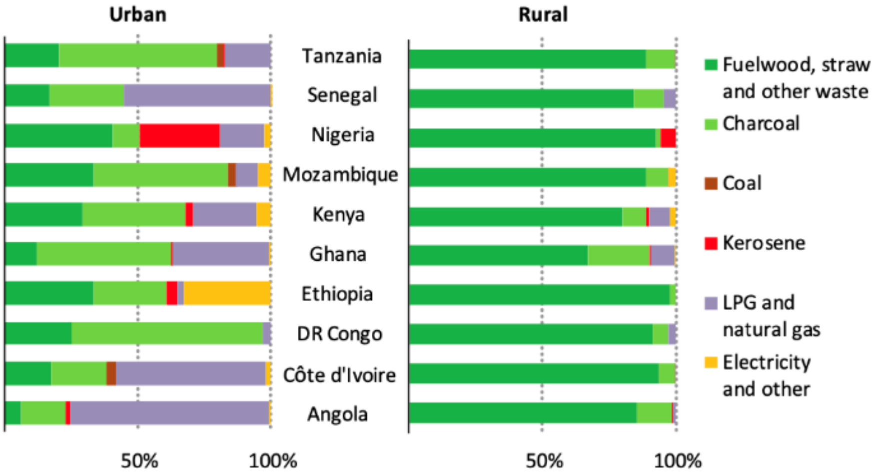


Figure 10 Main fuels used by households for cooking, 2018 (sources: Africa Energy outlook 2019)

Figure 11 presents the predominant solid fuel cookstove technologies and kerosene cookstoves used across urban, rural and remote areas of Sub-Saharan Africa. The cooking technologies used in these regions range from less efficient three-stone open fire to higher efficiency cookstoves, such as improved cookstoves and cookstoves using more cleaner fuel options such as LPG and ethanol (M. Njenga et.al, 2016). There are several options regarding cookstove technologies and generally, the population understands why it is important to replace the less efficient cookstoves with slightly more efficient cookstoves. However, the cost of fuels associated with the available technologies and the economic level of the regions makes it difficult to access modern cooking technologies in rural areas of the region (D. B. Rahut et.al, 2016; M. Vaccaria et.al, 2017).

In Ethiopia (the second-most populous country in the region), as shown in Figure 12, three-stone open fire is the most common cookstove option with a share of 63.3% of the total households, 13.6% uses self-built stoves, 18.2% uses improved cookstoves, 4.1% uses electric cookstoves and below 1% uses LPG cookstoves. Therefore, more than 93% of the population uses biomass fuels and biomass cookstoves as their primary cooking solution. In rural and remote areas, 76.6% of households use three-stone open fire cookstoves and 85.4% of the fuel used is firewood (World Bank/Ethiopia, 2018; G. T. Tucho and S. Nonhebel, 2017). As a result, to improve the existing situation, it is necessary to study different kinds of cooking technologies and their impacts, which could be helpful to shift the cooking system from traditional to cleaner technologies.

Figure 11 Common solid fuel and kerosene cookstoves (clockwise from upper left): three-stone open fire stove, wood stove made from clay, wood stove made from metal, Kerosene stove made from metal, the last two- charcoal metal stove with a different design (N. G. Johnson and K. M. Bryde,n 2015)

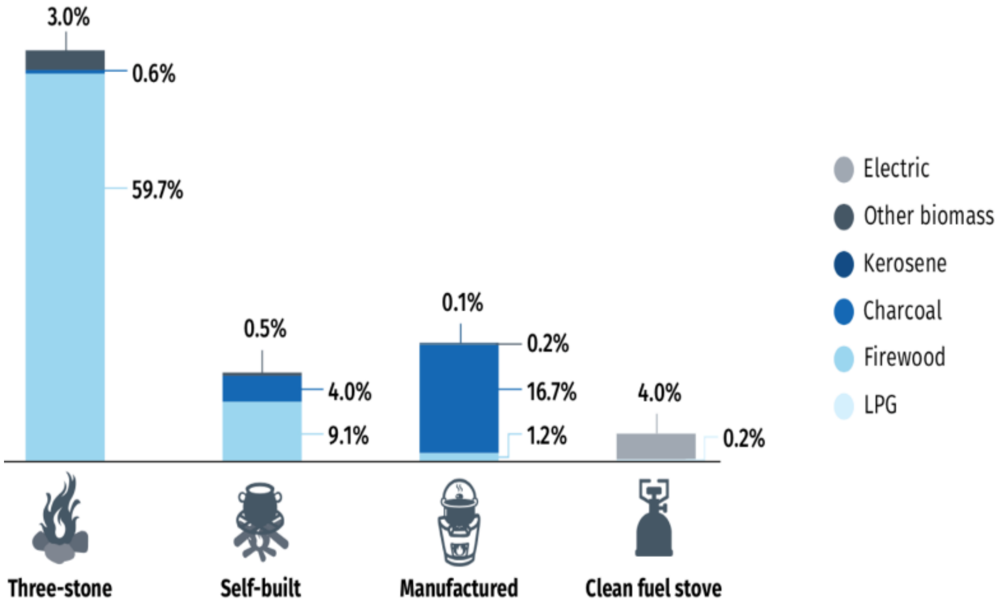


Figure 12 Cooking technologies in Ethiopia. Source: (World Bank/Ethiopia 2018)

In Ethiopia and other countries in Sub-Saharan Africa, traditional cooking technologies with their associated fuels are dominant, resulting in high emissions and health impacts. Based on the global burden of disease study made in 2013, household air pollution is ranked as the top environmental health risk factor in Sub-Saharan Africa, as well as the most considerable environmental health risk factor worldwide (Mock et.al, 207). Figure 13 shows the risk pathway of using solid biomass fuels starting from source and emissions, moving to concentration levels of solid particles and pollutants to the environment and exposures of humans, then doses of the pollutants in the human body, as well as health impacts.

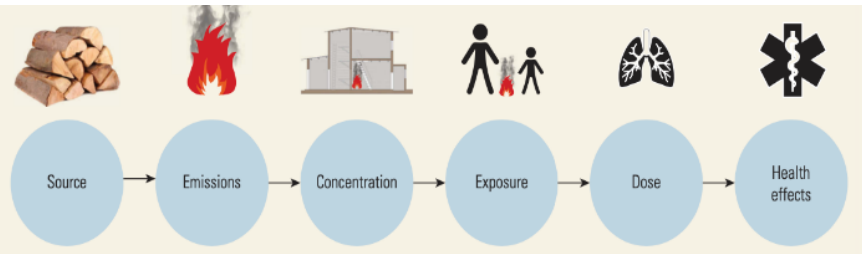


Figure 13 Classic environmental health pathway (Mock et.al, 2017)

In 2016, close to 4 million deaths were estimated to be caused by Household Air Pollution (HAP) resulting from cooking using polluting technologies. The majority of the deaths were recorded in developing countries. As indicated in Figure 14, about 40% and 32% of the deaths are recorded in South East Asia and Western Pacific regions, respectively. Close to 20% of deaths are registered in the African region and the remaining deaths have occurred in the Eastern Mediterranean region (5.5%), Americas (2.2%), Europe (1.4%) and about 0.2% in high-income countries (WHO 2018).

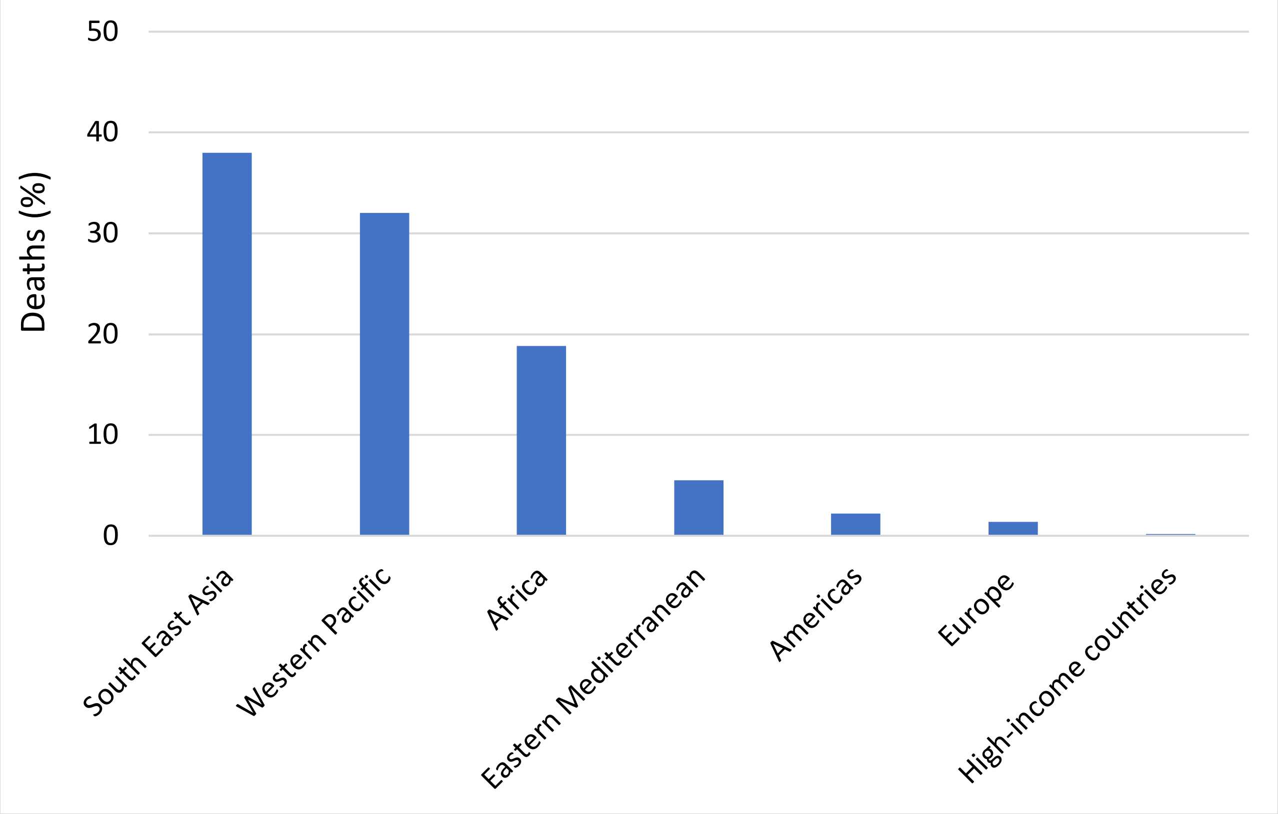
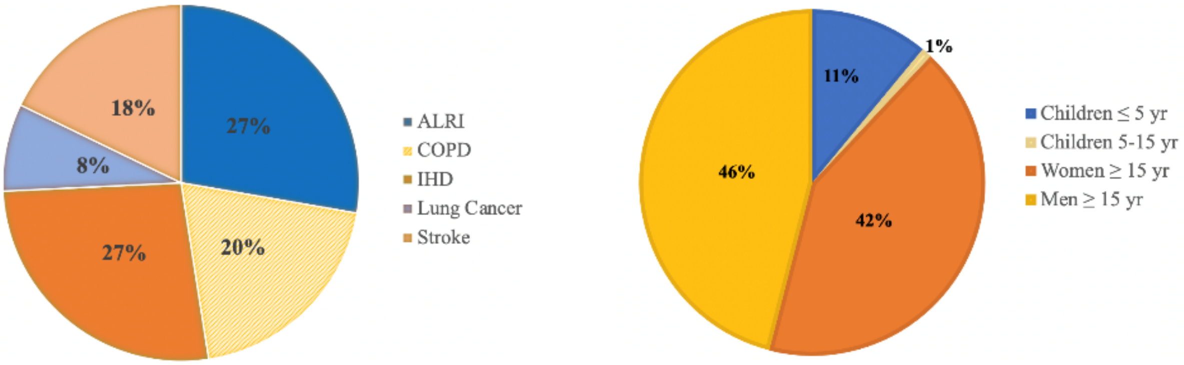


Figure 14 Total deaths caused by HAP in 2016 by region (WHO 2018)

The diseases and deaths caused by household air pollution (HAP) have different impacts on different age and sex groups of the population. Figure 15 presents the deaths attributed to HAP by disease (a) and by age and sex (b). Acute lower respiratory disease (ALRI) and Ischaemic heart disease (IHD) are responsible for about 27% of deaths caused by HAP followed by the chronic obstructive pulmonary disease which is 20%. On the other hand, the deaths attributed to HAP affect mainly women and children, with 54% of the cases.



a. Deaths attributed to HAP in 2016 by disease

b. Deaths attributed to HAP in 2016 by age and sex

Figure 15 Deaths attributed to HAP by disease (a) and age and sex (b) (ALRI: Acute lower respiratory disease; COPD: Chronic obstructive pulmonary disease; IHD: Ischaemic heart disease) (WHO 2018)

Figure 16 and Figure 17 presents the number of deaths attributed to HAP in Ethiopia and Ghana, respectively. In Ethiopia, air pollution is the main environmental risk factor behind the recorded premature deaths and above 65,000 premature deaths were caused by household air pollution, as well as over 3.1 million disability-adjusted life-years per year are caused by household air pollution. Most of the deaths related to HAP are due to lower respiratory tract infections which accounts for over 36,000 cases in 2016 (Beyene GE et.al 2018). In Ghana air pollution is also one of the leading environmental risk factors for premature deaths and about 23,000 deaths were attributed to air pollution in 2015. In 2012, 7796 deaths from stroke in adults and 4238 deaths from respiratory illnesses are attributed to polluting fuels from using less-efficient cooking technologies with its associated fuels (WHO/Ghana 2018).

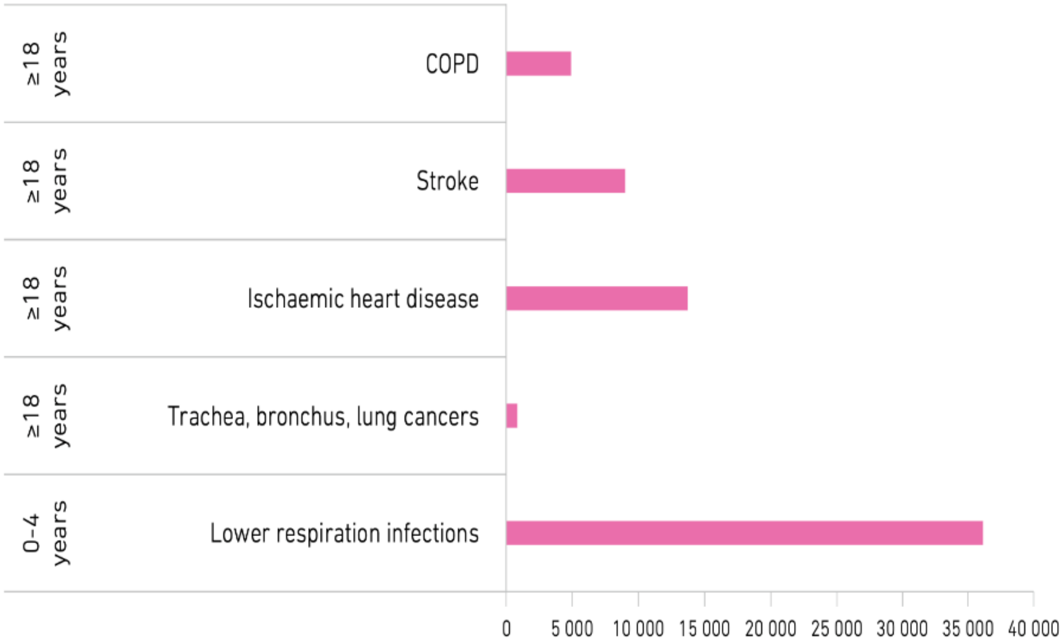


Figure 16 Number of deaths caused by HAP in Ethiopia (Beyene GE et.al 2018)

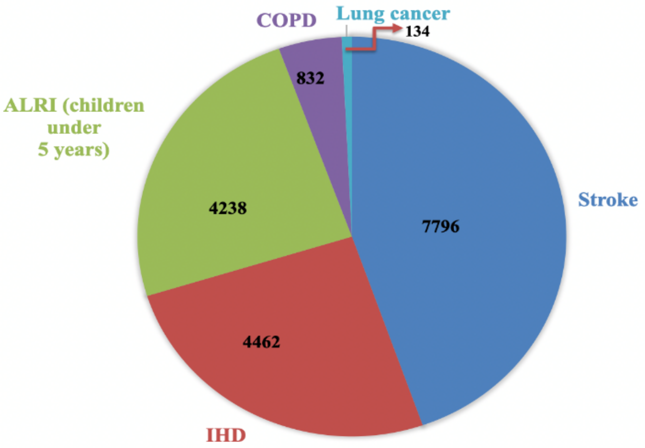


Figure 17 Number of deaths caused by HAP Ghana (WHO/Ghana 2018)

However, in recent years there is the development of solar cooking technologies. The rapid distribution of solar photovoltaics across Sub-Saharan Africa, the falling costs of PV and batteries, the increasing solid fuel prices due to deforestation that makes the availability of solid biomass fuels at risk, could lead to transforming the cooking system from traditional to solar cooking systems (S. Batchelor et. al, 2018). There are different kinds of solar cookers, such as box cookers, concentrating cookers and panel cookers which are classified based on the structure of the cooker. It can also be divided into direct and indirect cookers based on the cooking method (M. Aramesh et.al, 2019). These solar cookers have advantages over the current cookstoves widely used in rural areas including the reduction of fuel costs and demand for solid biomass fuels and the improvement of indoor and outdoor air quality by removing the release of solid particles and reducing GHGs emissions (S. M. Situmbeko, 2018). However, the distribution and penetration of these technologies are progressing at a lower rate (Clean Cooking Alliance, 2019) and also the socio-economic viability of the solar cookers is still at infant stage for different reasons including its low efficiency, low mass production, the variability of solar energy availability and the need of variable configuration for different locations (M. Aramesh et.al, 2019).

2.2.3. Gaps and Major Innovation needs

As discussed above, there are multiple dimensions to the problems and challenges of energy access in Sub-Saharan Africa, where the majority of the population lack a reliable, affordable and sustainable supply of electricity and modern cooking fuels and technologies: including insufficient power generation capacity, poor and weak management of energy infrastructure, lack of private investments, as well as good working environment to attract investors in the sector. Such issues are challenges in serving low-income users. Additionally, high and continuous population growth, urbanization, industrialization and ambitions of economic development are also factoring which increases the energy demand and requires more and more investment in the sector. According to the International Energy Agency estimation, the electricity demand in the region increased by about 35% from 2000 to 2012 and it forecasts that the total electricity demand in the African continent will increase at an average rate of 4% per year until 2040. To supply such demand the region requires high investments in power generation, as well as significantly expanding the grid to the areas where there is no electricity access, being not possible to supply the growing demand with the current electrification rate. Therefore, the current supply-demand mismatch and growing demand are the largest challenges that have to be addressed to improve energy access and modern energy services in sub-Saharan Africa.

The lack of electricity access highly affects the region's economic growth and prevented it from attaining several of its health, education, gender equality and zero hunger development goals. The causes for low modern energy services is not only lack of electricity generation facilities rather lack of generation capacity to supply power to grid-connected regions, weak grid infrastructure to deliver this power, regulatory impediments to providing steady revenue to maintain and invest in new generation capacity, and dispersity of population in rural and remote areas are also major factors. Except for South Africa, weak grid infrastructure leads to about 18% of transmission and distribution losses in the region.

Furthermore, most of the countries are dependent on imported fossil fuels which have huge impacts related to climate change, economic and price variability that results in consumers suffering economic losses during the period of price uncertainty. In general, the current challenges of the sub-Saharan Africa energy sector are lack of system capacity, poor sector management, high system losses, dependence on large dams (in Ethiopia about 99% of the current sources are from large hydropower dams) and dependence on fossil fuels. This multidimensional challenge brings an opportunity for Sub-Saharan African countries to plan, design and implement a sustainable energy system based on distributed energy resources including wind, solar, geothermal, mini-hydro and biomass resources, as well as efficient and cost-effective energy management systems.

Sub-Saharan Africa is a region with abundant renewable energy resources and fossil fuels. The technical generation potential is estimated at about 10,000 GW of solar power, 350 GW of hydropower, 109 GW of wind, 15 GW of geothermal and 400 GW of natural gas, totaling more than 11,000 GW, which is able to supply the current and future energy demand of the region (Avila, 2017).

Figure *18* presents the renewable energy resources potential of sub-Saharan Africa and regional distribution, where East Africa is a region with the highest wind, solar PV and concentrated solar power potential compared with the other regions, whereas Central and Southern Africa have higher hydro potential.

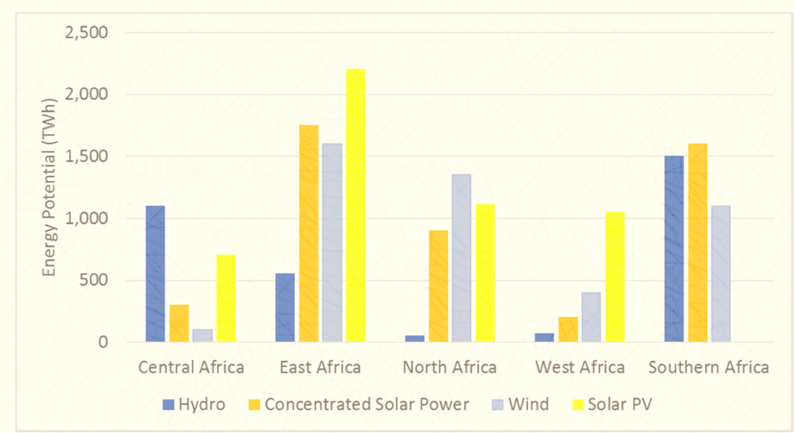


Figure 18 Total energy resource potential in sub-Saharan Africa and its regional distribution (Avila, 2017)

Table 1 presents the potential of five different renewable energy resources for some selected countries located in East and West Africa, including biomass, solar, wind, hydro and geothermal.

Ethiopia has a large renewable potential in each renewable energy resource compared with the other countries, followed by Niger.

Table 1 Renewable energy resources potential for different countries in East and West Africa

Country	Type of renewable energy resource and potential				
	Biomass	Solar	Wind	Hydro	Geothermal
Burkina Faso	High	5.5 kWh/m^2	1-3 m/s	N/A	N/A
Burundi	Medium	4-5 kWh/m^2	4-6 m/s	170 MW	N/A
Ethiopia	High	5.2 kWh/m^2	7-9 m/s	45,000 MW	Up to 10,000 MW
Niger	High	5-7 kWh/m^2	2.5-5 m/s	270 MW	N/A

The way forward to address the large energy access gap in sub-Saharan Africa is to exploit the abundant renewable energy resources. However, this path could be challenged since most capacity is ensured by intermittent renewable energy resources, which are affected by different seasonal and external factors like climate changes. On the other hand, to balance supply and demand analyzing demand patterns is critical, so that energy is available when needed and not wasted when demand is low. The design of the energy system must be flexible enough to respond to rapid changes in both demand and generation and to keep the energy system balanced. Therefore, the energy system has to be designed to benefit from the maximum potential of distributed energy systems by considering demand patterns and the selection of energy-efficient appliances to balance the supply-demand mismatch. Furthermore, the areas with huge energy deficits are located in rural and remote areas of sub-Saharan Africa which require local energy solutions. In this regard, off-grid solutions are promising solutions to exploit renewable energy resources as well as to address the energy access gap in rural areas of sub-Saharan Africa.

2.3. Off-grid Solutions

Since the rural areas are located far from the grid, the grid extension in sub-Saharan African countries is very expensive and requires a long time. To solve these problems and deliver sustainable energy solutions, off-grid small-scale electricity generation technologies and systems are taken as appropriate options for rural electrification or as a base for future grid extension efforts (S. Mandelli, 2016). On the other hand, off-grid solutions will allow rural communities to use electricity for other energy services apart from lighting and cooking. It will allow them to use off-grid appliances such as TVs, fans, refrigerators, etc.

Furthermore, using off-grid appliances will give these populations social and economic benefits and at the same time, it will improve the quality of life in those underserved communities. The quality of life can be greatly enhanced by the availability of energy services provided by off-grid systems such as lighting, refrigeration, ventilation, entertainment, communication equipment, water pumping and purification, farm machinery, small and micro industries, etc. Figure 19 presents the socio-economic, human development and environmental benefits of rural off-grid solutions for the millions of people located in rural areas of sub-Saharan Africa and other developing countries.

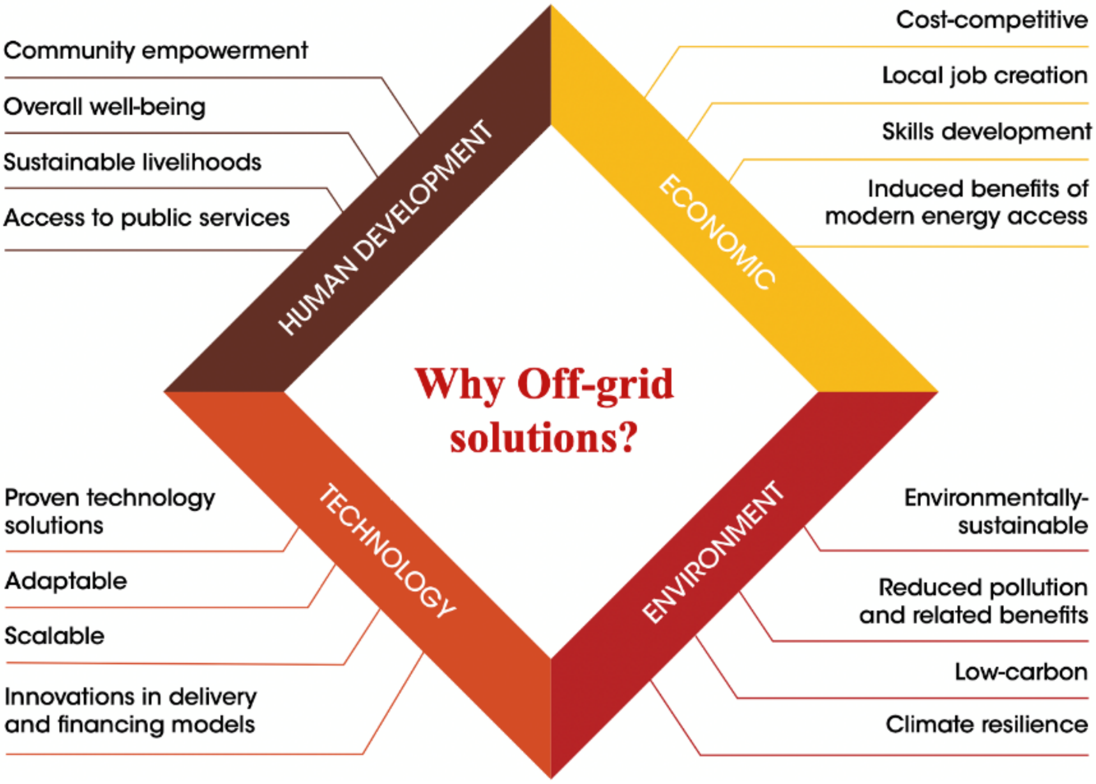


Figure 19 Multiple benefits of off-grid solutions (IRENA, Off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed, 2019)

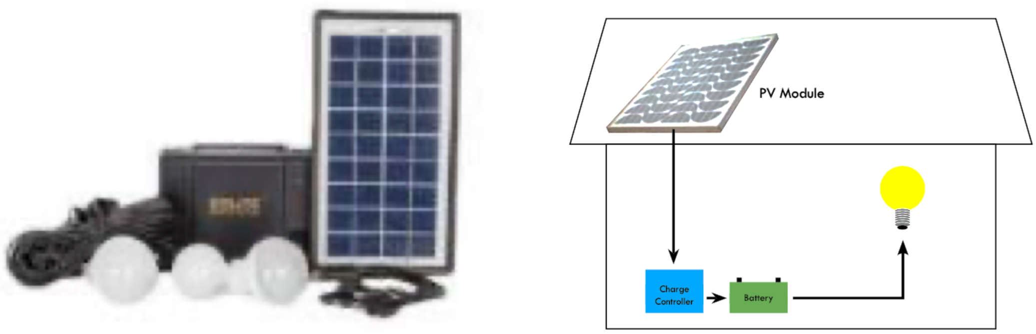
Off-grid systems can be decentralized (stand-alone and micro-grid systems) or distributed (hybrid micro-grid systems) (K. Narula, 2012) and used for household basic needs, productive uses, and community services, as presented in Table 2. Those systems are based on solar PV, wind, diesel, biomass, fuel cells, being stand-alone or hybrid systems and can also include energy storage systems. Distributed systems are systems based on renewable energy resources, which can be constituted by more than one decentralized conversion unit, connected to the distribution grid (S. Mandelli, 2016). Due to the randomness and intermittence of renewable sources, like wind and solar power, it is necessary to integrate different renewable sources for their better utilization and to have continuous energy generation and supply. With this regard, micrograms (sometimes called mini-grids, nano-grids, and pico-grids) (K. Carlin, 2017) integrate distributed renewable sources, energy storage devices and a large variety of loads. Microgrids can work as isolated systems or connected to the main grid, which makes them more favorable options to users in need of sustainability, reliability and power quality (E. Planas, 2015).

Table 2 Off-grid Systems Matrix for rural electrification systems in developing countries (S. Mandelli, 2016)

Off-grid systems Matrix	**Decentralized**		**Distributed**
Rural energy Uses	Stand-alone systems	Microgrid Systems	Hybrid Microgrid Systems
Household basic loads	Home-based systems	Systems including a distribution gird	Systems including a distribution gird
Community services	Community-based systems		
Product uses	Productive-based systems		
Consumer Number	Single	Multiple	Single or Multiple
Energy Resources	Single		Multiple

2.3.1. Standalone Solutions

Pico products include small, portable solar lanterns, flashlights, or lanterns designed to meet basic lighting needs as a direct replacement for kerosene lamps in a small household. These products are typically packaged either as a simple, one-light system with one LED light, an embedded 0.5–3.0 Watt-peak (Wp) solar panel, and an internal rechargeable lithium-ion (Li-ion) battery or as multi-light systems of up to three or four LED lights with a standalone solar panel rated up to 10 Wp and a rechargeable Li-ion battery. Some models include USB charging for mobile phones. Whereas Solar Home Systems (SHS) are stand-alone photovoltaic systems that offer a cost-effective mode of supplying amenity power for lighting and other services to rural off-grid households, SHS has a solar panel rated 11 Wp and higher and include both home lighting systems and large systems which can power appliances (IFC, 2020). Figure 20 presents a standalone off-grid solution used in rural areas of developing countries including pico products and SHS. Worldwide standalone off-grid solutions supply power for millions of households in rural and remote areas of developing countries such as sub-Saharan Africa. SHS usually operates at a rated voltage of 12 V DC and provides power for low power DC appliances, such as lights, radios and small TVs for about three to five hours a day. Atypical SHS contains one or more PV panels, a battery storage system and a charge controller which controls the power coming from the PV and battery, as well as distributes power to the appliances and protects batteries from damage (energypedia, 2018).



a) Pico products *b) SHS*

Figure 20 Stand-alone off-grid solutions (a) Pico products and (b) SHS (energypedia, 2018)

For the last decade, the off-grid solar market has increased unexpectedly to a US$ 1.75 billion annual market, which is expected to grow fast in the coming years as well. So far, the system is providing electricity for 420 million users and presented a revenue growth of 30% annually. Out of the total sale, pico products comprise around 83% since 2010, the continued growth of the pico products and the SHS market implies that nearly half a billion people are getting a clean, modern, and reliable source of electricity access for about 4 hours/day (i.e., "Tier 1") (IFC, 2020). Figure 21 presents the sales of pico-solar products from 2014 to 2015 for sub-Saharan African countries. Compared with the other sub-Saharan African countries, Ethiopia, Kenya and Tanzania have a larger share of pico-products sales that accounts for about 65% of the total sales. The sales in DRC, Rwanda and Uganda are relatively small compared with the other countries (Nygaard, 2016).

Surveys and market trends in sub-Saharan Africa indicate that how a vast majority of the customers buying pico-solar products show interest in either purchasing a second light or upgrading their system to have increased capacity and functionality (Scott & Miller, 2016). The market for SHS is also experiencing a need for larger systems that can supply multiple devices such as televisions, fans and small refrigerators. For instance, M-KOPA a leading supplier of Pico and SHS products from Kenya supplied and installed more than 300,000 units in Kenya, Tanzania and Uganda since 2012. In comparison, before 2012 around 320,000 SHS had been installed in total in Kenya over the past 30 years (Hansen, Pedersen, & Nygaard, 2015; Nygaard, 2016).

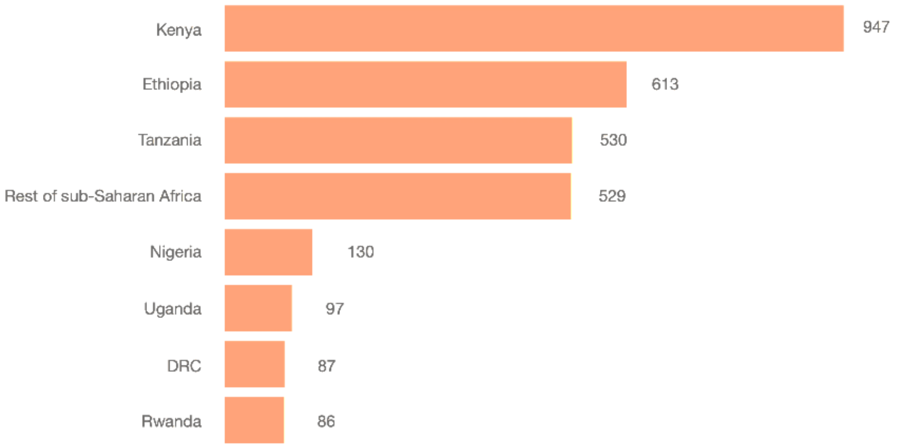


Figure 21 Sales of Pico-solar products in Africa in 2014-2015 (thousands of units) (Nygaard, 2016)

2.3.2. Microgrids

In the last couple of decades, a major shift has been observed in power systems due to the change in generation and transmission systems. The need of improving power quality, optimize the operation and maintenance cost, increase energy access in places where the power grid is distant, environmental and social sustainability, are some of the main reasons behind these changes. The increasing penetration of renewable energy sources along with the depletion of fossil fuels and their associated environmental issues and investment costs are among the factors for the observed power system changes (Ghadimi, Nojavan, Abedinia, & Dehkordi, 2020). However, with the randomness and intermittence of renewable sources, like wind and solar power, it is necessary to integrate different renewable sources for their better utilization and to have a continuous energy supply. With this regard, microgrids can have a key role to achieve these goals and accommodate the changes required in the current power system, as well as supplying energy locally for people located in rural and remote locations of developing countries (Aemro, Moura, & de Almeida, 2018).

A microgrid is a power system composed of distributed generation, loads, energy storage and control systems that can function as an isolated system or connected with the main grid. It is important to achieve more operational flexibility compared with conventional power systems. Microgrids can then provide solutions for commercial, industrial, and residential consumers in order to achieve objectives such as lower GHG emissions, lower stress on the transmission and distribution system, and ensure local, reliable, and affordable energy security for urban and rural communities (Jackson, Francis, Ju, & Jin-Woo, 2013; Laaksonen, 2010; Lonkar & Ponnaluri, 2015; Kanellos & Hatziargyriou, 2009). Figure 22 presents a schematic diagram of a microgrid that consists of different components including distributed renewable generation, diesel generator, energy storage, loads, connection to utility grid and control systems. Based on the compatibility among different components and operating voltage microgrids can be classified as AC, DC and hybrid AC/DC (Praiselin & Edward, 2018).

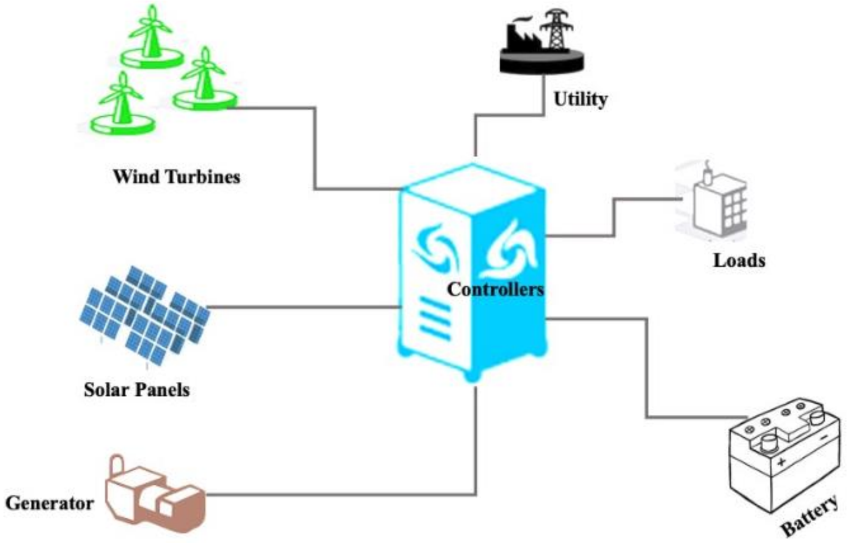


Figure 22 Schematic of a microgrid connected with a utility grid.

2.3.2.1. AC Microgrids

Figure 23 presents a typical AC microgrid for rural electrification, consisting of wind turbines, photovoltaic systems, battery storage and loads (AC and DC loads). An AC bus is created and all sources with variable frequency and variable voltage are connected to the AC bus through AC/AC and DC/AC converters. The DC/AC inverters are necessary to convert the outputs of DC sources, such as battery storage and photovoltaic systems for any type of AC microgrids, whereas the sources with AC output are connected with AC/AC converters. Furthermore, AC to DC converters is installed to supply DC loads. Therefore, due to the use of different power electronics devices and conversions of power outputs from AC to DC or DC to AC, AC microgrids present higher losses.

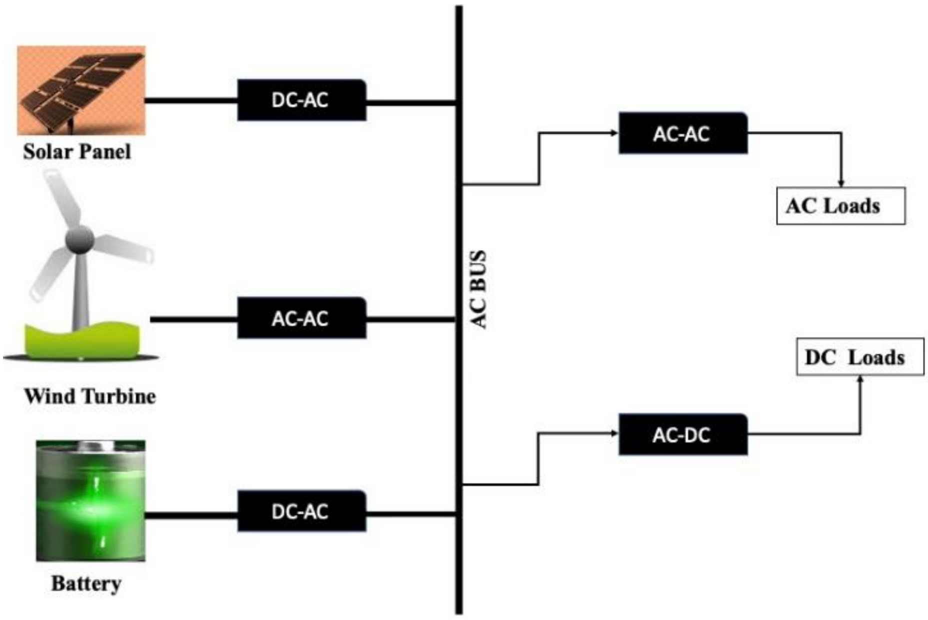


Figure 23 Typical off-grid AC microgrid.

On the other hand, due to the variable nature of the different distributed power sources and the need of many power electronic devices, as well as the magnitude of power availability from different sources at different periods, a smart load controlling, and management system is needed (Lopes, Moreira, & Madureira, 2006; Pogaku, Prodanovic, & Green, 2007; El-Shahat & Sumaiya, 2019). With this regard, AC microgrids are compatible with the existing power system infrastructure, and as a result, extensive research has been made on understanding and improving their performance. However, the controlling and management system is still complex, inefficient and expensive compared with the emerging DC microgrids due to the need to control reactive power flows, synchronization, power quality, and frequency regulation (Dragicˇevic´ & Li, 2018).

AC microgrids are extensively studied for rural electrification applications. For instance, an AC microgrid containing diesel, natural gas, PV, wind, and energy storage was designed for the electrification of isolated communities in Latin America (northern Chile) (C. Bustos, 2017). A study in Nepal (Makawanpur and Nawalparasi) shows the possibility of designing and implementing green and hybrid microgrids by combining PV, wind turbines and micro-hydro for rural electrification. The system installed in the Makawanpur district of Nepal in 2012 consists of 20 kW of micro-hydro, 5 kWp of PV system, 3 kW of wind power and a battery bank for storage aimed to supply power for 170 houses, two poultry farms and a grinding mill of the village. The other installed hybrid microgrid was in Nawalparasi district of Nepal in 2011, which consists of 2 wind turbines with 5 kW each and a solar PV array of 2.16 kWp with a battery bank storage with a capacity of 40 kWh. The system supplies power for 46 households with an estimated daily load of 33.6 kWh. According to the survey made, these systems gave multiple benefits for the rural community, such as the use of modern electronic devices (TV, radio, mobile phones, laptops, and sound systems), use of electrical appliances like refrigerators and pressing iron, use of computer in schools, studying in the night hours, improve adult education, women participation in social gatherings, savings from not purchasing of kerosene, use of batteries and small solar photovoltaic systems for lighting purposes etc. As concluded in the study, the two green and hybrid microgrids installed in Nepal helped to increase living standards, improve health care services, education, information exchange and women empowerment in the rural community (S.K. Jha, 2016).

A Study done in Tokombere for the North region of Cameroon assessed the replacement of a 2 kW diesel generator, supplying electricity for 15 households, and water pumping service, in a community with 7.84 kWh daily demand, by a stand-alone PV system supported by battery storage. The authors concluded that from different economic, environmental and social impact perspectives, replacing the diesel generator with a stand-alone PV system is feasible with the additional benefit of a GHG emission reduction. The proposed system considers a 4.25% financial discount rate and ensures 2.5 tons of CO_2 emissions savings annually. The results achieve an NPV of $20,556, 12.8 years simple payback period, 12.8% IRR-equity, 7.2% IRR-assets and $1,1351 annual life cycle savings makes the proposed stand-alone PV system economical feasible and profitable as compared with the system used currently (A. Adam, 2015).

According to (Matteo Ranaboldo, 2015), the off-grid community electrification done to electrify 88 users (350 inhabitants) in Nicaragua, combining solar and wind power, reduces the total life-cycle cost of the project and the levelized cost of energy by 16.4% and 14%, respectively, in comparison with the independent use of solar and wind power. The result shows that such a solution could be effective for electrifying the 22% of the people of Nicaragua who do not have access to electricity.

Another study was done in Dudhagon village, near Dharva in Maharashtra, India for a daily load of 731 kWh proposed a hybrid system consisting of solar PV, wind turbine and battery. The study used HOMER software for the simulation and optimization of the systems and concluded that the proposed hybrid system is economically viable to solve the rural electrification problem of the site (Daigavane, 2015). The same study was done in Madhya Pradesh, India and shows that PV/wind hybrid systems are possible for rural electrification (S.C.Gupta, 2014). Likewise, a study was done for Bangladesh rural electrification by combining 30 kW solar PV and 30 kW biomass hybrid systems, being concluded that it is economically viable for electrifying rural communities that still do not have access to electricity (S. Ahammad, 2015).

The performance of 11 PV-diesel hybrid off-grid systems which comprises PV modules as a primary energy generator, battery as energy storage, diesel generator as a backup and inverter installed in schools in rural Sabah, Malaysia was analyzed (A. M. Mahmud, 2016) and the result shows that 10 of the systems were found highly reliable, using only the PV system to respond for the energy demand of the schools whereas in the other school a high consumption of diesel to respond for the load demand was observed, due to the insufficient capacity of the battery.

Several studies (Akbar Maleki, 2014; Alireza Haghighat Mamaghani, 2016; Binayak Bhandari, 2014; Chong Li, 2016; Ghassan Zubi, 2016; Mohan L. Kolhe, 2015; Rohit Sen, 2014), have been done using different combinations of renewable energy sources for off-grid rural electrification and concluded that off-grid systems whether stand-alone or hybrid systems are economically viable, eco-friendly and promising technologies to address the problems of affordable, reliable and clean energy in rural and remote areas of developing countries. Although, the people living in rural and remote areas of developing countries, like sub-Saharan Africa, live in poverty and do not have income even for basic needs (food, shelter and cloth). Therefore, all the mentioned studies suggest the need to further study the business model. Moreover, the energy demand in rural and remote areas is far from lighting that requires optimization and identification of the potential renewable sources in each location and increases the access to other energy services such as heating, cooling, clean cooking, electricity for appliances (TV, Radio, Mobile charging, freezer and refrigeration...etc.).

2.3.2.2. DC Microgrids

The conventional power systems were designed to run based on high voltage AC transmission lines and low voltage distribution lines to households, service buildings and business centers which use different kinds of AC-based loads like lamps, appliances, AC motors and other AC equipment. DC power systems have been used in industrial power distribution systems, telecommunication infrastructures and point-to-point transmissions over long distances or via sea cables and for interconnecting AC grids with different frequencies. Nowadays, the use of DC-based electronic devices such as computers and other Information Communication Technology (ICT) loads, LED lights, variable speed fans and compressor refrigerators, as well as the increasing penetration of DC power sources including photovoltaic, wind turbines, fuel cells and others, is increasing more than ever. However, if the system still sticks with the conventional power grid and use an AC off-grid system, all these advanced DC devices require conversion of the available AC power into DC for use, and the majority of these conversion stages typically use inefficient rectifiers and inverters.

Moreover, the power from DC-based renewable generation units must be converted into AC to tie with the traditional AC electric network, to be converted later to DC for many end uses. Therefore, the need and use of DC microgrids are very much useful to avoid such losses and to simplify the control and management units (Ghadimi, Nojavan, Abedinia, & Dehkordi, 2020; Xu & Chen, 2011). For off-grid applications, since the generation sources are DC and the most loads can be in DC, the feasibility of DC microgrids is much more efficient when compared with the AC microgrids. Moreover, the problem of harmonics due to power electronic converter is not present due to DC nature of output power (Arif & Hasan, 2018). Figure 24 presents a typical off-grid DC microgrid composed of a battery, solar panel and DC loads with a charge and load controlling unit.

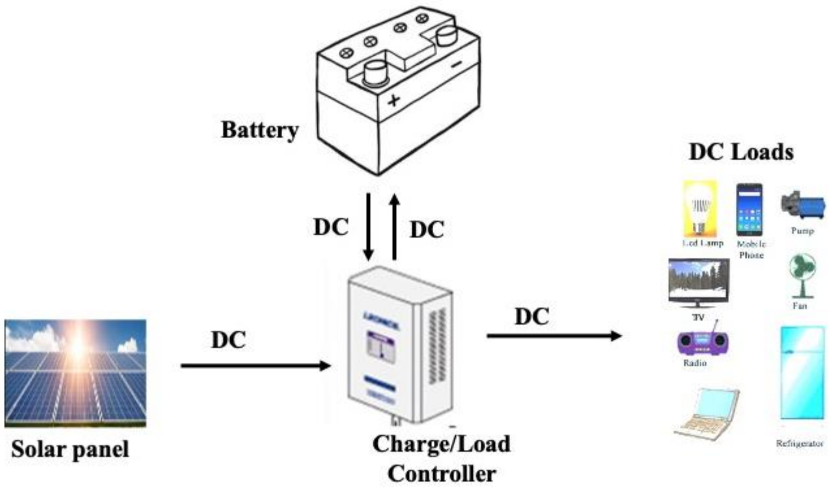


Figure 24 Typical schematic of off-grid DC microgrid.

Compared with AC microgrids, DC microgrids have several advantages: (1) higher efficiency and reduced losses due to the reduction of multiple converters used for DC loads; (2) elimination of synchronizing generators requirements, with rotary generating units, allowing them to operate at their own optimum speed; (3) easier integration of various DC distributed renewable energy resources, such as energy storage, solar PV, small wind turbines and fuel cells, to the common DC bus with simplified interfaces; (4) more efficient supply of an increasing number of high-efficiency DC loads, like LED lights, fans, computers, TVs, refrigeration; and (5) providing higher safety level and easier primary control. Therefore, in terms of high reliability, easy operation and maintenance, smaller size, high efficiency, lower design and operating cost, modularity and fault tolerance, DC microgrids in the low-medium power range (below 100 kW) are the best option for off-grid applications compared with AC microgrids (Cairoli & Dougal, 2013; Chauhan, Rajpurohit, Hebner, Singh, & Gonzalez-Longatt, 2016; Chauhan, Rajpurohit, Hebner, Singh, & Longatt, 2015).

Despite such advantages, the protection and standardization of DC microgrids have been a challenge for a long time (Ghadimi, Nojavan, Abedinia, & Dehkordi, 2020). However, recently a draft standard for DC Microgrids for Rural and Remote Electricity Access Applications was developed by the "IEEE P2030.10™ for DC Microgrids for Rural and Remote Electricity Access Applications Working Group." The standard covers and presents the design, operations and maintenance of a DC microgrid for rural and remote applications. Furthermore, the standard defines requirements for providing low voltage DC and AC power to off-grid loads (Decuir & Michaei, 2020). This standard is a breakthrough in the DC microgrid topic enabling further research and advancing the application to electrify rural and remote areas in developing countries, including sub-Saharan Africa.

Furthermore, many countries with a low level of electricity access in sub-Saharan Africa, are installing microgrids in rural areas to improve electricity access. This is due to the cost-effectiveness of microgrids and to increase the utilization of locally available renewable energy resources. On the other hand, expanding the existing grid is too expensive and is not reliable from economic, social and technical aspects, because many of the rural areas are located far away from the grid. Minigrid market trends show that about 5544 mini-grids are installed in Sub-Saharan Africa, but still, the cost of the mini-grids and lack of policies and regulations are some of the challenges to scale up, promote and realize their potential and increase electricity access in rural and remote areas (SEforALL, 2020). This indicates that there is a need for cost optimization and efficiency improvement in microgrids and the customers, as well as the government body at every level, should select the most cost-effective and efficient system to overcome the challenges in microgrids, as well as to achieve energy access for all plans. Studies by (M. Nasir H. A., 2018; R. Farooq, 2014; M. Nasir H. A., 2018; C. Phurailatpam, 2016) the design, modeling and optimization of DC microgrids for rural electrification application in developing countries

2.3.2.3. AC-DC Hybrid Microgrids

Figure 25 presents a schematic diagram of an AC–DC hybrid microgrid, including AC and DC buses connected with a bidirectional converter which allows flow power between both buses in the two directions. Both buses are connected with renewable energy sources depending on the output power, which implies that sources with AC output are connected with the AC bus or connected with the bus using an AC-DC converter if the output power is DC. Similarly, the DC bus is connected with sources with DC output or connected with an AC-DC converter if the output power is AC, as well as with the utility grid.

Whether the microgrid is an AC or DC structure or hybrid AC-DC structure it requires power electronics for the conversion of power outputs of the sources and for controlling and management of power flows. On the other hand, the interaction between sources, loads both AC and CD loads, AC and DC buses as well as with utility grid (if it is not standalone microgrid) through converters, inverters and bidirectional converters, this makes the control and management scheme more complex compared with AC or DC microgrid alone. Therefore, coordination and a simplified controlling and management scheme is necessary to facilitate the power flow between AC, DC and load networks (Yashwant Sawle, 2018).

A study made by (Kaushik, 2014) presented the architecture and energy management of hybrid AC-DC microgrid. The study discusses the effectiveness of hybrid AC-DC microgrids for making use of the maximum potential of distributed renewable energy and satisfying the local load demand. It concludes that, although it has clear benefits over individual AC or DC microgrids, the complexity, control and protection requirements, largely limit those benefits. Therefore, it requires rigorous research in terms of system simplification, as well as an easy and manageable control system.

Another study made by (Unamuno & Barrena, 2015) presented the review and classification of different microgrids. It presents integration, synchronization, voltage transformation, and economic feasibility as the main advantages of hybrid AC/DC microgrids over individual AC and DC microgrids. A hybrid microgrid can be developed by the addition of a power converter to the current distribution grid and the communication network for the connected devices. This makes the overall cost higher than AC microgrids due to the main power converter. However, if the number of attached devices increases, the investment will be returned faster as the number of total interface converters is reduced. However, it also presented drawbacks including protection, reliability, and control complexity are the main drawback of hybrid AC/DC microgrids. Studies made by (Liu & Loh, 2010; Sarangi, Sahu, & Rout, 2020) also presented the design and architecture and assessed the advantages and disadvantages of hybrid AC/DC microgrids.

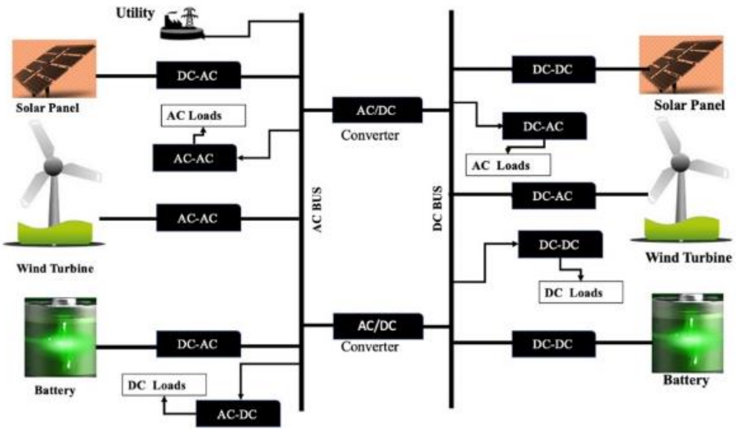


Figure 25 A schematic diagram of an AC–DC hybrid microgrid

2.3.3. Off-grid Appliances

As per Global LEAP, off-grid appliances are defined as electricity-consuming products that plug into and can operate on an off-grid system (GlobalLEAP, 2015). Since the off-grid systems are small by nature compared with the main grid power system, highly energy-efficient appliances are required for the effective and efficient use of off-grid power systems. Energy-efficient appliances are becoming more important for rural and remote communities, since lower energy consumption requires a smaller generation system, ensuring long term economic viability. Additionally, most of them become DC-based which can be suited with DC-based renewable energy generation like solar PV. These appliances range from lighting lamps, TV, fans, to refrigerators and freezers.

Table 3 presents the best available emerging energy-efficient technologies in the market. The development of off-grid solar home systems (SHS) and microgrids are promising solutions to tackle the challenge concerning low access rates of off-grid appliances in rural locations in developing countries. Among the appliances, clean cooking appliances, lighting appliances and the refrigerator are among the most important appliances to improve the quality of life for these people. Since food is one of the basic needs in life, cooking in a short period in a safe and sustainable system is essential. For instance, one of the reasons why refrigeration is an essential appliance is to improve food security (SDG 2) by reducing post-harvested food waste and loss. On the other hand, refrigerators are also important for vaccine storage and distribution in rural areas (EforA, 2019). In the following section, the need and importance of off-grid appliances are presented in detail.

Table 3 Best available energy-efficient appliances

Type of appliance	Best available technology
Lamps	LED
TV	LED-LCD (Standard), LED- LCD (DC powered)
Fan	DC table fans
Refrigerator/Freezers	DC powered refrigerators
Cooking	Pressure cookstoves, induction cookstoves

2.3.3.1. Lighting, TVs, Fans

Lighting appliances, TVs and fans are the most important appliances which are necessary and have to be found in every household. To work at night, entertain, and cool houses in a period of the hot season, lighting appliances, TVS and fans are necessary, respectively. Sub-Saharan Africa by nature is a hot area whose temperature records above 40 °C in some seasons which requires cooling. On the other hand, many of the population located in rural areas of the region do not have such appliances due to the lack of electricity access and economic level of the inhabitants. Therefore, off-grid solutions are the most appropriate options to electrify rural communities.

Appliances with high efficiency consume less energy ensuring that, with an appropriate selection of appliances, a small off-grid system can be enough to electrify a village. Figure 26 presents the daily energy consumption of a typical rural household. It shows that energy-efficient appliances significantly decrease the daily energy consumption of a given rural household. For instance, using three LED bulbs, radio, and phone charging decrease energy consumption by 90% compared with using three incandescent bulbs, radio and phone charging, also decreasing the need for generation by 90%.

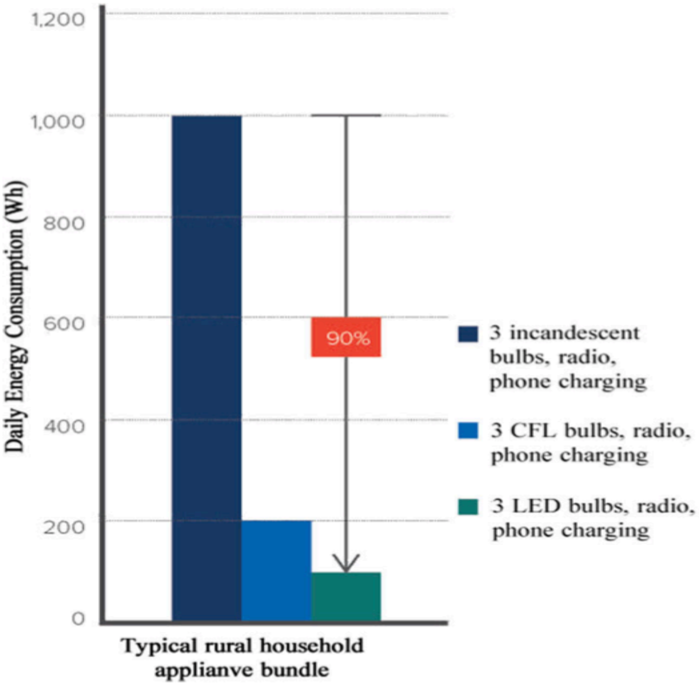


Figure 26 Energy consumption under the use of different energy efficiency appliances (de Almeida, Moura, & Quaresma, 2020)

Based on a survey made by the efficiency for access coalition (EforA, 2018) (Figure 27) LED room lights are the highest-ranked household appliance in terms of both anticipated consumer demand and potential impact. Whereas television ranked second household appliances in terms of consumer demand and ranked fifth in terms of impact potential followed by mobile phones, refrigerator/freezers and fans in terms of consumer demand. In terms of impact potential mobile phones and refrigerators are the third-ranked household appliances. This demonstrates that such household appliances are consumers' preferences and will have a significant impact on the design and model of microgrids, specifically DC microgrids. Since most of them are DC powered the integration with DC power sources and DC bus will be easier and will avoid the need for power conversion of steps.

Furthermore, the penetration of such appliances has a positive socio-economic impact. For example, a study made in India indicates that the introduction of cable television resulted in improved status of women in rural households; the effects included improved behavioral changes in low preference for female children, attitudes toward spousal abuse, and efforts toward child education. The research has also found that social messages embedded in serial TV dramas with gripping storylines change financial behavior, family planning, literacy, and health in Africa, Latin America, and Asia (LEAP, 2017).

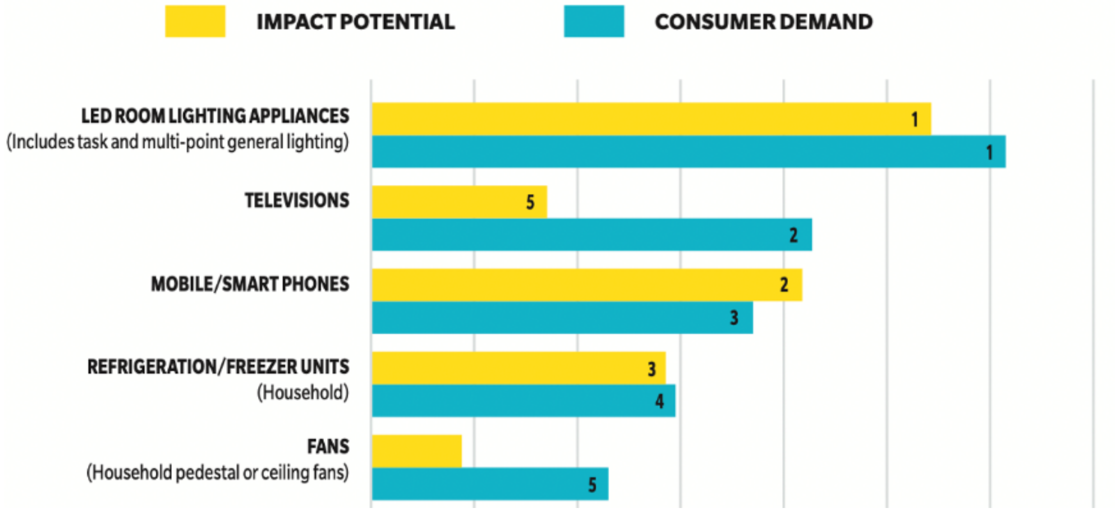


Figure 27 Comparative rankings of perceived consumer demand versus impact potential of household appliances, 2018 (EforA, Off-grid appliances market survey: Perceived Demand and Impact Potential of Household, Productive Use and Healthcare Technologies, 2018)

2.3.3.2. Refrigeration

Refrigerators are important appliances in households (depending on the socio-economic and geographic profile of households), business retail (to preserve drinks, food, pharmaceuticals, etc.) and agricultural value chains (input retailers, dairy, fisheries). The advantages of off-grid refrigeration are in driving economic growth by reducing food wastage, improving food security and reducing food-related illness. Furthermore, it is important to create new business opportunities for suppliers and consumers (who can use it in mini/supermarkets and business centers). However, most of the people located in rural areas of developing countries do not have access to refrigerators. The reason for the low rate of refrigerator penetration is the lack of access to electricity and economic constraints (the typical off-grid refrigerators are expensive for people living with low income) (EforA, 2018).

The need for off-grid refrigerators in rural areas is increasing due to the growth of off-grid electrification technologies (solar home systems, microgrids and minigrids) (Abagi, 2019). There are not many studies available in the literature about the impacts of off-grid refrigeration on peoples' living standards. However, a few studies are indicating how off-grid refrigerators impact the living standards of rural communities. For instance, in Kenya, M-KOPA, CDC and Dalberg assessed the real impacts of off-grid refrigeration on households. The assessment indicates that for a given household using an M-KOPA refrigerator, the family could save up to $4.82 per week. This saving comes from fewer trips to the market, less spending on cooking fuel and less food wasted due to spoilage. Figure 28 presents the estimated cost savings for a typical household if an M-KOPA refrigerator is used (CDC, 2018).

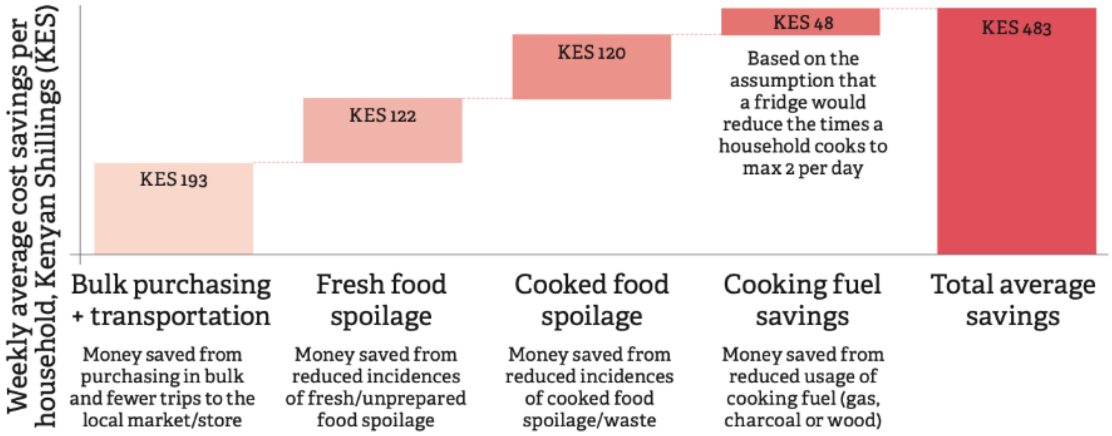


Figure 28 Household estimated cost savings by source (CDC, 2018)

In general, off-grid refrigeration provides singular benefits spanning health and productivity, significantly reducing the domestic burden on women and young children, who are usually responsible for gathering and preparing food. The possibility of preserving food can drastically reduce the amount of spoiled/wasted food, as well as allow more efficient preparation of cooked meals, reducing the time spent on gathering perishable food items, and ensure a reduction of the time spent in cooking duties. Additionally, refrigeration may unlock productive potential in communities for use in agriculture, small and micro-businesses which may contribute to job creation and the development of the local economy.

Different organizations are focused on promoting off-grid refrigerators. The Global LEAP Awards promotes a series of international competitions to assess the quality and efficiency of different off-grid appliances (de Almeida A. M., 2019), including refrigerators. Table 4 presents the off-grid refrigerators presented in the Global LEAP Awards. The refrigerators in Table 4 were the winners of the Award in 2017 (Awards, 2017) and 2019 (Awards, 2019).

The penetration of refrigerators in developed countries is more or less saturated. It implies that the growth rate in the market will be limited taking into account the 99% or more penetration rate and a typical 15 years' lifespan of the refrigerators. Figure 29 presents the global penetration of household refrigerators (Awards, 2017). Whereas globally close to 0.8 billion people do not have access to electricity (de Almeida A. M., 2019), which indicates that they do not have access to refrigeration, this number shows that the market for off-grid refrigerators is huge. On the other hand, these people are located in rural areas of developing countries, which implies that there is a vast untapped potential to the market. The market potential for off-grid refrigeration represented USD 4.4 billion at the end of 2018 and is estimated to grow to USD 14.3 billion in 2030, as presented in Figure 30.

Table 4 Selected Global LEAP Award off-grid Refrigerators-Winners (Awards, 2017; Awards, 2019)

Model	Capacity (L)	Energy Consumption (kWh/Day)	Specification	Manufacturer	Cost (US$)	Remarks
DCR50	50	0.118	Small	SunDanzer	699.00	2017- Winners
LC86	86	0.154	Medium	Palfridge	NA	
LC221	192	0.281	Large	Palfride	NA	
DCR165	163	0.191	Large	SunDanzer	1,189.00	
NILO 50	42	0.143	Small	Youmma	NA	2019- Winners
NILO 100	96	0.182	Medium	Youmma	NA	
PF166-H	173	0.164	Large	Steca	1000- 1400	

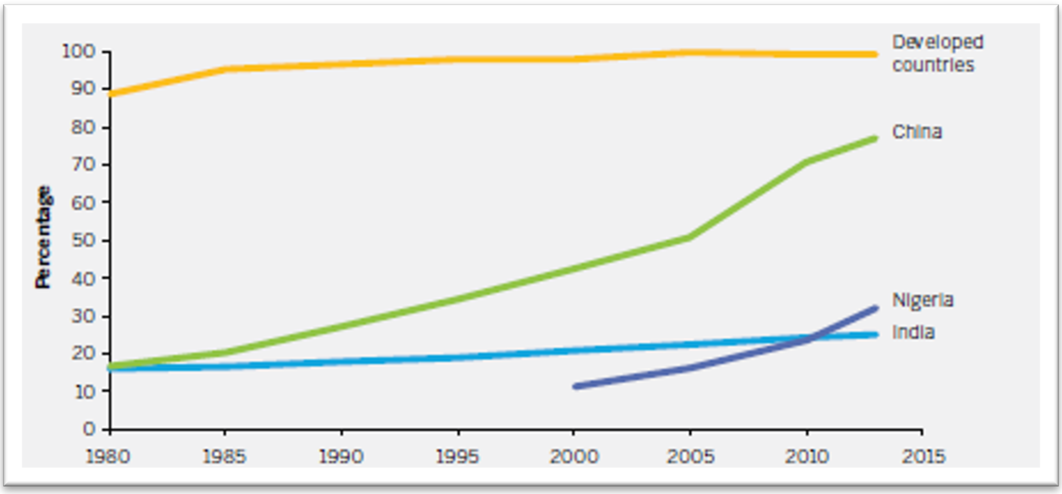


Figure 29 Global household penetration of refrigerators (1980–2013) (Awards, 2017)

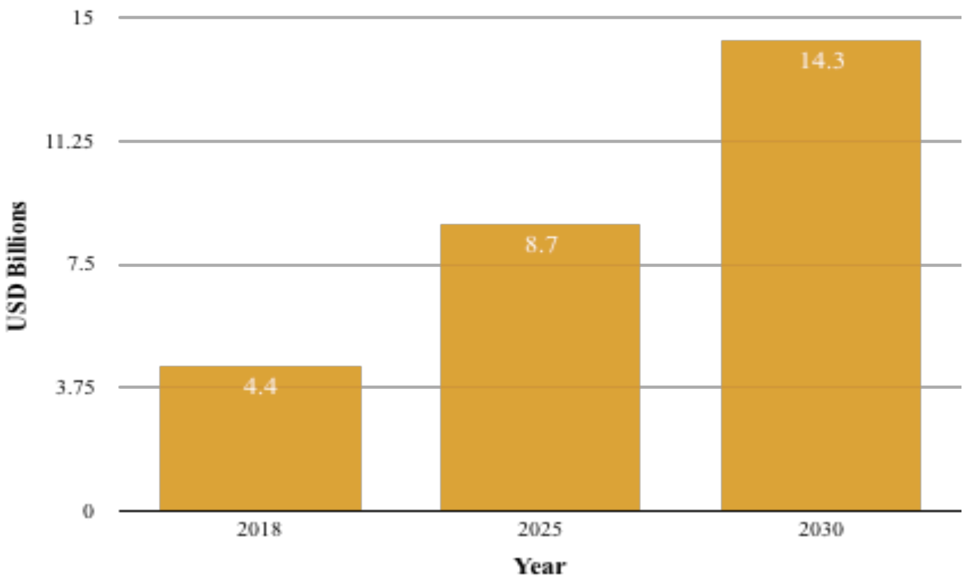


Figure 30 Estimated market potential of the off-grid refrigerator (EforA, 2019)

Table 5 presents the penetration of off-grid refrigeration and the population living in rural areas in different developing countries. Among the eight presented countries, six of them are in sub-Saharan Africa and the penetration is below 2%, except for Nigeria (the most populous country in the continent) i.e., 11%, in Ethiopia (the second-populous country in the region) the penetration rate is 0.4% with 58 million people located in off-grid areas. Furthermore, off-grid refrigerators will avoid 30% of food loss in sub-Saharan Africa which is equivalent to USD 4 billion (EforA, 2019; Awards, 2017).

Table 5 Off-grid Refrigeration Penetration in different developing countries (Efora,2019)

Country	Off-grid Population (%)	Off-grid Population (millions)	Off-grid Refrigerator Penetration (%)
Cote D'Ivoire	40	10	NA
Ethiopia	55	58	0.4
India	11	168	16
Kenya	27	13	1.5
Myanmar	44	24	6
Nigeria	40	77	11
Sierra Leone	80	6	NA
Uganda	80	34	1.8

Although the market potential and the need are quite high, the penetration is extremely low, since different barriers are affecting the penetration of off-grid refrigeration. High product cost, high power demand and longer running periods are among the reasons for the low household penetration of off-grid refrigerators.

2.4. Gaps and Major Innovation Needs

The type of loads determines the technological mix and technology selection to improve energy access for rural and remote locations of sub-Saharan Africa and other developing countries. The loads can be household loads, commercial building loads, service building loads (for clinics, schools, refugee camps). Based on the level of income it is possible to classify residents into three levels, such as low income, medium income and high income. Even if every resident needs to get the optimum energy services, the service they will get depends on whether they can pay for it or how much the government can subsidize it for them, leading to different loads. Table 6 presents the loads associated with each type of service required.

Table 6 Loads with the type of services for communities living in rural and remote areas

Type of loads		**Type of service**
Households	Low income	Lighting, mobile charging, TV, Refrigeration(option)
	Middle income	Lighting, mobile charging, TV, refrigeration, clean cooking, ironing
	High income	Lighting, mobile charging, TV, refrigeration, heating/cooling, clean cooking, ironing, ventilation ….
Commercial buildings		Lighting, heating/cooling, refrigerator, computers/TV, mobile charging, …
Service buildings	Clinics	Lighting, refrigerator/freezers, TV/Computers, washing/drying, heating/cooling
	Schools	Lighting, TV/Computers,
	Refugee camps	Lighting, TV, mobile charging, refrigerator/freezers, cooking/heating, washing/drying

2.4.1. Energy Efficiency and Cost

The conventional appliances including TVs, lighting bulbs and refrigerators used in off-grid locations are often energy inefficient and some types are potentially dangerous (e.g., propane refrigerators). In locations with a weak electrical grid, most consumers will run standard AC appliances, the refrigerators will only run for 2–4 hours a day, and long electricity outages will frequently occur. Given the high initial current surge the appliances demand every time they turn back on; this is a highly energy-inefficient method of use. Moreover, irregular refrigeration results in minimal prevention of spoilage of perishable food and preservation of its nutritional value and can lead to a mistaken belief that spoiled food is fresh.

Another common refrigerator type used in remote locations without access to electricity is the propane refrigerator. This kind of refrigeration is not a good option for many different reasons. The first reason is that such refrigerators use fossil fuel and are energy inefficient, as well as a propane refrigerator has high operating costs. Another reason is the fact that they can be dangerous since they use a flammable combustible. Additionally, the education level of the population sector in these locations is low, which is makes it difficult to use such kinds of refrigerators as good options (Stassopoulos, 2014). Figure 31 presents the mapping of income vs energy demand for off-grid appliances. The challenges for off-grid refrigeration, fans, super-efficient TVs and clean cooking viability are related to technical and economic factors.

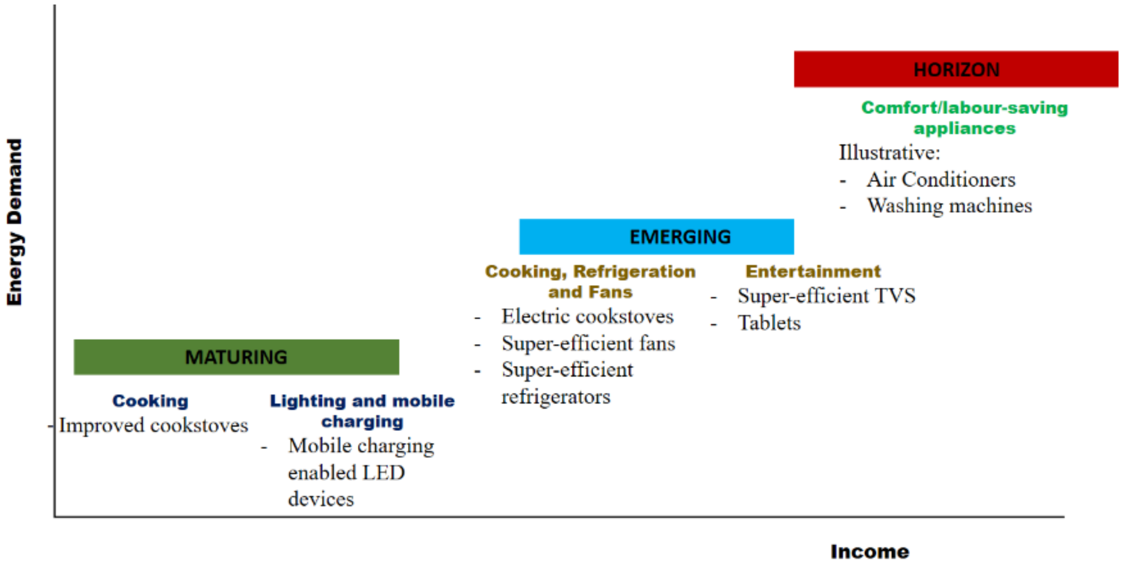


Figure 31 Mapping of off-grid household appliances by energy demand and income (Adapted from (CDC, 2018)

From a technical point of view, developing energy-efficient off-grid appliances and adapting and promoting such products could push the market forward, since the high energy demand and its inefficiency are the main obstacles for the use of conventional appliances in off-grid systems, such as solar home systems. On the other hand, developing low-cost off-grid refrigeration and other appliances may flourish the market in rural areas of developing countries. As presented in Table 4 off-grid refrigerators are expensive, and the cost is depending on the capacity and size (EforA, 2018). The cost issues are the same in other appliances including TVs and fans. For instance, off-grid TVs with more than 19 inches are very expensive and consume more energy compared with lower display TVs (LEAP, 2017). The cumulative cost off-grid appliances are far beyond the income of people located in rural areas. For instance, in Kenya, the GDP per capita in 2018 is $1710.5, in Ethiopia $772.3, and in Nigeria is $2,033 (WorldBankGroup, 2019). This implies that the current cost of off-grid appliances (e.g., refrigerators) is not affordable for people in these low-income communities. To increase the penetration and get the advantages off-grid appliances, affordability, as well as availability in the local market is critical and needs to be addressed.

2.4.2. Lack of Access to Electricity

Although there are efforts made to increase rural electrification in developing countries through solar home systems and mini-grids, access to electricity is also a huge challenge in rural areas causing a low rate of penetration of off-grid appliances. Conventional off-grid appliances need higher generation demand which is difficult to supply using small SHSs. Additionally, there are other specific barriers to the penetration of off-grid appliances and off-grid solutions, such as policy and governance, technology, skills and capacity, business models and investments (ITPEnergised, 2019). Overcoming the challenges and improving energy access in rural areas of developing countries is the basic requirement for rural development, minimizing migration from rural to urban areas, creating local businesses and job creation, gender equality and women empowerment, economic development, social and environmental sustainability. Moreover, addressing such issues is a pillar for achieving the Sustainable Development Goals (SGDs) set by the United Nations. In this regard, this thesis work analyzes different kinds of clean cooking options and off-grid appliances to select the best energy-efficient appliances to couple with the DC-microgrids. Furthermore, DC microgrids were designed, modeled, and analyzed for school, household and village energy supply applications.

CHAPTER THREE

CLEAN COOKING ACCESS, SOCIO-ECONOMIC IMPACTS AND RECENT DEVELOPMENTS

3.1. Introduction

According to the Energy Progress Report 2020, nearly 3 billion people are living without access to clean cooking (IEA I. U., Tracking SDG 7: The Energy Progress Report, 2020). The majority is located in rural and deep rural areas of developing countries (Lombardi, Riva, Bonamini, Barbieri, & Colombo, 2017) where the cooking is mainly ensured with solid fuels, such as wood, charcoal, coal, animal dung and crop wastes (IEA I. U., Tracking SDG 7: The Energy Progress Report, 2020) using inefficient cookstoves, including three-stone open fire, charcoal stoves and mud stoves (Kara & Zerriffi, 2018). The use of these inefficient cookstoves has a variety of negative impacts on the community, such as poor quality of life and living standards, health problems, injuries, safety risks, high indoor air pollution, excessive time spent for gathering fuel, deforestation and high fuel expenditures in households where the monthly income is very low (Karabee Das, 2018; Poddar, 2016; Barbieri, Riva, & Colombo, 2017).

The use of inefficient cooking technologies with its associated fuels causes the release of health-damaging pollutants, including particulate matter (small soot particles), which penetrate deep into the lungs and causes non-communicable disease, such as stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer that causes for the death of about 4 million people every year. Among the total premature deaths attributed to household air pollution, women and children are the most affected with about 54% of the total deaths (WHO, 2018). Furthermore, due to the high levels of pollutant emissions, the use of low efficiency cookstoves and solid fuels has a significant impact on the climate. GHGs including carbon dioxide, methane and nitrous oxide (Wilson, Talancon, Winslow, Linares, & Gadgil, 2016), which result from the biomass combustion process, and other types of pollutants, like black carbon, also have high-risk potential to increase global warming (Dinesha, Kumar, & Rosen, 2019).

On the other hand, the basic needs of human life such as health services, housing, education, production and preparation of food, as well as clothing, are linked with the lack of access to energy services. As a result, access to clean energy is critical for sustainable socio-economic development at every level such as household, regional, national and global levels (Mbaka, Gikonyo, & Kisaka, 2019). Therefore, the Sustainable Development Goals, in particular, SDG3 (Good health well-being), SDG7 (Affordable and Clean Energy), and SDG 13 (Climate Action), are not assured through the use of low efficiency cooking technologies, leading to dangerous household air pollution, and destructive solid fuel harvesting (Mehetre, Panwar, Sharma, & Kumar, 2017). Although there is agreement among different stakeholders on the development and promotion of clean and efficient clean cooking technologies and fuels, there are still challenges due to key technology and market barriers, such as the lack of policy and regulation, lack of cookstoves quality standards, low consumer education level, low access to finance, lack of business development support and lack of sustainable fuel supply (ESMAP, 2018).

In developing countries, especially in rural and remote areas, access to modern energy services is very limited. This causes a substantially higher impact of low efficiency cooking in rural areas rather than in urban areas. Moreover, the economic limitations in developing countries do not allow to guarantee access to services such as clean energy, clean water, and healthcare to all the inhabitants. In addition, there is a lack of awareness and accessibility to clean and efficient cooking systems and technologies which create strong barriers in their adoption. There are different kinds of clean cooking technology options (Hager & Morawicki, 2013) that need to be investigated and compared from energy consumption, energy costs, cooking time, thermal energy losses and heat transfer behaviors, to reliability and affordability perspectives. In this chapter, four different electric cookstoves including two electric resistance cookstoves (electric cookstove locally manufactured in Ethiopia and single hot plate), an induction hob (Tefal Everyday), and an electric pressure cooker (Instant Pot Duo 7-in-1) were investigated in experimental work from the thermal and electrical energy consumption perspectives, as well as for costs.

There are plenty of studies on the assessment of different options of cooking technologies with their associated fuels, as well as their impacts on health, environment and climate change. For instance, (Kshirsagar & Kalamkar, 2014), presented a comprehensive review of biomass cookstoves from different perspectives and presented the energy and emission performance for 31 biomass cookstoves like three-stone open fire, wood flame fan stove, eco-stove, Uganda 2-pot stove, etc. In another study by (Pooja Arora, 2016), a review of various cookstove assessment methods is presented. Such a study presented cookstove testing methodologies applied in lab and field conditions, as well as testing results, such as energy and emissions. In another study by (Arora, Das, Jain, & Kishore, 2014), a laboratory-based comparative analysis of biomass cookstove performance using the Water Boiling Test (WBT) was performed by taking into consideration thermal efficiency, emission factors for carbon monoxide and particulate matter as performance indicators. In (Sutar, Singh, Karmakar, & Rathore, 2019), the thermal performance of three different biomass cookstoves (three-stone fire, Panval rocket stove and Berkeley-Darfur stove) is studied using a variable input power. Another study by (Grimsby, Rajabu, & Treiber, 2016) assessed multiple biomass fuels and improved cookstoves with a Water boiling test and presented the results from the emission of GHGs and particulate matter among different fuels, thermal efficiency and boiling time perspectives.

Another study made by (Karunanithy & Shafer, 2016) presented the impacts of using a different type of cooking pans on induction, electric resistance and gas cookstoves for heating water. They found a difference in cooking efficiency, energy costs, heating and cooking time and they concluded that these differences are due to differences in heating principles and cooktop wattage, as well as pan size and shape, composition, base thickness and mass. Another study made by (Villacís, et al., 2015) discussed the energy efficiency of different materials used for making cookware commonly used on induction cookers. The study was made for heating of water using different kinds of cookware made from stainless steel, cast iron and aluminum and concluded that the cookware made from cast iron (Enameled iron) and stainless steel (AISI 430 Stainless steel) present higher efficiency in the same stove due to its ferromagnetic behavior required to cook on induction stoves.

Several studies by (Lombardi, Riva, Bonamini, Barbieri, & Colombo, 2017; Pooja Arora, 2016; Kshirsagar & Kalamkar, 2014; and Mehetre, Panwar, Sharma, & Kumar, 2017) presented developed testing methods and protocols to assess biomass and improved cookstoves, as well as factors influencing the use of clean cookstoves. There are also some studies by (Karunanithy & Shafer, 2016; Sweeney, Dols, Fortenbery, & & Sharp, 2014) made on electric and induction cookstoves, but they are limited to the heating of water. However, there is a limitation in the studies, in particular, on testing and analysis among clean cookstoves (electric cookstoves) concerning energy consumption, energy/cooking efficiency, energy costs and life cycle costs for specific food type, country and location, because the food and cooking culture is different from country to country, and from location to location. Ethiopia is a country with 115 million people, and some African countries in the region also use this type of food. This study intended to fill this gap and was focused on Ethiopian traditional food called shiro (powdered beans with spices) and rice cooking, as well as water boiling. Other African countries in the region have similar types of food.

The main contribution of this work is to assess the cooking efficiency, energy consumption and life cycle costs (taking into account the lifespan, capital costs and maintenance costs) of four different cookstove technologies, such as a made in Ethiopia electric cookstove (Locally Manufactured Electric Cookstove - LMEC), induction hob (Tefal Everyday Induction Hob - TEIH), electric pressure cooker (Instant Pot Duo 7-in-1 Pressure Cooker - IPPC) and hot plate (Antlion Single Hot Plate - SHP). In developing countries, billions of people do not have clean cooking access, which affects the quality of life, place a heavy burden on women and children (who are usually responsible for cooking and gathering solid biomass), increases global warming due to the pollutants emitted, and is a risk factor for the premature death of millions of people attributed to HAP, due to household air pollution. Some of the reasons behind the lack of access to clean cooking are reliability and affordability of the available electric cookstoves, lack of electricity access in many countries especially in rural areas (where most of the population is located), high energy consumption and durability of the locally available technologies, lack of public knowledge and awareness of environmental protection and energy-saving options, as well as lack of policy and regulation which favors clean cooking technologies and fuels. The outcome of this study will give information about which technology is more advantageous from the perspective of each indicator. As a result, local government and other companies working on the promotion of clean cooking technologies can use it as a reference to select the best technology, taking into account the needs of the population and sustainability aspects.

3.2. Cookstove Options

Delivering modern energy services for all human beings at affordable costs is a challenge for developing countries. Thus, energy services can be classified as services necessary for basic human needs and incremental welfare improvement. On the other hand, the choice of technology with its associated fuels depends on the households' socioeconomic status and the availability of the technology at the local market at affordable costs (Kimemia & Niekerk, 2017).

In this regard, in developing countries, modern cooking technologies including electric cookstoves and LPG are in urban areas, but still with a low penetration rate (Vaccari, Vitali, & Tudor, 2017). Furthermore, in some countries, there is a development in the use of methanol, ethanol and ethanol gel, as energy sources. The dominant cooking technology, with its associated fuel, is different from country to country and from area to area (rural, pre-urban and urban areas). For example, in South Africa wood, kerosene, coal, LPG and grid electricity are the main energy sources used by low-income households. In rural areas, the use of wood is predominant, whereas kerosene is the primary fuel in off-grid peri-urban areas (Kimemia & Niekerk, 2017). In Ethiopia, one of the topmost access deficit countries, the penetration of cleaning cooking access is only 7%, the other 93% being dominated by low efficient cooking systems like three-stone open fire and improved cookstoves (IEA I. U., Tracking SDG 7: The Energy Progress Report, 2020).

Figure 32 presents some of the cookstove options which are commonly used in rural and urban areas of developing countries. These cookstove technologies are mostly used in the urban areas of developing countries, whereas in rural areas due to the economic level and accessibility of the technologies the penetration is at a very low rate with the exceptions of three-stone open fire and improved cookstoves. The reliability, accessibility and penetration of modern cookstove technologies in rural areas are challenged by different barriers, such as lack of electricity, cost of the technologies, the high energy consumption of the available technologies (difficult to integrate with small generation units like solar home systems) and lack of awareness on the relative merits as well as the best operation methods of the different technologies (Rahut, Behera, & Ali, 2016).

Improved stove *LPG stove* *Kerosene stove* *Ethanol stove*

Three stone open fire *Electric single hot plate* *Pressure cooker* *Induction stove*

Figure 32 Different types of cookstove technologies

Figure 33 presents the types of cookstove technologies with their associated fuel types and their impact on climate and health, as well as the affordability of the stoves. As cooking technology goes from traditional to modern cooking technologies, the negative impacts on health and climate decrease, but the cost increases. These factors determine the selection of cooking technology by households and are also important factors for governments and stakeholders to develop a policy framework for the promotion of clean and cost-effective cooking technologies and fuels.

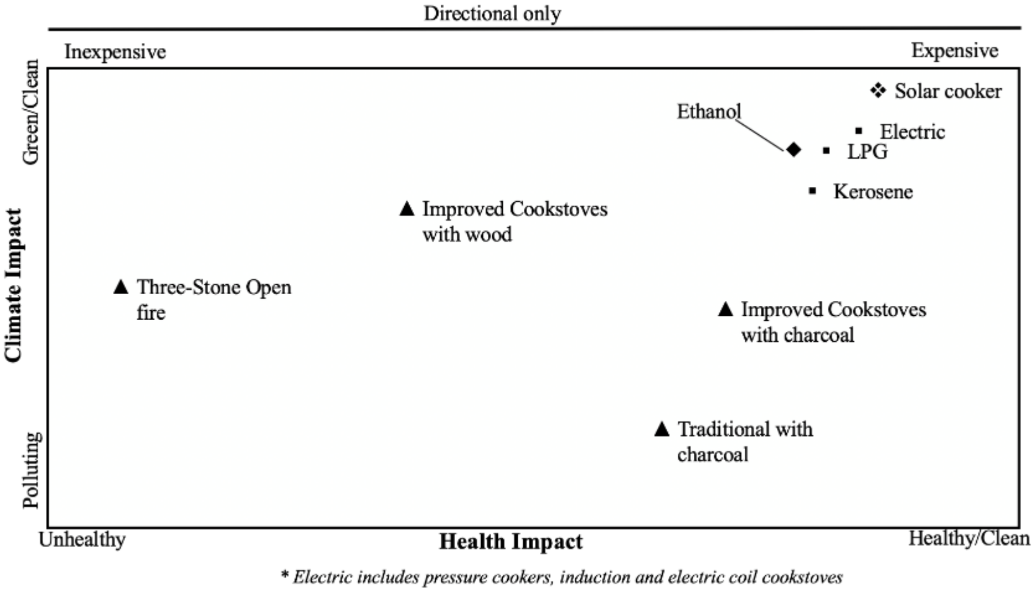


Figure 33 Indicative cost, health and climate impact, by stove and fuel type (adapted from (Putti, Tsan, Mehta, & Kammila, 2015)

3.3. Experimental methodology

3.3.1. Cookstove Technologies

The laboratory experiments in this study used cookstove technologies: Locally Manufactured Electric Cookstove, Tefal Everyday Induction Hob, Instant Pot Duo 7-in-1 Electric Pressure Cooker and Antlion Single Hot Plate. Compared with the traditional and improved cookstoves, the selected cookstoves for the analysis are clean, since they consume electricity. On the other hand, from technology to technology the energy consumption, cost, thermal behavior and other related characteristics are different which needs to be investigated. Therefore, this part of the thesis aimed to analyze these emerging technologies from energy consumption, NPC, cooking time, efficiency and thermal heat transfer behaviors. Below all the selected technologies are described in detail:

Locally Manufactured Electric Cookstove (LMEC): It is a type of electric resistance cookstove (shown in Figure 34) made in Ethiopia and mainly used in the capital Addis Ababa. Because of its durability, compared with imported portable electric cookstoves, most people prefer it. It is made up of steel in the main body and the top from ceramic with resistance coils inside. The drawback of this cookstove is the requirement of changing the coils every six months, due to corrosion and melting problems.

Figure 34 Locally manufactured electric resistance cookstove

Tefal Everyday Induction Hob (TEIH): It is a type of induction cooker (Figure 35), which is often considered one of the most efficient technologies for stove top cooking. As presented in Figure 35 (b), an induction hotplate works by heating a receptacle using the currents induced by a high-frequency magnetic field. When an alternating electric current pass through a coil, it generates a variable magnetic field. On an induction hotplate, this alternating magnetic field induces electric currents into the base of the cooking vessel (the base must be made from a ferromagnetic material like an iron alloy (such as Figure 36) to generate sufficient heat for cooking). The energy transferred is converted to heat in the metal base.

a) *Tefal Everyday Induction Hob* b*) Working principle of an induction hob*

Figure 35 Tefal Everyday Induction Hob (a) and working principle of an induction hob (b)

The principle behind the induction hotplate control is to change the frequency and amplitude of the magnetic field to heat the bottom of the receptacle. The heating process is instantaneous, since as soon as the coil power supply is activated, the receptacle is heated. Food is then heated through contact with the base of the pot.

This cooker has six different cooking power setting such as manual, heat milk, stew, stir fry, deep fry and boil water. The manual mode was used for this study because it enables one to cook all types of food by manually adjusting the heating power and time (Tefal, 2019). Secura Duxtop Whole-Clad Tri-Ply Stainless Steel Induction Ready Premium Cookware with Lid, 3 Quart shown in Figure 36 were used as cookware since other kinds of cookware do not work with magnetic field principle due to the non-magnetic characteristics of the material. The same cookware was also used for locally manufactured and single plate cookstoves to avoid variability in the analysis due to the use of different cookware.

Figure 36 Secura Duxtop Whole-Clad Tri-Ply Stainless Steel Induction Ready Premium Cookware with Lid, 3 Quart

Instant Pot Duo 7-in-1 Electric Pressure Cooker (IPPC): Instant Pot® Duo (Instant Brands Inc, 2020) shown in Figure 37 is a smart Electric Pressure Cooker designed to be safe, convenient and reliable. It speeds up cooking by 2~6 times using up to 70% less energy and, above all, because of the reduced cooking time conveniently and consistently produces nutritious healthy food. It also has 14 smart built-in programs – Soup/Broth, Meat/Stew, Bean/Chili, Poultry, Sauté/Searing, Steam, Rice, Porridge, Multigrain, Slow Cook, Keep-Warm, Yogurt, Pasteurize & Pressure Cook. It also gives the option of an automatic keep-warm that holds the temperature of the food until ready to serve (Instant Brands Inc, 2020). In this study, the saute/searing program was used for shiro and the rice in-built program was used for rice cooking.

Figure 37 Instant Pot Duo 7-in-1 Electric Pressure Cooker

Antlion Single Hot Plate (SHP): It is a kind of electric resistance coil cookstove shown in Figure 38, that is similar to the locally manufactured electric coil cookstove. The drawback of this type of cookstove is that it takes a longer time for cooking (which is also proved in this study), as a result, customers prefer locally manufactured models over this one.

Figure 38 Antlion Single Hot Plate

Table 7 presents the different characteristics of the assessed technologies including manufacturer, initial costs, lifespan and maintenance costs.

Table 7 Compares the characteristics of the assessed technologies

No.	**Type of cookstoves**	**Manufacturer**	**Costs (US $)**	**Maintenance and Repair (US $/year)**	**Lifespan/years**	**Remark**
1	Electric cookstove	Locally manufactured in Ethiopia	14	7	3 to 4 (customer review)	Every 6 months it requires changing the coil
2	Tefal Everyday Induction Hob	Tefal	60	2	8	
3	Instant Pot Duo 7-in-1 Electric Pressure Cooker	Instant Brands Inc	105	2	Up to 5 (customer review)	
4	Single Hot Plate	Antlion	10	6	2 to 3 (customer review)	
5	Secura Duxtop Whole-Clad Tri-Ply Stainless Steel Induction Cookware	Secura	45	NA	15	

3.3.2. Testing Procedures

The cooking was performed on rice, shiro (traditional Ethiopian food which is common in rural and urban households), and water boiling. Shiro or shuro or sometimes shero is a blended powder of beans and spices often made gently hot with tomato, berbere (pepper) spice (a spicy mix of chili peppers, coriander, garlic, ginger, basil, korarima, rue, ajwain or radhuni, nigella, and fenugreek), oil, and onion. Based on personal experience and also confirmed by a 1985 United Nations report “for the common families, *shiro* is the only thing used for making stew every day of the year, except some important festivals like the New Year, Mesqel, Christmas and Easter, at which every family will slaughter at least a chicken” (Kloman, 2013). Figure 39 presents the shiro cooked in the experiment made in this study.

Figure 39 Shiro Wet cooked in the experiment

Table 8 presents the ingredients of the food cooked in this experiment with its respective weight. For rice, water and rice were used and the ratio was 1 gram of rice per 1.5 gram of water, for the three stoves with exception of the instant pot pressure cooker (used 1:1 ratio as per the manual). One advantage of the instant pot pressure cooker is it uses less water compared with other cooking technologies (Instant Brands Inc, 2020). For shiro; onion, olive oil, water, tomato sauce and shiro powder were used as per the composition presented in Table 8.

Table 8 Food types, their ingredients and weight

Food Type	**Rice**		**Shiro**					**Water Boil**
Components	Rice (g)	Water (g)	Olive Oil (g)	Onion (g)	Tomato sauce (g)	Water(g)	Shiro powder (g)	Water (g)
Weight (g)	500	750 500 (for instant pot	20	200	100	1200	125	1500

For the assessment of energy consumption and thermal efficiency, the current, voltage, power, energy and power factor were measured using a Wattman power meter (Inc., 2020) and the temperature was measured using an infrared thermometer, throughout the cooking process for each food types. The energy and the temperature were monitored throughout all cooking samples and process. For the case of rice and water boiling, the samples were cooked and boiled 5 times, so that the optimum and the uniform result were taken for further analysis of the study. On the other hand, in the case of shiro cooking, since the cooking time is a bit longer compared with the rice and water boiling, the sample were cooking 3 times. As a result, the recorded outcome with uniform and optimum result compared with each cooking result were compared and taken as final result for further analysis. The testing procedure was the following:

A. *Cooking process:* For cooking rice, the rice and water were added together and cooked until the water is finished, implying that the rice is already cooked. Whereas for shiro, first the onion was chopped and simmered with olive oil until the onion changes its color and smell. Then, the tomato was added and stirred until well cooked, meanwhile, water was added to avoid sticking. Then, the remaining water was added and wait until it boils and then mixing the shiro by adding a small portion of the shiro flour at a time and continuously stirring. And then let it cook until it becomes thick and well cooked.

B. *Energy Monitoring*: The energy consumption was monitored by connecting the Wattman power meter (HPM-100A) from the power source and the cookstove to the Wattman power meter. The Wattman power meter is a plug & play measuring device that can measure power consumption with a standby feature to show the measured items instantaneously when connecting the plug to the power source and the device to be measured under working conditions (Inc., 2020). It displays current, voltage, power, energy and power factor, and the measurements were performed by connecting the power meter to a computer throughout the cooking process from the start to the end, as presented in Figure 40. The duration of cooking and the data measurement interval was set in the software before the start of the cooking. The energy values were measured once per second during the cooking period.

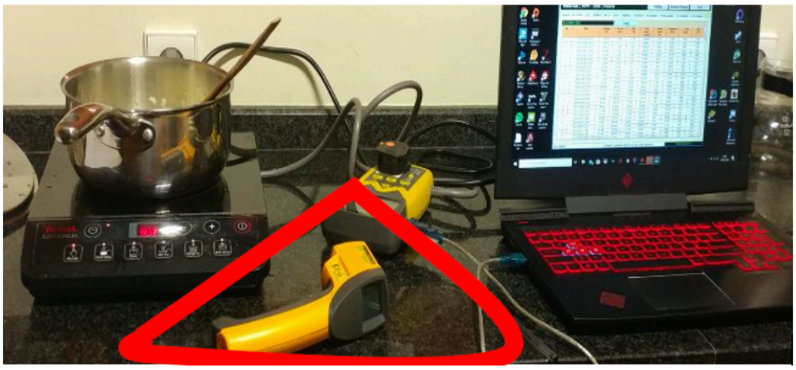
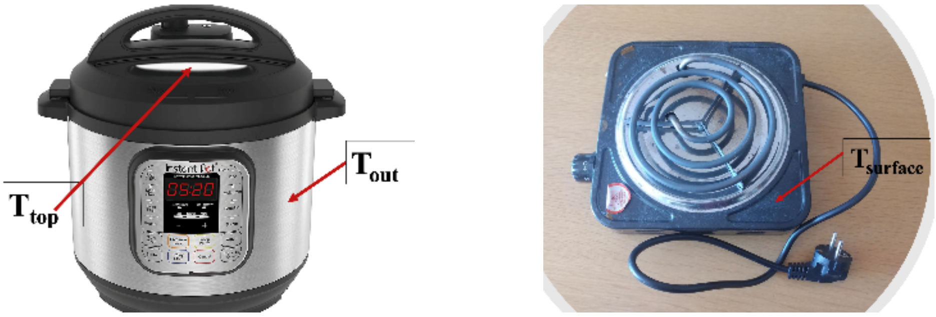


Figure 40 Cooking Set-up

C. *Temperature monitoring:* The temperature was monitored using an infrared thermometer (Fluke 63) which is used for contactless temperature measurements. It displays the surface temperature of the measured object when one points the thermometer to it and pulls the trigger. The thermometer determines the temperature of the target by measuring the amount and wavelength of the infrared energy radiated from the target's surface. The used FLUKE 63 IR thermometer (encircled in red in Figure 40) used in this study has a fixed preset emissivity of 0.95 (Fluke Corporation, 2004). The temperature measurement was performed by making readings at a constant spot marked with a mat black paint dot on the body of the cookware (on the spot where the temperature is measured) for outer surface temperature. The procedure is aimed to avoid temperature reading errors due to the emissivity of the material that the cookware is made. The temperature was measured on the surface (outer and inner side/food media) of the cookware, on the extra (outer surface of the cookstoves) at every 5 minutes for rice and every 10 minutes for shiro. Figure 41 shows where the temperature values are measured in the cooking process and each temperature value was recorded.

Locally manufactured electric cookstove

Tefal Everyday Induction Hob



Instant pot pressure cooker (for shiro T_{in} measured inside the cookware)

Single hot plate

Figure 41 Temperature measurements indication

3.4. Experimental Results

3.4.1. Heat Transfer

Figure 42 presents the cooking time for each cookstove in the case of shiro and rice. In the case of rice except for TEIH (which took 12 minutes to cook), it took about 20 minutes to cook. In the IPPC, although the built-in program for rice indicates 12 minutes to cook, since it took about 10 minutes to warm up the cooker the total is about 20 minutes. Whereas in the case of shiro for SHP, LMEC, TEIH and IPPC a total period of 130, 70, 70 and 60 minutes was needed, respectively.

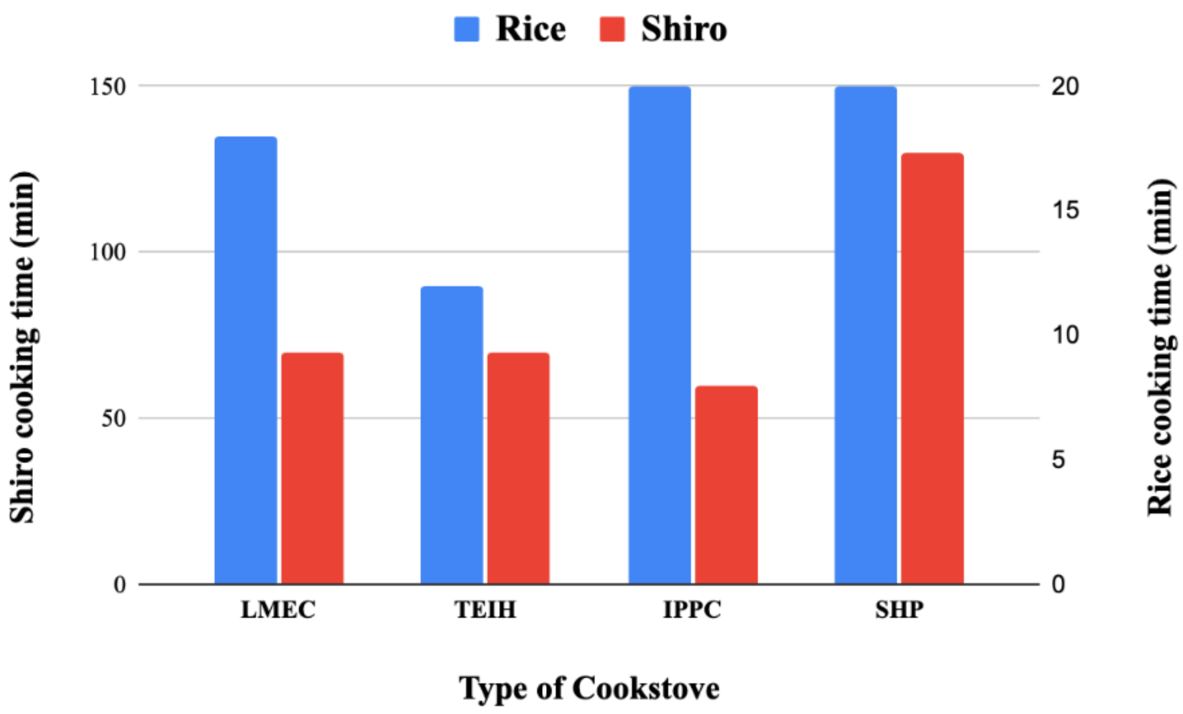


Figure 42 Cooking time for each food type

The heating transfer behaviors of the cookware, food media and the surface of the cooking stove are presented in Figures 43-45 for each cookstove and food type. The temperature values used to present the heating transfer behaviors are the temperature variations (**Δ**T**)** which is the difference between the temperatures measured every 5 minutes for rice and every ten minutes for shiro and the initial temperature (equivalent to room temperature). In the case of Instant Pot Duo 7-in-1 Electric Pressure Cooker (IPPC), the food media temperature is measured at the top cover of the cooker (assumed to be similar to the inside temperature with a small difference) as shown in Figure 37, because the working principle of the pressure cooker is under a closed system which is impossible to measure the inside temperature in the cooking period, specifically for rice.

As depicted in Figure 43, it was observed that the heat transfer behaviors of each cookstove to the food media (ΔT_{in} ^{O}C) had similar behaviors with exception of Single Hot Plate (SHP). In the SHP, the cookstove by itself turns on and off in the process of cooking, after it gains a certain temperature. For instance, for rice cooking, it turns on and off frequently after minute 6 so that it presents a different heat transfer behavior to the food media (ΔT_{in} SHP) i.e., deep blue curve. Whereas for the cookware (ΔT_{Out} ^{O}C), it is observed that SHP and LMEC had similar heating behaviors and TEIH and Instant IPPC presents similar heating behaviors. It is observed that for the same cookware SHP presents lower ΔT_{Out} (^{O}C) compared with the LMEC and TEIH, which implies the heat loss on the cookware is lower in SHP. On the other hand, the heat transfer behavior (ΔT_{Out} (^{O}C) in IPPC is lower than the others, which implies that it has low heat loss on the body of the cooker.

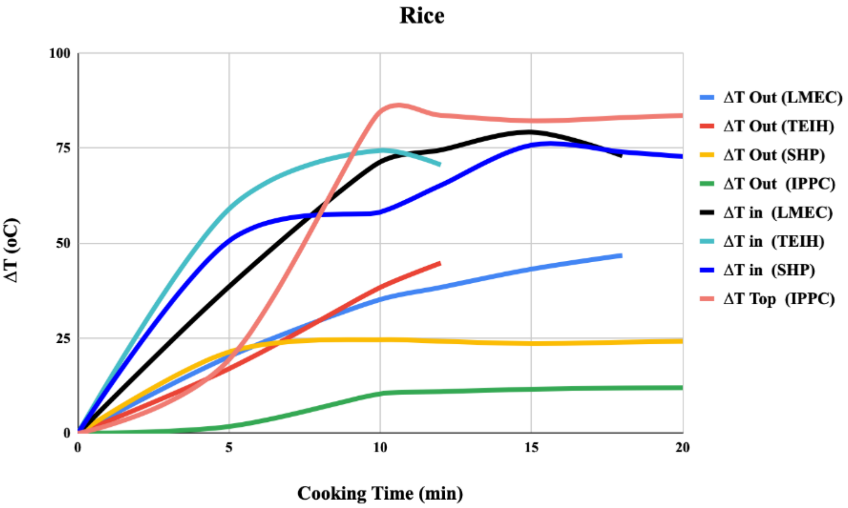


Figure 43 Heat transfer behavior of cookware and food media on each cookstove (LMEC, TEIH, SHP and IPPC) for Rice

Figure 44 presents the heating transfer behaviors of each cookstove in the case of shiro, being clear that all the cookstoves present similar heating transfer behaviors for the cookware (ΔT $_{Out}$ ^{O}C) and food media (ΔT $_{in}$ ^{O}C). Additionally, it is clearly shown that SHP took a longer time to reach the first stage of cooking (about 25 min), i.e., cooking onion and tomato with oil after that water was added, whereas for the other three cookstoves the first stage of cooking was finished in 20 minutes. In each cookstove after reaching a maximum temperature, the temperature decreases when water is added (the temperature measurements were taken every 10 minutes irrespective of when the ingredients are added). In LMEC, the cookware heating transfer (ΔT $_{Out}$ ^{O}C) shows a different heating transfer behavior, and the temperature changes are larger than the others. Whereas in the food media, SHP presents lower heating transfer behavior between 25 and 50 minutes, and after that, it presents a higher value than the other cookstoves. On the other hand, in both rice and shiro, SHP took a longer cooking time compared with the other cookstoves, in particular, for shiro the difference is much higher (it is about double).

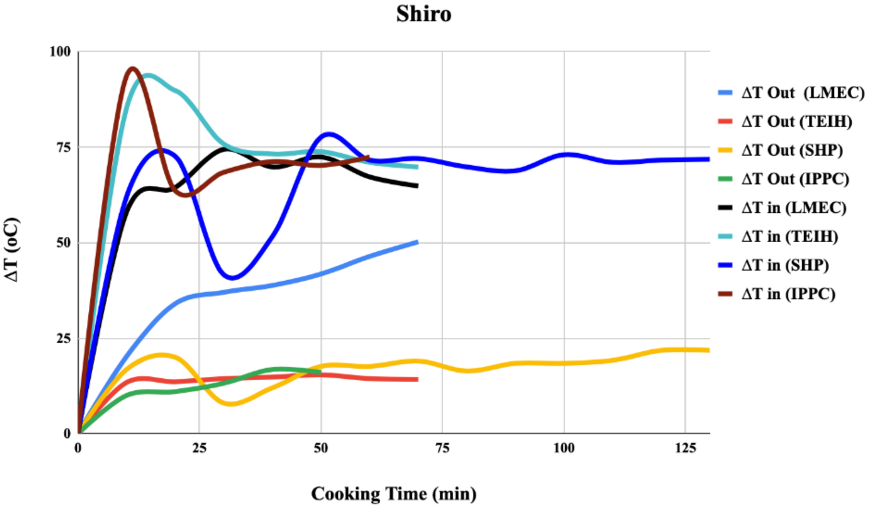


Figure 44 Heat transfer behavior of cookware and food media on each cookstove (LMEC, TEIH, SHP and IPPC) for Shiro

The heating transfer behaviors on the surface of SHP, LMEC and TEIH cookstoves in the case of shiro are presented in Figure 45. The presented result indicates that LMEC had a higher **Δ**T $_{\text{Surface}}$ (126.6 ^{O}C) than TEIH (9 ^{O}C) and SHP (86 ^{O}C) at the same cooking time (70 minutes). This implies that the heat loss in the surrounding in the case of LMEC is higher than TEIH and SHP. On the other hand, TEIH has a low-temperature difference on the surface compared with the initial temperature (room temperature), which implies that almost all the heat generated in the cooking process is transferred to the cookware. Therefore, the heat loss in TEIH is much lower than LMEC and SHP. In the case of SHP, even if the heat loss is lower than LMEC by 32% at the same cooking period, since the cooking time is much higher than both cookstoves and the **Δ**T$_{\text{Surface}}$ at the end of the cooking is 96 ^{O}C.

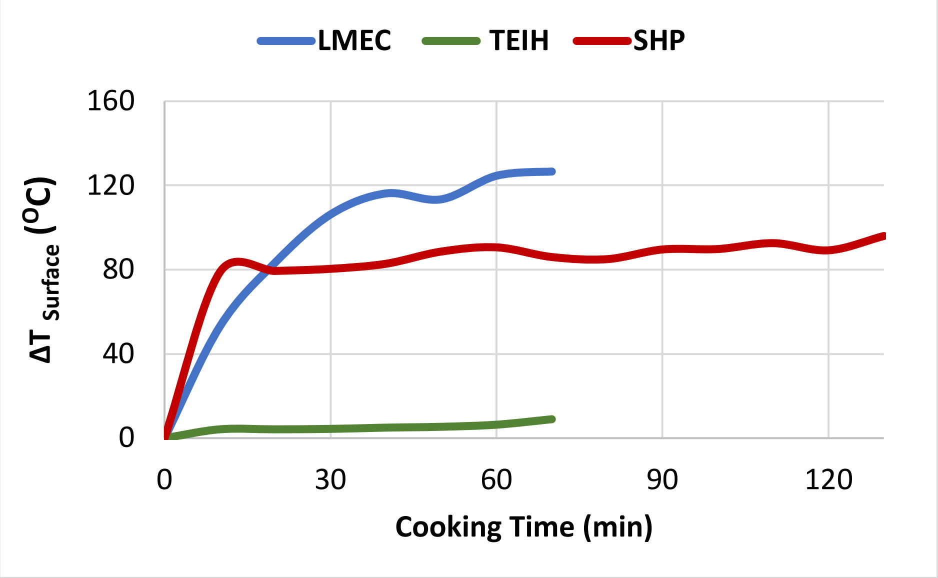


Figure 45 Heat transfer behavior of cookstove surface for each cookstove (LMEC, TEIH and SHP) for the case of shiro

3.4.2. Energy Consumption

Figure 46 presents the energy consumption of each cookstove investigated in this study, in the case of rice, shiro cooking and water boiling. It was observed that cooking with LMEC requires more energy, in both rice and shiro cooking as well as in water boiling. For the case of rice, using TEIH, SHP and IPPC saves energy by 68.6%, 67.2% and 56.8%, respectively as compared to LMEC. SHP and TEIH consume more or less the same amount of energy to cook a half kilo of rice. For the case of shiro, using IPPC, LEIH and SHP save energy by 62.8%, 44.2%, and 57.7%, respectively compared with LMEC. The result implies that IPPC and SHP consume less energy compared with LMEC and TEIH, for the case of shiro cooking. Although SHP took about double cooking time, the energy consumption is lower than the LMEC by about 67.2% for the case of rice and by 57.7% for the case of shiro. In the case of water boiling, LMEC consumes more energy than the other cooking technologies to boil 1.5 kg of water. The energy consumption is larger than SHP, LEIH and IPPC by 55%, 55.4% and 44.9%, respectively. In each rice, shiro cooking and water boiling, the LMEC consumes more energy than the others followed by LEIH, SHP and IPPC, with the exception of shiro cooking, because in the case of shiro cooking TEIH requires higher input energy compared with SHP and IPPC which was not observed in the case of rice cooking and water boilingOn the other hand, IPPC consumes less energy in the case shiro cooking, compared with other cooking technologies.

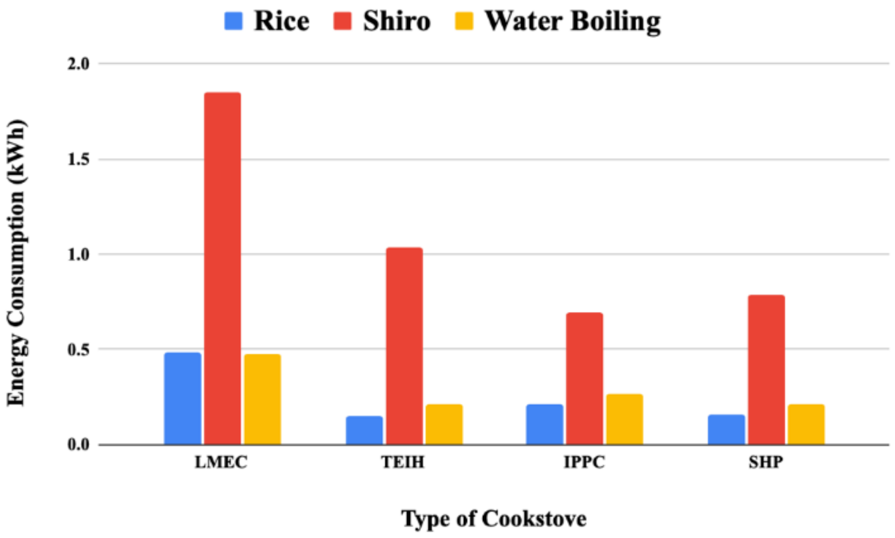


Figure 46 Energy consumption per cooking task for rice, shiro and water boiling in each cookstove

On the other hand, the output thermal energy was calculated using Equation 1 (Karunanithy & Shafer, 2016) for rice and shiro cooking considering the mass and specific heat capacity of each ingredient(i.e. onion, oil, water, shiro powder for shiro and water and rice for rice) and the energy efficiency of water boiling calculated using Equation 2 (Villacís, et al., 2015) .

$$E_{output} = \sum_{i=1}^{N}(C_{pi} * m_i) * (T2 - T1) \qquad (1)$$

$$\eta = \frac{\sum_{i=1}^{N}(C_{pi} * m_i) * (T2 - T1)}{E_{input}} * 100 \qquad (2)$$

Where: E_{output} is output thermal energy (kJ), i is the ingredient of the food, N is the total number of ingredients, C_{pi} is the specific heat capacity of ingredient i (kJ/kg. °C) and m_i is the mass of ingredient i (kg), T_2 and T_1 are the final and initial temperature (°C), respectively, η is energy/cooking efficiency (%) and E_{input} is the energy consumed during the cooking test in kWh. Table 9 presents the specific heat capacity of each ingredient for each food prepared in this study and for the cookware used.

Figure 47 and Figure 48 presents the thermal energy output and the input energy for rice and Shiro cooking using each considered technology, respectively. For the case of rice cooking, the result indicates that TEIH has lower energy output compared with the other technologies. However, its energy consumption is higher when compared with IPPC and SHP and lower when compared with LMEC for the case of rice cooking. On the other hand, in the case of shiro cooking, LMEC has a lower energy output compared with the other technologies. Comparing the input and the output energies for each technology, LMEC has a larger energy difference with the input and output energy in both rice and shiro cooking followed by TEIH, SHP and IPPC. This implies that LMEC has a lower output to input ratio that indicates that it is less efficient than other technologies for both rice and shiro cooking.

Table 9 Specific heat capacity of food ingredients used for the preparation of each food (EngineeringToolBox, 2001)

No.	Ingredients	C_p (kJ/kg. oC)
1	Rice	0.782
2	Water	4.18
3	Olive oil	1.97
4	Onion	3.77
5	Tomato	3.98
6	Shiro	3.68

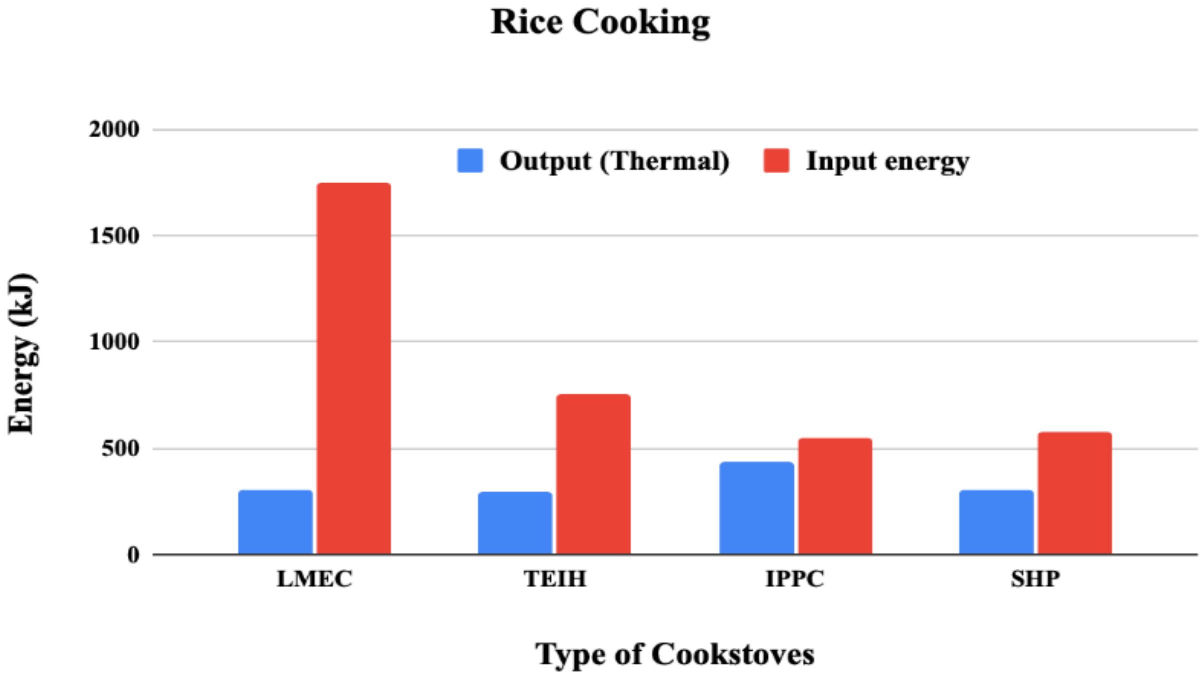


Figure 47 The output and input energy of each cooking technology for rice cooking

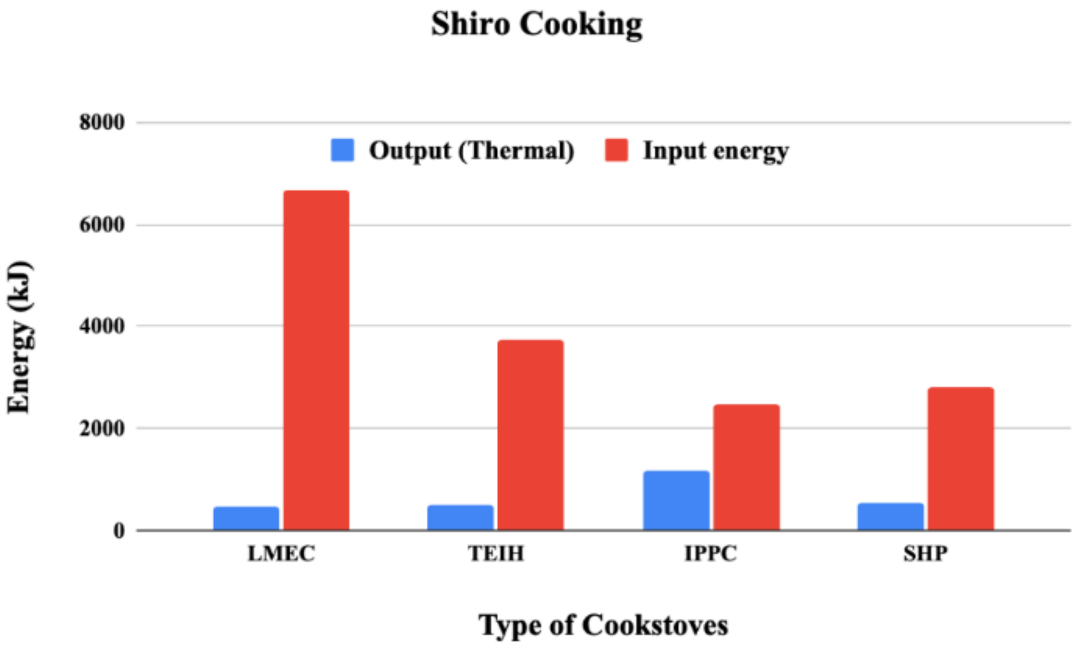


Figure 48 The output and input energy of each cooking technology for shiro cooking

In the case of water boiling the efficiency for each technology was calculated using Equation 2, resulting in 32.6%, 70.5%, 78.8% and 67.5% for LMEC, TEIH, IPPC and SHP, respectively. This shows that LMEC has lower efficiency compared with all the other technologies and IPPC has higher efficiency. The TEIF efficiency is in line with the results reported by (Karunanithy & Shafer, 2016) for heating water which is about 70%, whereas the LMEC and SHP efficiency is lower than the efficiency found in the literature by 37.4% and 2.5%, respectively. On the other hand, the efficiency in the case of IPPC is higher by 8.8% compared with the result found in the same study. The LEIH, IPPC and SHP efficiencies are higher than the result presented by the same authors which are 39.3% and by (Sweeney, Dols, Fortenbery, & & Sharp, 2014) which is 42%, whereas in the case of LMEC the result found in this study is lower.

3.4.3. Cost-Benefit Analysis

In this section, the energy costs and the Net Present Cost (NPC) of the cookstoves are assessed and compared considering 8 years of lifespan which is the longest lifespan among the technologies considered in this study (Tefal Everyday Induction Hob). Based on the acquisition (initial cost), maintenance and repair costs presented in Table 7 and the energy consumption (Ethiopian electric utility charges US$ 0.015/kWh), as well as a 10% interest rate (typical interest rate in Ethiopia and other developing countries), the energy cost and NPC calculations were made. If a household with 2 family members cooks shiro for 330 days (with exception of days on holiday and around holidays like Easter, new year, Christmas), cooks rice for 104 days per year (only 2 times a week, since rice is not commonly used in Ethiopian community like the other food shiro) and boiling 1.5 kg of water once per day all year, the energy costs and NPC were calculated.

Figure 49 presents the annual energy costs to cook rice, shiro and boiling of water using the stoves considered in this study. The large energy costs can be observed in the LMEC compared with other cookstoves. For instance, the energy cost using LMEC is higher by 57.8% for cooking shiro, by 67.9% for cooking rice and by 55% for water boiling compared with SHP. In the case of IPPC and SHP, the energy costs are more or less the same for the case of rice cooking i.e., US$ 0.24/ and 0.25/, respectively. If a household would like to shift from LMEC to LEIH, the household spends only 55.8% of the energy cost for the case of shiro, 42.3% of the energy cost for the case of rice and 44.6% for the case of water boiling, implying that the household would save about 47.3% of the total cost. On the other hand, the energy costs in the case of IPPC and SHP are lower than LMEC and TEIH for the case of rice and shiro cooking, this is due to the lower energy consumption in the SHP which manages the on and off button by itself and in IPPC the cookstove has small thermal energy losses, compared with LMEC due to the thick well insulated wall surrounding the cooking pot. On the other hand, in the case of water boiling, SHP and TEIH present more or less similar energy costs and lower energy costs compared with LMEC and IPPC.

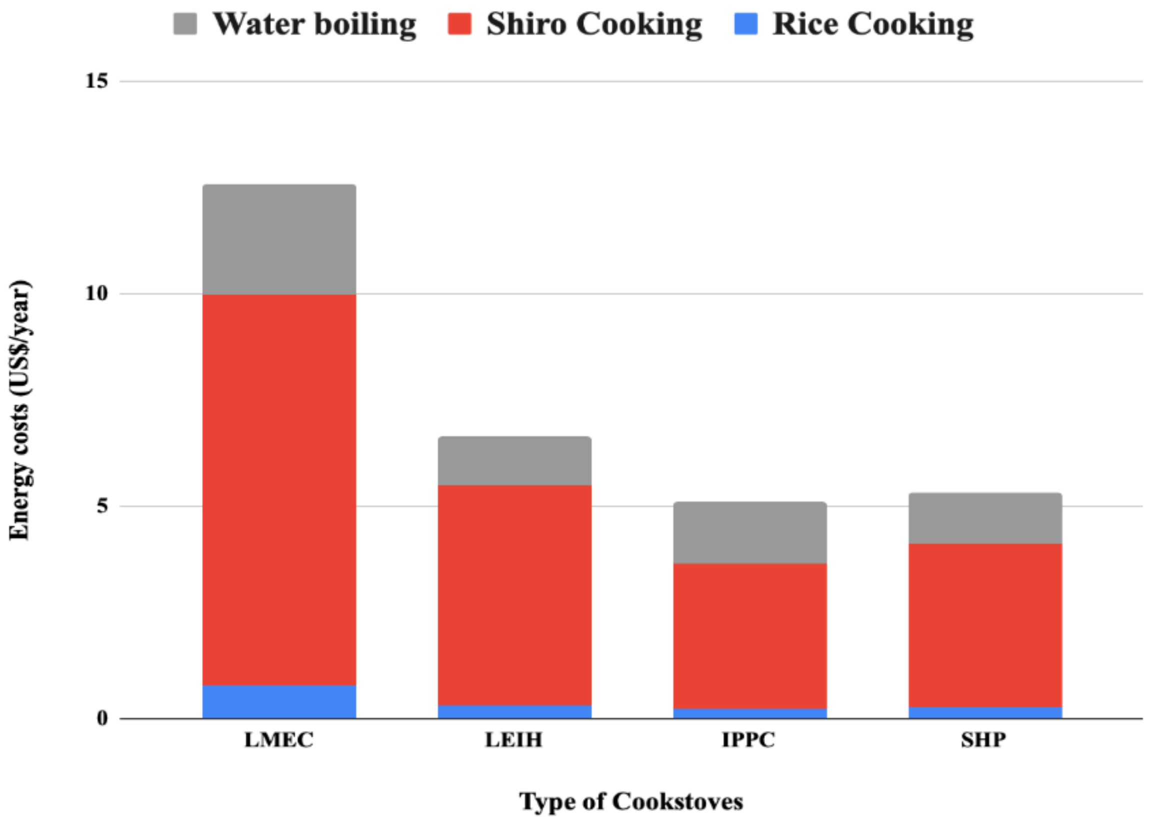


Figure 49 Annual energy costs to cook rice and Shiro and boiling water for 2 family member household

Furthermore, the energy costs, maintenance and repair costs as well as investment costs over the lifespan of the cookstoves were calculated and presented in Figure 50. In the case of investment costs, replacing the cookstoves which have a shorter lifespan was taken into account for the calculation of the NPCs. The result indicates that the NPC ranges from US$ 91.22 for SHP to 225.39 for IPPC over the eight years of lifespan. The NPC for LMEC is lower than TEIH and IPPC by 3.1% and 41%, respectively. Due to the higher energy costs and maintenance costs, the NPC of LMEC is higher than SHP even if the investment cost is more or less similar i.e., US$ 42 for LMEC and US$ 40 for SHP per 8 years lifespan. On the other hand, in the case of TEIH, since it requires special cookware with ferromagnetic properties, the initial investment cost is much higher than LMEC and SHP, while it is lower than IPPC over the lifespan (since IPPC needs to be replaced because of its shorter lifespan). Although, in the case of IPPC, the energy and the maintenance costs are lower than the other cookstoves because of its investment cost the NPC is higher than the other cookstoves. For instance, if a household would like to switch from LMEC to SHP, the household saves about US$ 41.83/ETB 1444.81/lifespan considered in this study i.e., 8 years. Therefore, Single Hot Plate (SHP) cookstove presents a better cost-benefit ratio than the other cookstove options irrespective of the cooking time and efficiency and IPPC presents the higher cost-benefit ratio.

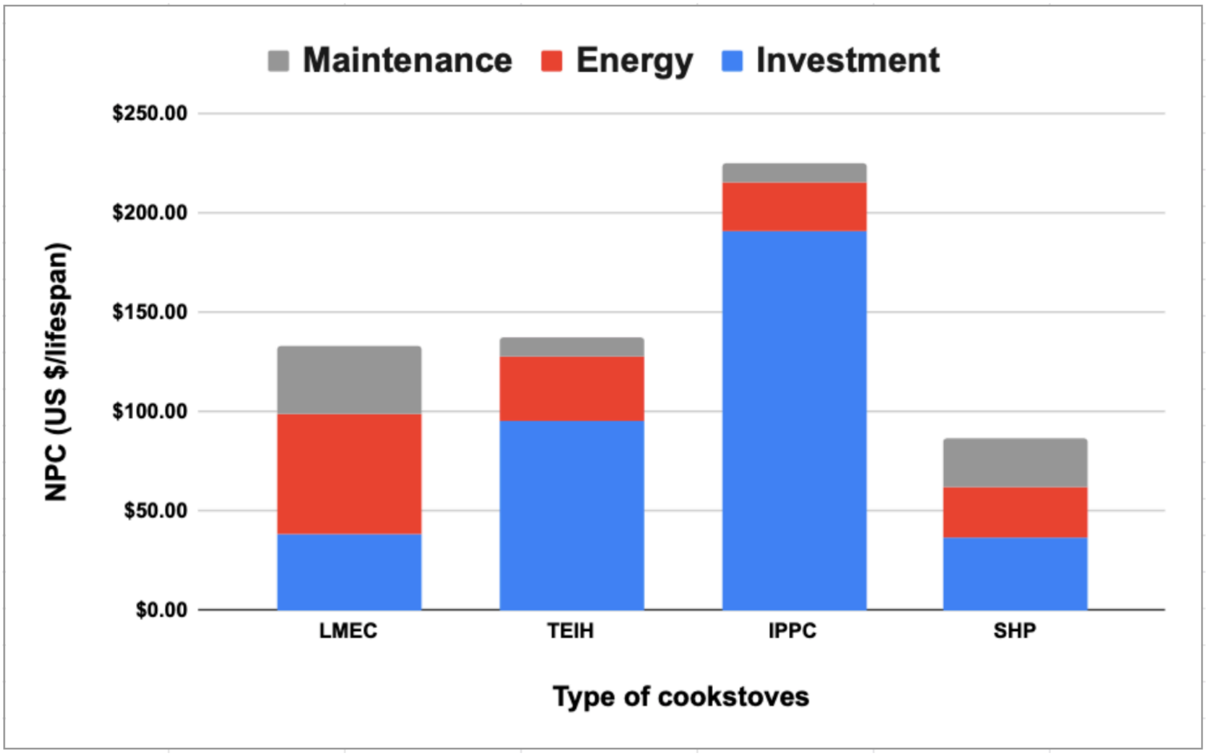


Figure 50 NPCs for each cookstove

3.5. Policies to Promote Clean Cooking

The use of traditional cooking stoves with solid fuels has a substantial impact on climate, public health and socioeconomic issues. Its use leads to household indoor air pollution in countries, like Ethiopia, mainly in rural areas, as well as significant GHGs emissions, including carbon dioxide, methane (Wilson, Talancon, Winslow, Linares, & Gadgil, 2016), black carbon and particulates that magnifies global warming, forest depletion (IEA I. U., Tracking SDG 7: The Energy Progress Report, 2020) and contributes to the premature death of about four million people annually (WHO, 2018). On the other hand, cooking with inefficient stoves and solid fuels creates an enormous burden on women and children, since they are not only in charge of cooking, and therefore directly exposed to the created air population, but also spend up to six hours per day for the gathering of wood (Putti, Tsan, Mehta, & Kammila, 2015).

Therefore, addressing the use of inefficient stoves and pollutant emitting fuels is one of the most challenging health and environmental problems in rural areas of developing countries. Substituting these cookstoves with energy-efficient and cleaner cooking options and fuels such as electric cookstoves can reduce indoor air pollution and emissions, provide energy and cost savings, avoid the time needed for gathering solid fuels, and reduce the time and resources needed to procure fuel. As a result, the adoption and promotion of clean electric cooking technologies options, like the technologies analyzed in this study, could have a fundamental contribution to solving such problems. Furthermore, to make this transformation of clean cooking a reality, well-framed policies and strategies are necessary. Therefore, the following policies and strategies are recommended to adapt and promote clean electric cooking solutions in rural areas of developing countries, such as Ethiopia:

1. *Develop clean cooking policy and strategy*: Most of the developing countries have national electrification plans, which are regularly updated (Kyriakarakos, Balafoutis, & Bochtis, 2020; MWIE, 2020), but access to clean cooking is not included in such plans. Therefore, it is necessary to develop a strong policy and strategy and form a dedicated government body at the national, regional and local levels to follow the implementation of the policy, as well as give solutions at each level based on the barriers, gaps and findings in the implementation process. The policy should include the benefits of using clean electric cookstoves investigated in this study based on the finding of this study from a cost, energy-savings and efficiency point of view, as well as sort out the possible means to distribute such cooking solutions for people located in rural areas.
2. *Enhance supply and demand:* User awareness (ESMAP, 2018) is crucial to stimulate the demand for any service or product. Simultaneously, the supply must be enhanced to attend to the demand. The household cooking technology preferences depend on cultural norms, household dynamics, as well as the availability and affordability of the cooking technology with its associated fuels (Langbein, Peters, & Vance, 2017). On the other hand, the knowledge of the benefits that can be achieved on health, environment, gender and socioeconomic benefits (ESMAP, 2018) are important for the enhancement of the demand. Therefore, awareness creation about clean cooking technologies and fuels through different strategies, such as information campaigns, training in nearby schools or community-based institutions, educational and training campaigns, and other advertising campaigns are very important to enhance the demand for electric cleaning cooking technologies. Furthermore, presenting the results found in this study for the rural communities could be useful in increasing the awareness of the users. For instance, discussions and awareness creation events with end-users of available technologies could be important in terms of saving bills in short and long-term scenarios. The cost, durability, and efficiency of the technologies are important ingredients to discuss with the users. On the other hand, financial support and incentives for organizations working on clean electric cookstoves and fuels, as well as for buyers should be one aspect of the policy, and mainly for rural communities where finance is a key barrier. In this regard, developing an appropriate business model that could increase the attraction of users and promotion of electric cookstoves is critical.
3. *Develop and implement efficiency, emission and safety standards:* It is necessary for the development of standards for the verification of thermal and electrical efficiency, emission levels, safety and durability of the cooking technologies. This should be supported and enforced by the dedicated body government at national, regional and local levels. On the other hand, it is important for the adoption and promotion of clean cookstoves if such kinds of policies are in place. The customers, as well as distributors, will have confidence in buying and using the clean electric stoves including those studied in this study.
4. *Gender*: it is also a key component in the adoption and promotion of clean cooking solutions since women and children are the ones mostly affected by the use of inefficient cooking

technologies and fuels. Therefore, gender is an important element for policies and programs to promote and adopt clean cooking solutions, as well as a gender approach, which is key for the dissemination purpose (Kumar & Mehta, 2016). As a result, the government of any nation as well as stakeholders should develop a policy and strategy to engage women in the adoption and promotion of clean electric cooking solutions. The inclusion of such an aspect in the policy of clean cooking access will fasten the promotion and adoption of clean electric cookstoves.

5. *Energy access:* In remote areas off-grid solar electricity systems, which are experiencing a sharp decrease in costs, may be used to enable low electricity cooking options.

In general, the development of clean cooking policy and strategy, the inclusion of gender empowerment, development of quality standards of cooking technologies and enhancement of supply and demand, are key elements of the policies for the adoption and promotion of efficient, clean and safe electric cookstoves including the ones investigated in this study. Moreover, the experimental results of this study could be used for technology selection and promotion for any country that is looking for efficient, clean and safe cooking technology for adoption, promotion and distribution.

CHAPTER FOUR

DESIGN AND SIMULATION OF DC- MICROGRIDS

4.1. Introduction

This chapter presents the design of DC microgrids with the simulation results with the objective of ensuring a techno-economic analysis of DC for inclusive rural energy access and community service building applications. The presented microgrid design and analysis in this chapter of the thesis is for a rural primary school application. The design considers the selection of the location in Ethiopia, as well as load estimation based on high efficiency and standard efficiency appliances, as well as the renewable energy variabilities. The design and simulations were implemented using MATLAB/Simulink and the simulation results are presented from different perspectives including validation of the design and model of the proposed DC microgrid, simulation results (power flow curves) and cost analysis of the system.

The socio-economic development of any nation and its inhabitants depends on the availability of cost-effective energy supply systems to ensure the required demand (Al Mamun & Amanullah, 2018). However, the access to energy services in the developing world presents a low rate (IEA, 2020), which is aggravated by high transmission and distribution costs, weak infrastructure, poor operating and maintenance performance (Prinsloo, Mammoli, & Dobson, 2017), high greenhouse gas emissions and its associated environmental and health impacts, as well as lack of capital (UN, 2020). The impact of these problems on the balance between energy supply and demand in developing countries like Sub-Saharan Africa is huge, leading to poor living standards and a lack of human development (Roy & Kabir, 2012).

Currently, about 771 million people do not have access to electricity, with the majority of them located in rural and remote areas of developing countries, the majority of them located in Sub-Saharan Africa (IEA, 2020). Due to the remoteness and geographical location (usually far from the grid) of the rural and remote areas, connecting with the grid is expensive and difficult to achieve. The huge investment needed to connect with the grid, as well as the economic condition of developing countries and their inhabitants makes the problem more challenging (Adefarati, Bansal, & Justo, 2017). Therefore, alternative power systems such as microgrids are proposed by policymakers, researchers, governments and utility companies to supply the energy services demanded by the population sector located in rural and remote areas (Dawoud, Lin, & Okba, 2018).

Many developing countries including Sub-Saharan Africa set plans for energy access and sustainable energy development (UN, 2020), being one of the options the deployment of renewable energy resources into the grid ensuring a reduction of GHG emissions, improving the power stability and reliability, and reducing operation and maintenance costs (Boait, Advani, & Gammon, 2015). Therefore, electricity access has been improving mainly due to the deployment of distributed renewable energy resources (IEA, 2020) in locations without previous generation sources or access to the main grid (Nosratabadi, Hooshmand, & Gholipour, 2017). However, there are still many people living without access to electricity in sub-Saharan African countries, South Asia and Latin America (IRENA, 2019), which requires efficient systems to supply reliable and affordable energy services. On the other hand, due to the lack of electricity access, the level of services such as education, health, and clean water is much lower than in urban areas (Davies, Currie, & Young, 2015).

There are several studies proposing microgrids for rural electrification applications in developing countries. For example, authors in (E.Khodayar, 2017) discussed the past and current practices to improve modern energy services, as well as promoting rural electrification using microgrids in China, India, The Philippines, Africa, and North America. On the other hand, as per (Veilleux., et al., 2020), different kinds of microgrids such as AC, AC/DC, or DC are studied for rural electrification applications. Authors in (T.Adefarati, 2019) presented the reliability, economic and environmental analysis of a microgrid composed of diesel generator, PV system, wind and battery.

In another study authors by (Eunice C.Nnaji, 2019) assessed the model and management of a smart microgrid model consisting of a solar photovoltaic array, battery energy storage and a diesel generator for rural electrification in Nigeria. On the other hand, DC microgrids are also studied for rural electrification applications. For instance, authors in (Kitson, et al., 2018) assessed a DC microgrid consisting of solar PV, wind power and a battery for rural communities in Ruksibhanjyang village, Mityal, Nepal. The study used Hybrid Optimization of Multiple Energy Resources (HOMER) and MATLAB-Simulink for the design and modeling of the proposed DC microgrid.

A study by (Chauhan, Chauhan, Subrahmanyam, Singh, & Garg, 2020) also presented the design and model of a DC microgrid consisting of solar PV and battery banks for residential buildings. The authors considered distributed and centralized DC microgrids to supply loads of the five houses with a centralized battery bank system. For the case of the distributed systems, the DC microgrid is designed to supply loads of the houses independently which is the houses have rooftop mounted solar PV and battery bank. In the case of the centralized system, the centralized battery bank system is responsible for the demand when there is a shortage of power generation and to store the power when there is surplus generation. The authors in Ref. (Jafari, Derakhshandeh, Baharizadeh, & Fadaei, 2015; M. Nasir H. A., 2018) also presented the design and analysis of DC microgrids for rural electrification.

Furthermore, a study by (Saha, Bhattacharjee, Elangovan, & Arunkumar, 2017) assessed the electricity needs of one school and presented the design requirements for an AC/DC hybrid system and AC microgrid composed of a solar PV and battery storage system for a microgrid in a rural area of Malawi. These previous studies indicate that microgrids with several renewable energy sources are studied widely for rural electrification applications. However, there are still questions that should be addressed on the selection of off-grid systems and options for inclusive energy access applications due to the diversity of off-grid technologies and systems, as well as the variability of renewable energy sources and variety of commercially available appliances. Furthermore, this thesis addresses the large impact of high-efficient DC appliances on the system’s overall feasibility and performance, as well as on the sizing of off-grid solutions, which is a limitation in other previous studies.

4.2. Literature Review of Related Works

Worldwide, nearly 660 million children are enrolled in primary schools and about 188 million children (about one-third) attend primary schools that do not have electricity access. Data suggests that in sub-Saharan Africa approximately 90% of children go to primary schools without electricity (UNDESA, 2014). To address energy access problems in rural areas of developing countries, minigrids/microgrids, and mainly DC microgrids are becoming one of the most efficient and reliable solutions (Van Gevelt, et al., 2018) to solve the energy access problems in rural schools. Due to the absence of reactive power in DC distribution lines and the reduction of conversion steps, DC-microgrids can be more advantageous than AC-microgrids in terms of reduction of losses and voltage drops and can increase the capacity of the electrical lines. Additionally, the development of DC-based household and office appliances, as well as the fact that energy storage and renewable generation technologies are directly compatible with DC microgrids, facilitates the introduction of DC microgrids.

Therefore, planning, implementation and operation can be simpler and cheaper with DC-microgrids than AC-microgrids (Estefanía Planas, 2015; SEforALL, 2020; Aemro, Moura, & de Almeida, 2018). The advantages of DC microgrids over AC microgrids are the main criteria to focus this study on DC microgrids for rural school applications. Furthermore, the development of a draft standard for DC-microgrids for rural and remote electricity access applications from different perspectives including design, operation and maintenance, market needs, technical aspects and testing procedures (Decuir & Michaei, 2020). This standard development will make DC microgrids more effective and efficient, as well as a widely accepted system for rural electrification and to electrify rural schools, health centers and other service centers than the conventional microgrid system.

In Ethiopia (the second-most populous country in sub-Saharan African), above 80% of the population is living in rural and remote areas (WorldBank, ETHIOPIA|Beyond Connections: Energy Access Diagnostic Report Based on the Multi-Tier Framework. 2018. Available the Multi-Tier Framework, 2018) and 76% of the primary schools do not have access to electricity (MWIE, 2020). Access to electricity in schools is crucial to improve the quality of schools by providing electricity for electricity-dependent materials and equipment, by increasing the number of hours of classes and by improving the quality of training (IEG, 2008). On the other hand, electricity access increases teaching hours by allowing to have class in the early morning and late afternoon when the rooms do not have access to natural light (UNDESA, 2014). It is also important to ensure make-up classes in places that do not have enough staff to cover the courses with the available teachers. For example, in Kenya, electricity access gives the possibility for teachers to give make-up classes in the early morning and late evenings for courses that are not covered in normal teaching hours due to the lack of teachers (Tanzsolar, 2012). Furthermore, electrifying schools is important to attract teaching staff in quantity and quality. In most rural areas, attracting quality teaching staff is a great concern due to electricity access in the school as well as in the surrounding.

A study in Ghana presents that teachers' living condition including having electricity access in their house affects the morale and absenteeism of teachers (MWIE, 2020). In Tanzania, Mara region (a rural area), teachers housed in the school with no access to electricity even to charge their mobile phones, implying that the lack of qualified teachers is attributed to lack of energy services in remote locations (Diniz, Franca, Camara, Morais, & Vilhena, 2006). Additionally, a microgrid deployed in a school can give multiple benefits to the nearby community. It can promote healthcare services, pump and purify water for drinking, sanitation, reduce rural/urban migration, prepare and preserve food and medical supplies, as well as air conditioning (Welland, 2017). For instance, in Brazil and Kenya, electrification of schools, solve water and sanitation issues, which in turn may help to reduce absenteeism and even aid the wider community (Kammen & Mills, 2009). This work presents and proposes the model, design, and simulation of a DC microgrid system using MATLAB/Simulink composed of solar energy and battery storage for a rural school located in Ethiopia, considering different generation and load scenarios by considering the use of standard and high-efficiency appliances.

Due to the variability of available renewable energy sources throughout the year and the commercial availability of different appliances, there are still ambiguities on off-grid system preferences, as well as on the selection of appliances with different efficiency levels for diverse applications, as well as on the system sizing. On the other hand, there is also limited literature on the electrification of off-grid schools. To address this knowledge gap and contribute to the literature in the area of the energy supply system of off-grid schools, this work proposes the design and modeling of a DC-microgrid for off-grid schools' application, based on different load estimation and generation scenarios. The main objective of this work is to design and model a standalone DC microgrid composed of a solar PV system, system controller and battery storage system using MATLAB/Simulink for rural off-grid energy-efficient school applications. In many studies (Ghenai & Bettayeb, 2020; Ssennoga & Makbul, 2018) of off-grid solutions for rural energy access HOMER and other mathematical models are used as design and optimization tools. In this study, MATLAB/Simulink is used due to its higher flexibility compared with HOMER. It has the advantage of to easily modify the system and optimization rules depending on the analysis outputs and optimizations needs, whereas in HOMER it is not possible to change the design and the model except the inputs such as load demand and energy sources, as well as optimal cost for each energy sources. On the other hand, the chosen modeling and optimization tool for this study allows the assessment of data, development of algorithms, and models. Furthermore, it has also the potential to integrate the system with the grid with some modification of the layout or expand the system to electrify the community by increasing the PV size and the battery storage system size.

A case study for a rural primary school in Ethiopia is considered and one main innovation of the study is the consideration of high-efficiency DC appliances and comparing them with the standard efficiency appliances, the associated load estimations, as well as considering the variability of renewable generation. The load estimation scenarios are based on standard efficiency (appliances widely available in the market) and high-efficient appliances (emerging off-grid appliances with high efficiency compared with the standard appliances available in the market) necessary for the school. The appliances are categorized as high and standard efficiency based on the data platform for off-grid appliances developed by the Efficiency for Access Coalition (EforA, 2020), which compared the efficiency of different appliances by grouping the standard efficient appliances as a baseline, which are widely available in the market, and the emerging off-grid appliances with efficiency, quality, durability improvements as high-efficiency appliances. For instance, for table fans, the high-efficiency group has efficiency up to four times the volume of air per minute per Watt of input power compared to the standard efficiency fans (Lai, Muir, & Erboy Ruff, 2020; de Almeida, Moura, & Quaresma, 2020). Whereas the generation scenarios consider the maximum and minimum solar generation months in the year, which is very critical for the sizing of the proposed off-grid system. Moreover, the efficiency of appliances and variability of generation is vital to the system sizing, in order to avoid oversizing the proposed DC microgrid, with the consequent higher system cost (solar PV, battery and controllers). On the other hand, oversizing also requires larger areas for installation and implementation of the system, which could be a problem in areas where space is limited. Therefore, analyzing the impact of appliances with different efficiency levels is one important aspect that should be addressed in the design and development of off-grid systems which is one of the many objectives of this study. Furthermore, by assessing the cost of the appliances and the overall system cost, the study aims to present the economic feasibility of the proposed off-grid system for rural school applications in developing countries.

4.3. Background and Load Estimation

4.3.1. School Data

Gomenege Primary School is a government-owned primary school located in Tachi-Gayint Worda, Amhara Region, Ethiopia with coordinates 11°38′20.4″ N 38°25′13.5″ E. Figure 51 presents the rural primary school with primary school children's in the class attending courses and Gomenege primary school location on the map. The school has more than 450 students, from grade 1 up to 8 with two shifts, one from 8 h to 13 h and the other from 13 h to 18 h. Sometimes, there are also classes from 18 h to 20 h. The school has 8 classrooms, one director's office, two staff offices, and one office for security. There is a great interest to perform the teaching-learning process through electronic media such as TVs, radio and basic computer skills classes and computer-aided course deliveries. Therefore, to improve the education system based on the global standard of primary schools, a DC microgrid system is proposed.

Figure 51 Rural primary school with primary school students in the classroom located in Ethiopia: (a) Rural primary school in Ethiopia; (b) Gomenege Primary School location.

4.3.2. Load Estimation

Load estimation is a crucial part of designing any kind of power system. In particular, it is important for off-grid distributed renewable energy systems, such as DC microgrids, due to the intermittency of renewable energy resources. On the other hand, the type of used appliances also determines the required load, and therefore the microgrid sizing and associated costs. For this study, the load was estimated using two scenarios, a first scenario using standard appliances and a second using high-efficiency appliances.

The common loads in most primary schools are lighting, computers, wireless internet, printers, photocopy machines, radio, table fans and ceiling fans (in hot seasons of the year), and mobile chargers. Table 10 presents the load estimation of the school considering appliances with standard efficiency and Table 11 presents the load estimation of the school considering high efficient appliances, as compared to the appliances listed in Table 10.

Table 10 Energy consumption of the school considering appliances with standard efficiency (Tembo & Mafuta, 2015; SolarDevelopmentPLC, 2019; Corporation, 2019; DssW, 2019).

Appliances/Services		**Specification**	**Power (W)**	**Average Use Time (h/day)**	**Energy Consumption (Wh/day)**
Lighting/CFL Lamps	Classrooms	11 W × 16	176	3	528
	Staff office	9 W × 4	36	10	360
	Director office	9 W × 1	9	10	90
	Security office	9 W × 1	9	8	72
	Outside	11 W × 3	33	8	264
Computers		200 W × 7	1400	10	14,000
Printer		360 W ×1	360	1	360
Photocopy		1000 W ×1	1000	2	2000
Fan	Ceiling fan	35 W × 8	280	3	840
	Table Fan	30 W × 4	120	3	360
Radio receiver		5 W × 1	5	3	15
Mobile Charging		3 W × 4	12	4	48
GSM wireless Tel		2 W × 4	8	8	64
Total Power consumption			3448		19,000

Table 11 Energy consumption of the school considering high-efficient appliances as compared to appliances with standard efficiency (Tembo & Mafuta, 2015; SolarDevelopmentPLC, 2019; Corporation, 2019; DssW, 2019).

Appliances/Services		Specification	Power (W)	Average Use Time (h/day)	Energy Consumption (Wh/day)
Lighting/LED Lamps	Classrooms	5 W × 16	80	3	240
	Staff office	3 W × 4	12	10	120
	Director office	3 W × 1	3	10	30
	Security office	3 W × 1	3	8	24
	Outside	5 W × 3	15	8	120
Computers		100 W × 7	700	10	7,000
Printer		150 W ×1	150	1	150
Photocopy		250 W ×1	250	2	500
Fan	Ceiling fan	25 W × 8	200	3	600
	Table Fan	12 W × 4	48	3	144
Radio receiver		5 W × 1	5	3	15
Mobile Charging		3 W × 4	12	4	48
GSM wireless Tel		2 W × 4	8	8	64
Total Power consumption			1,486		9,055

The load estimation was done taking into account three computers in each of the staff offices and one computer in the director's office, two lighting lamps in each classroom, one printer and one copy machine in the director's office, three lamps in the compound of the school outside the classrooms, one lamp in each director and security office, four table fans in each office (director, staff, and security), one ceiling fan for each class. Based on the classroom and office sizes, the type of lamps with their power capacity was selected, for instance, the size of classrooms is much larger than the size of offices requiring lamps with higher power capacity. In the case of mobile charging, radio receiver and GSM wireless telecommunication the same power capacity is considered for each appliance in both scenarios. The ceiling and table fans were selected from a recent report by Global LEAP Awards (Awards, 2019; Awards;2017).

Figure 52 presents the considered power consumption of the school over 24h, based on the load estimations in Table 10 and Table 11. The loads are distributed based on the hours of the day when the appliances are used, which is for computers from 8h to 18h, for classroom lighting from 18h to 21h (in case there are some classes given at night), and for other services such as photocopy, printer the load is distributed from 11h to 17h. The load follows the same profile for every working day over the year when the school is working, and it is changing every hour depending on the working time of the appliances as presented in Figure 52. The presented load profiles are aligned with the typical primary school consumption pattern in rural and remote locations of Ethiopia and other developing countries like India over a day (Abhi Chatterjee, 2019). As presented in the above tables, the estimated power over one day in the school gives a total energy consumption of 19 kWh for appliances with standard efficiency and 9 kWh for high-efficiency appliances. The estimation of energy consumption using less efficient appliances is more than double when compared to the highly efficient appliances scenarios. The peak loads are 2.47 kW for standard efficiency appliances and 1 kW for high-efficient appliances.

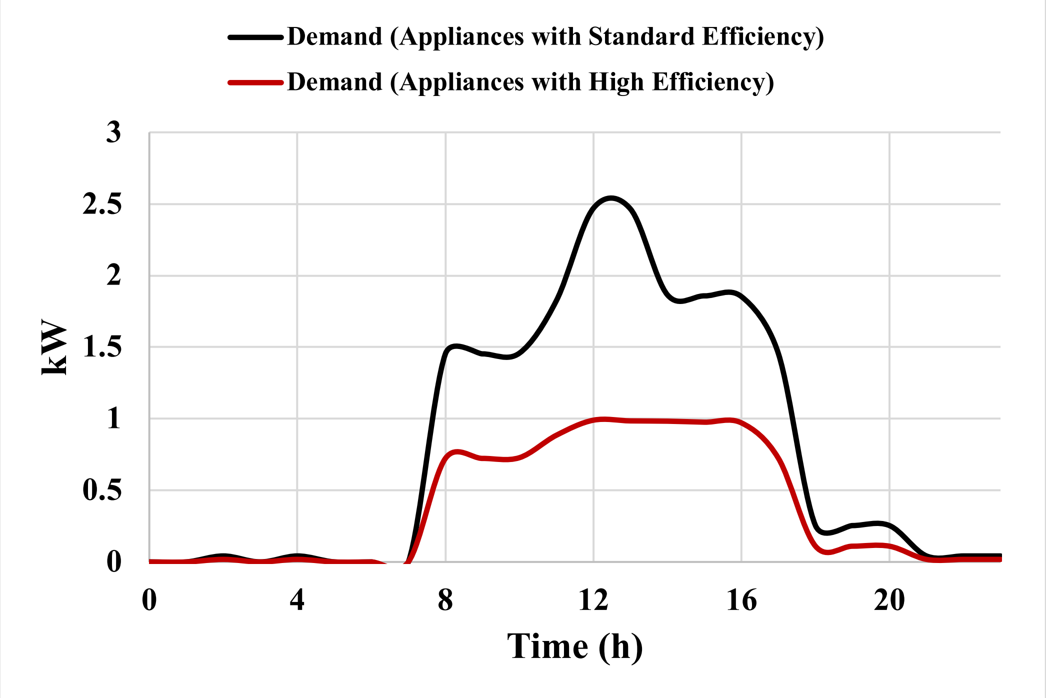


Figure 52 Daily Load Profile of the school with high and standard efficient appliances.

4.4. Design and Model of DC Microgrid

The proposed DC-microgrid is composed of solar photovoltaic (PV) panels, a control system and a battery storage system. The main purpose of this research work is to design, model and simulate the DC-microgrid that serves Gomenege Primary School. Such a model can then be used for other primary schools located in rural areas of Ethiopia and other countries in Sub-Saharan Africa which do not have access to electricity. The renewable energy potential analysis, the mathematical model of the solar

PV, the mathematical model of the battery storage system and the system model and design of the proposed DC microgrid are presented in the following subsections of the work.

4.4.1. PV Power System

Solar PV is selected as the main energy source for the proposed system because of its availability, technical and economic aspects. Compared with wind energy (which is about 3 m/s measured at 10 m height above ground (World Bank, 2016), solar energy availability (with average solar radiation of 6.09 kWh/m2/day) at the school location and the lower capital cost makes it the best option. However other sources can be used as input considering the necessary modification. If the source is DC-based the proposed system will work with no need for modification or addition of other components. If the source is AC based, it may need additional power electronics components to convert AC to DC. The solar energy potential of the location and the clearness index are presented in Figure 53, being such data generated from the nearby location of the school site from the National Renewable Energy Laboratory (NREL) using Pvwatts calculator (Bekele & Tadesse, 2012). The average daily solar radiation profile of the school site generated at a 10° tilt angle is presented in Figure 6. The used tilt angle value is the optimum angle to ensure the maximum possible annual PV generation for the school site considering the latitude of the site i.e., 11.4°. As shown in Figure 53 the minimum daily solar radiation is 4.96 kWh/m2/day in August and the maximum is 6.84 kWh/m2/day in March. The annual daily average solar radiation of the school site (6.09 kWh/m2/day) is higher than the annual national daily average solar radiation of Ethiopia which is about 5.5 kWh/m2/day (Kebede & Beyene, 2018). On the other hand, schools have activities from mid-September to mid-June, and therefore the lowest solar radiation is in July and August will not have an impact on the power generation to supply the school demand. Furthermore, from September to June the daily radiation variation in each month is very low, which implies that solar photovoltaic energy is the ideal source to supply the power demand of the school.

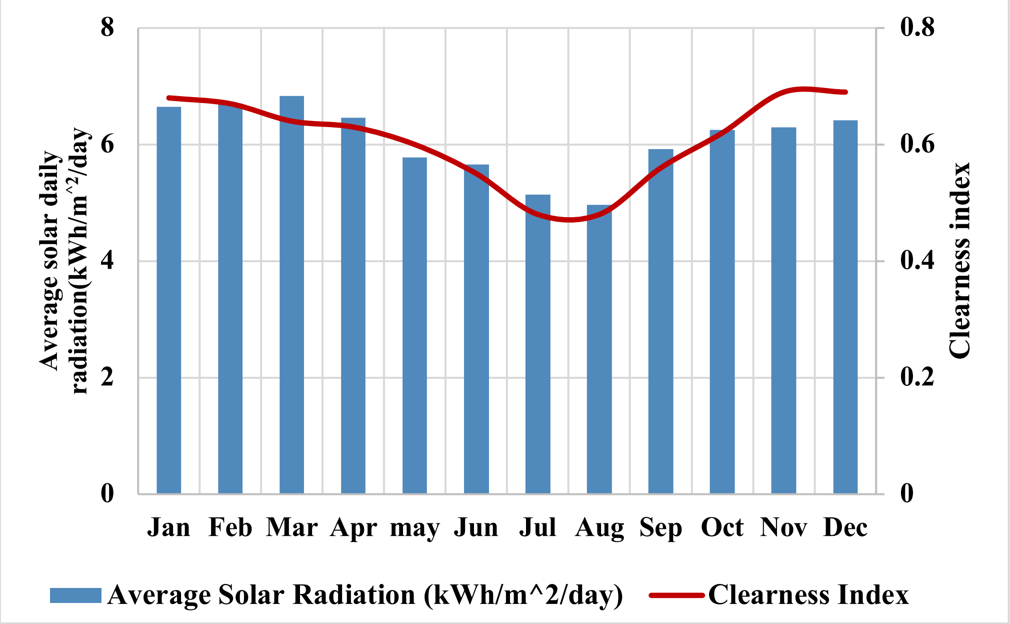


Figure 53 Average daily solar radiation of the school site in each month in 2018.

Due to the variability of solar radiation, the study considers maximum and minimum average solar irradiation days. The days are selected based on the daily average solar radiation in relation to the average daily solar radiation of the month, i.e., the days with solar radiation values closer to the daily average solar radiation. Figure 54 presents the solar irradiation profile for the selected days, which are 9 March and 22 June of the year are the ones that have maximum and minimum solar radiation days close to the average daily radiation of the year. The study considered for the generation and the battery sizing three days of full autonomy (which corresponds to more than three days with thick clouds, which usually does not happen).

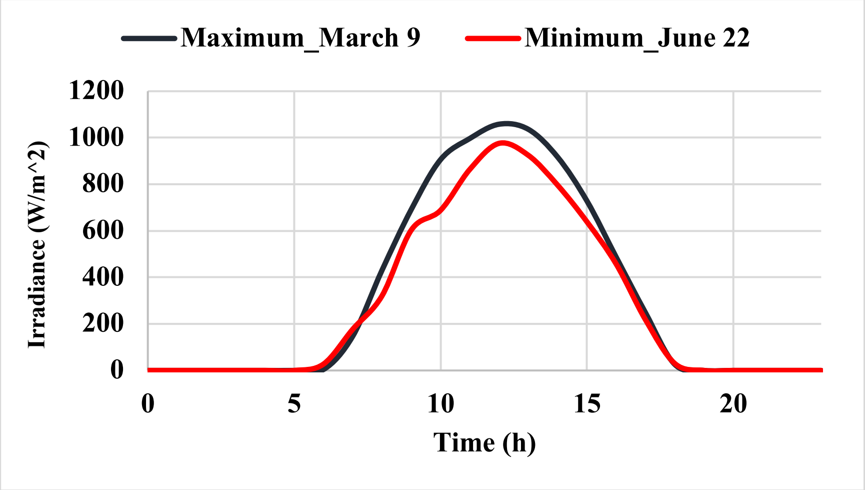


Figure 54 Solar irradiance of maximum and minimum irradiance days.

The total output power of the PV system at time t can be expressed by Equation (3) (Bekele & Tadesse, 2012). Where N_{pv} is the number of PV panels, A_{pv} is the area of the PV module (m^2), I_{pv} is the solar irradiation incident on the PV system (kWh/m^2), η_{pv} is the efficiency of the PV system and $P_{pv}(t)$ is the total power generated by the PV system:

$$P_{pv}(t) = N_{pv} \times A_{pv} \times I_{pv} \times \eta_{pv} \tag{3}$$

The PV system capacity is determined by considering the variation of the solar radiation during the day, the estimated load for both scenarios and the overall system efficiency. There are losses due to charging and discharging of the battery, Joule losses in the cable, but since the proposed system is a DC microgrid which is more efficient than the conventional microgrids, a 90% overall system efficiency is considered (Sirsi & Ambekar, 2015). On the other hand, inserting and testing different capacity values of the PV in PVwatts calculator were considered until the anticipated PV generation profile (which is able to supply the demand) resulted in assuming the tilt angle of the location, the nearby location of the site and systems losses. Based on the given conditions, the PV systems were sized at 3.7 kWp and 1.8 kWp for the load estimation using appliances with standard and high-efficiency appliances, respectively.

Considering the resulting PV capacity, the generated energy for the maximum generation scenario for both load estimation cases is 23.66 kWh (standard efficiency) and 11.21 kWh (high efficiency). Whereas for the minimum generation scenario the generated energy for standard and high-efficiency load estimation cases is 19.59 kWh and 9.53 kWh, respectively. The generated energy is higher than the estimated energy demand for the school load which is 19 kWh (standard efficiency) and 9.1 kWh (high efficiency). This implies that the sized PV system can supply the school energy demand and losses for a full day even without the need for stored energy. Figure 55 presents the demand and PV generation (maximum and minimum) profile for each load estimation scenario over 24 h.

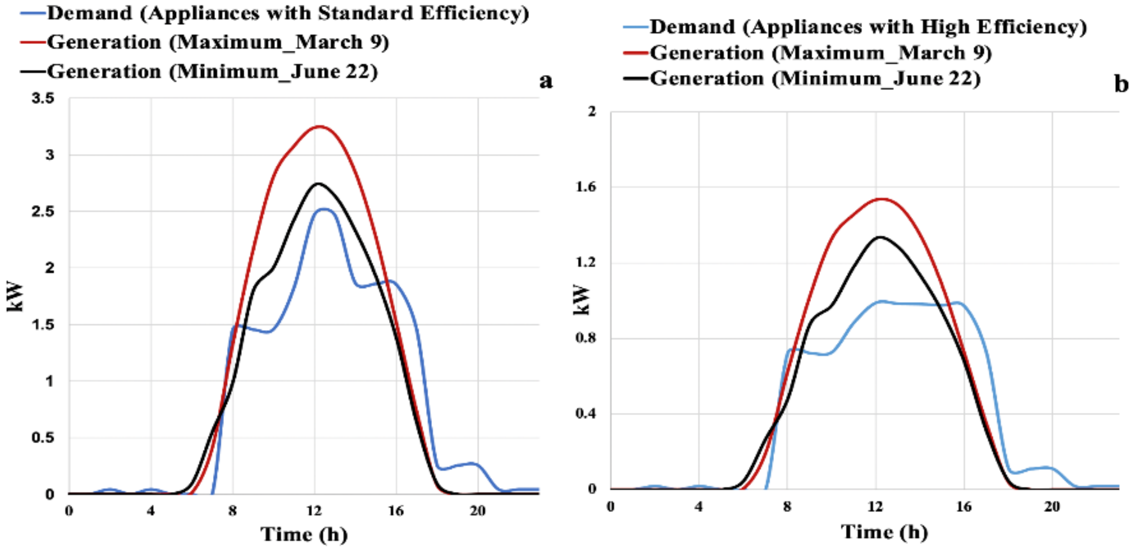


Figure 55 Demand and generation under different load estimation scenarios: (a) demand and generation (maximum and minimum) for standard efficiency; (b) demand and generation (maximum and minimum) for high efficiency.

4.4.2. Battery Storage System

Since renewable energy resources are intermittent, a battery storage system is necessary to compensate for the periods with low or no generation of solar energy. The battery storage system is utilized together with solar PV systems to reduce the uncertainty that is associated with the local availability of renewable energy sources (Battke & Schmidt, 2015). During the period of lack of enough generation and at the peak periods the stored energy in the battery system can be utilized to supply the required power (Adefarati & Bansal, 2017). The battery storage system will level out the impacts of power fluctuation of the available renewable energy sources where the microgrids' power systems are installed, and it will enhance its reliability and stability. The efficiency and performance of the battery depend on ambient temperature, state of charge, voltage effects, rate of charging and discharging. These factors also determine the lifespan of the battery. On the other hand, the impact of these factors depends on the type of battery used. In this study lithium-ion batteries are used considering their lifetime cost, high-efficiency advantages over other types of batteries.

As per Ref. (Adefarati, Bansal, & Justo, 2017), the battery should not be overcharged to be durable, because overcharging will affect the efficiency and the lifespan of the battery. Similarly, the battery must not be over-discharged because over-discharging will reduce the lifetime of the battery. The maximum State of Charge (*SoC*) of the battery should be set to its nominal capacity, which is a basic requirement for the durability of the battery. Besides this, the minimum *SoC* of the battery should not be less than 20%, being the SoC of the battery bank at a given time t expressed by Equation (4) (Das, Al-Abdeli, & Kothapalli, 2017):

$$SoC\ (t) = \ SOC(t-1) + \frac{P_i\ (t)\ \times\ \Delta t}{1000 \times C_b} \tag{4}$$

where $P_i\ (t)$ is the power flow towards the battery, Δt is the simulation time and C_b is the nominal capacity of the battery.

The battery bank usually operates between the maximum and minimum capacity of the battery, which means it is limited within the maximum and minimum allowable capacity. Mathematically it can be represented by Equations (5) and (6) (Adefarati & Bansal, 2017):

$$\mathrm{SoC}^{min} = (1 - DoD)\mathrm{SoC}^{max} \tag{5}$$

$$\mathrm{SoC}^{min} \leq SoC(t) \leq \mathrm{SoC}^{max} \tag{6}$$

where $\mathrm{SoC}^{\mathrm{min}}$ is the minimum allowable capacity of the battery, SoC^{max} is the maximum allowable capacity of the battery, and DoD is the depth of charge of the battery. The sizing of the battery bank can be calculated using Equation (7) (Pogaku, Prodanovic, & Green, 2007):

$$C_{BB} = \frac{E_d\ x\ T_{out}}{B_{eff}\ x\ Do.D} \tag{7}$$

where C_{BB} is the size of the battery bank in Wh (Watt-hours), E_d is the daily energy demand, T_{out} is days of autonomy which is days which can supply the load using the battery in case some faults occur in the PV panel for maintenance and/or rainy/cloudy days), B_{eff} the battery efficiency (the ratio of the energy out from the battery to the energy supply to the battery by the system) and DoD is the depth of discharge.

For the sizing of the battery storage system, the daily energy demand for the estimated load is 19 kWh for appliances with standard efficiency and 9.1 kWh for appliances with high efficiency. The considered days of full autonomy were 3 days (in case some faults occur in the PV panel for maintenance and/or several rainy/very cloudy days). For the assumption, the average daily radiation in June was considered, since it has minimum daily radiation as compared to the other months in the period when classes are given. For the battery and system controller, it was considered an efficiency of 90% and a depth of discharge of 80% (Ramli, Bouchekara, & Alghamdi, 2018). As a result, the battery is sized to 80 kWh and 38 kWh for appliances with standard and high efficiency, respectively.

4.4.3. System Modeling and Design

Figure 56 presents a typical schematic design of a DC microgrid containing a solar panel and battery storage system. It also contains the solar charger and load controllers/DC-DC converter, which controls the voltage coming from the solar panel and the battery as well as going to the battery to charge it and to the load. Compared with the conventional AC microgrids, DC microgrids have a simplified schematic design since they do not require many power electronics like inverters to convert the DC current to AC current or vice-versa. Moreover, the absence of many power electronics in the system makes the system more efficient by avoiding power losses and more reliable. Furthermore, it has the potential to be integrated with the grid with the addition of power electronics to link with it. Additionally, the application range is not only specified for schools rather it can be used for large community energy needs and other service centers including health centers and refugee camps.

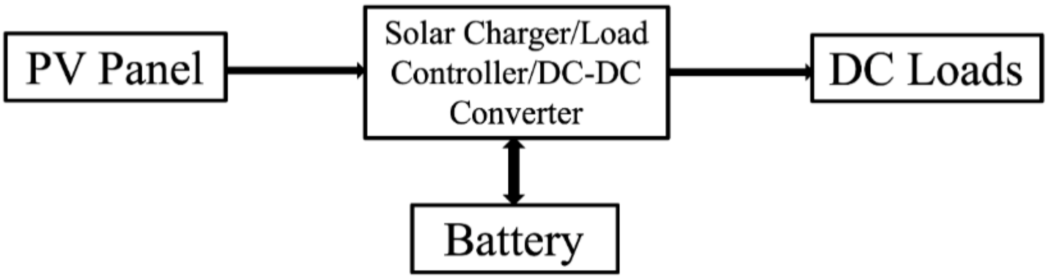
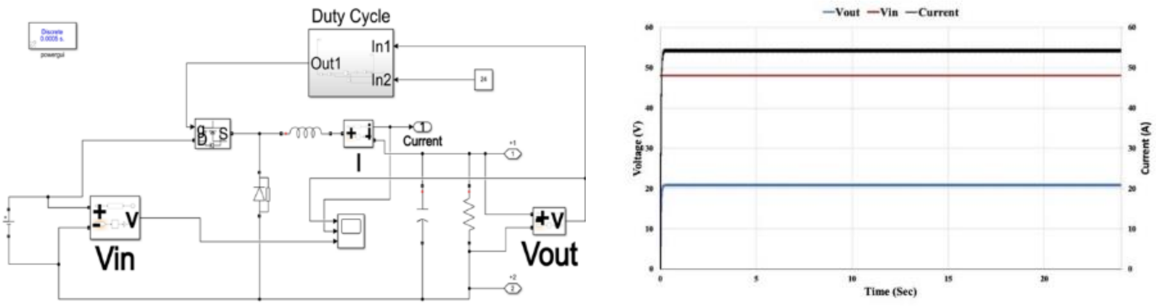


Figure 56 Schematic design of DC Microgrid composed of Solar PV, System Controller and Battery.

The proposed DC microgrid includes a PV system, DC-DC converter, and a battery and was modeled using MATLAB/Simulink. The DC-DC converters are used in conjunction with the PV system and the battery to control the power flow, as well as stabilize the voltage and generate maximum power. The type of DC-DC converter used in this system is a DC-DC buck converter, which reduces the input voltage since the voltage of most of the appliances and the battery is about 24 V and it is necessary to control the voltage coming from the PV system. Figure 57 presents the DC-DC buck converter modeled in MATLAB/Simulink and the simulation output of the converter. The simulation output indicates that the designed DC-DC buck convertor controls and reduces the input voltage from 48 V (assuming that the nominal voltage of the PV system is 48 V) to about 22 V, implying that the selected appliances are working in the range of 12–24 V.



(**a**) DC-DC Buck Converter Design in MATLAB/Simulink

(**b**) Simulation output

Figure 57 Design and simulation output of DC-DC buck converter design in MATLAB/Simulink: (a) DC-DC buck converter design and (b) simulation output.

Figure 58 presents the design of the proposed DC microgrid system with the PV system, battery and DC-DC buck converter which is connected with the loads. The battery controlling strategy which is encircled by red is also presented. The loads are connected with the supply system in a distributed mood over 24h. The PV system is connected with the DC-DC buck convertor and the DC-DC buck converter is also connected with the battery and with the loads.

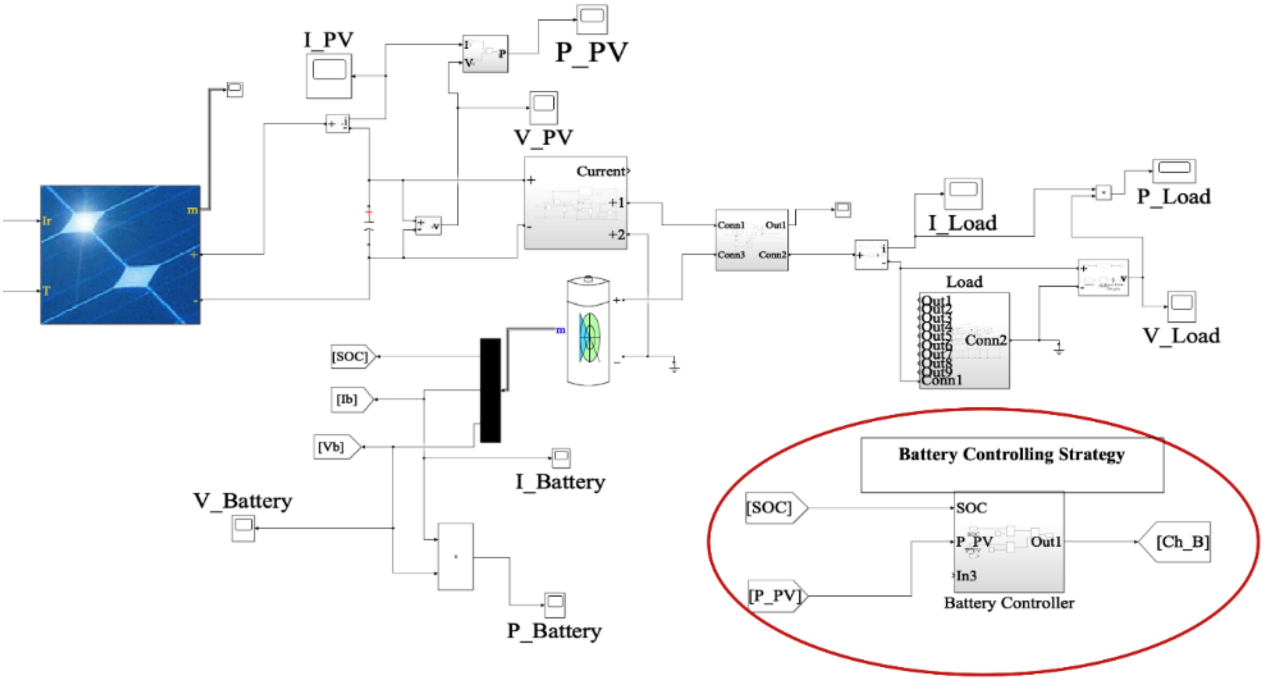


Figure 58 DC microgrid design using MATLAB/Simulink.

Figure 59 indicates the charge controller strategy in the developed DC microgrid (Figure 58). Most batteries are designed to operate in the state of charge range of 20–90%. Therefore, the strategy in the controller will check if the batteries are in the range of 20–90%. Besides that, the battery controller is depending on the power generation and load demand. If the power generated is higher than the required load power and the battery is at a low SoC below 90% the battery will be charged. However, if the load power is higher than the generated power load shedding should be taken into consideration to protect the safety of the battery. Similarly, if the generated power is greater than the power load and SoC is in the range of 20% to 90% the battery will be charged unless the battery should be discharged. The other scenario is if the SoC is higher than 90% up to a maximum of 100%, as well as if the DC microgrid generates power more than the required demand the current will be sent to a dump load (in the system controller) to avoid overcharging and prevent DC bus voltage increasing unless the battery will be discharged to supply power to the load.

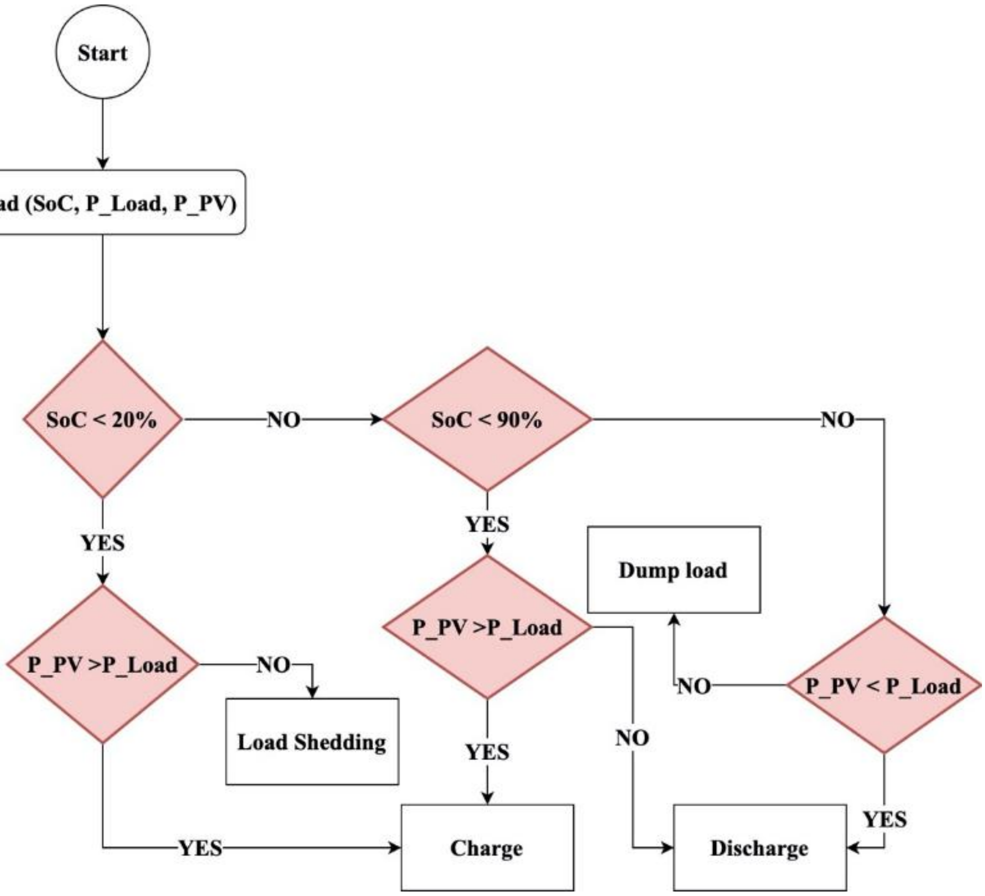


Figure 59 Battery controlling strategy.

4.5. Results

4.5.1. Validation of MATLAB/Simulink Model

The designed DC microgrid using MATLAB/Simulink was simulated for each load estimation and generation scenarios. The objective of this simulation was to validate whether the designed DC-microgrid is reliable or not. Figure 60 presents the voltage and current simulation outputs for standard efficiency appliances. The voltage curves indicate that it gives an output of around 24 V with about 2 V variation for the load and the battery which is the expected value provided that the appliances and battery voltages are set at 24 V for the design. Furthermore, the load current simulation result shows the same profile as the load profile and when there is less or no PV generation, i.e., from late afternoon to sunrise and early mornings, the battery supplies the load. On the other hand, it presents high variation due to the load being distributed as presented in the load profile curve (Figure 52) and the loads are connected in parallel. As the load increases the current increases and as the load decreases the current is also decreasing. The variations between the loads, battery and PV voltages would be different and higher if the selected microgrid was an AC microgrid. In other words, the losses would be higher, since it requires power electronic devices to ensure AC to DC power conversion, implying that the resulted voltage and current simulation outputs would be different from the presented ones if the assumptions were the same. Therefore, the results demonstrate that the designed DC Microgrid is suitable to supply the school demand under the presented load and generation variabilities. Moreover, it demonstrated the validation of the designed DC-microgrid under the given conditions to be used as a system for the school.

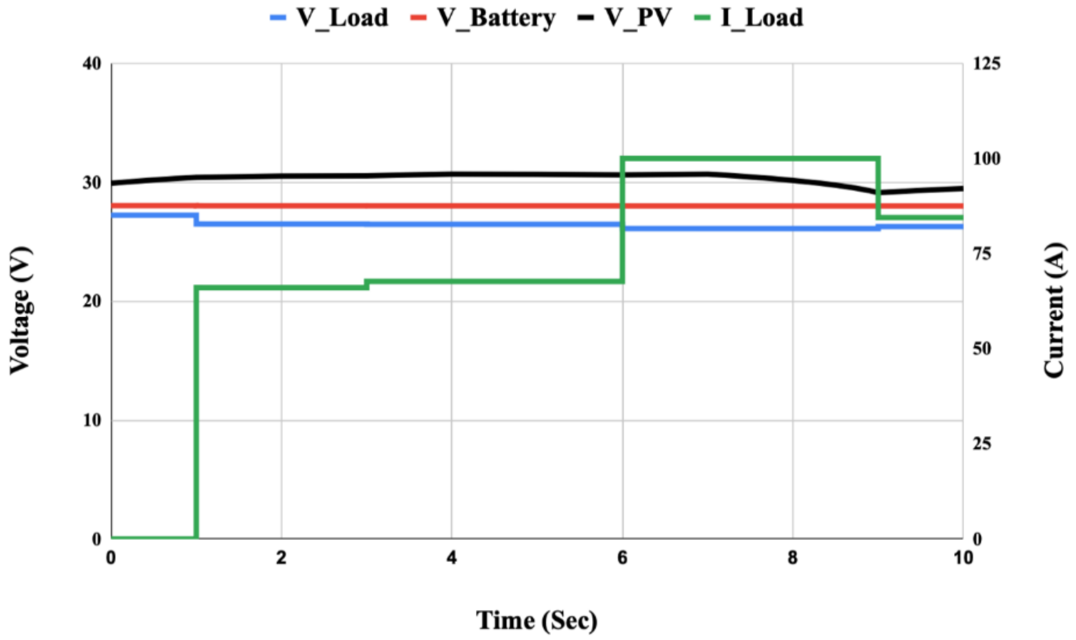
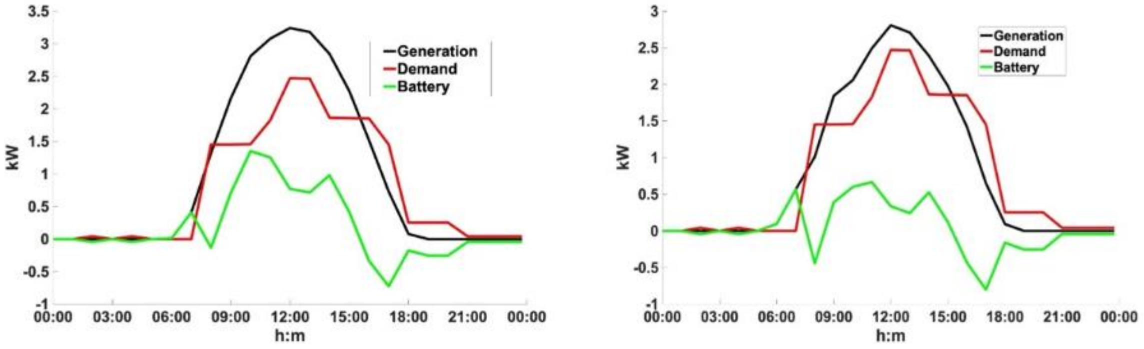


Figure 60 Voltage and current simulation outputs for load under standard efficiency appliances.

4.5.2. Simulation

The simulation was done considering the minimum and maximum generation days for 24 h in order to evaluate the power flows of the PV system, demand and the battery. The anticipated results are when there is a much higher generation than the load demand, the PV system will supply the load and will charge the battery provided that if the battery needs to be charged. Whereas, when there is a lower generation the battery will discharge and supply power to the load. This implies that the sum of the demand and the battery power and losses will be equal to the generation.

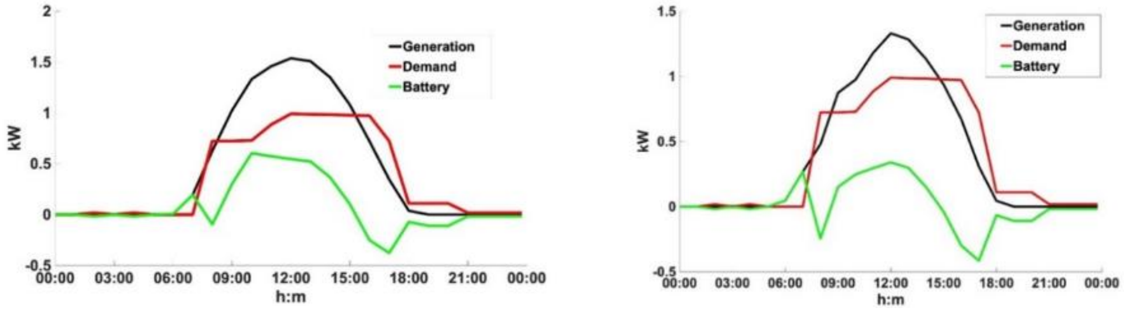
Figure 61 and Figure 62 present the power flows of the load, PV system and battery for the standard and high-efficiency appliances under maximum generation and minimum generation scenarios, respectively. The simulation output shows that the model gives the anticipated result in both load estimation scenarios which is when there is enough generation to supply the demand the load gets power from the PV system and the battery charges as well as when there is less generation to supply the demand the battery supplies power to the load.



(**a**) Under maximum Generation

(**b**) Under minimum Generation

Figure 61 Power flow for generation, demand and battery under Standard efficiency in the case of maximum and minimum generation: (a) under maximum generation; (b) under minimum generation.



(**a**) Under maximum Generation

(**b**) Under minimum Generation

Figure 62 Power flow for generation, demand and battery under high efficiency in the case of maximum and minimum generation: (a) under maximum generation; (b) under minimum generation.

Table 12 presents the generated, consumed and stored energy for both load estimation and generation scenarios. It shows that the generated energy is enough to supply the demand and also the surplus generation is stored in the battery. For instance, under the maximum generation scenario and standard efficiency load estimation, the generated energy is 23.66 kWh, and the consumed energy is 19 kWh. The stored energy which is the initial energy in the battery (50% of the battery capacity for each load scenario) plus the total energy entering the battery is 46.61 kWh. Considering a 10% loss in the periods of charging and discharging of the battery, as well as system losses, the total stored energy at the end of the day is 41.95 kWh.

Table 12 Generated, consumed and stored energy for both generation and load estimation scenarios.

Generation Scenario	**Standard Efficiency**		
	Generated Energy (kWh)	**Consumed Energy (kWh)**	**Δ Stored Energy (kWh)**
Maximum	23.66	19	1.95
Minimum	19.69	19	−0.89
High Efficiency			
Maximum	11.21	9.1	0.89
Minimum	9.53	9.1	−0.32

Although the power flow profile is the same, the charging and discharging of the battery depends on the generation. In each generation scenario the battery initial capacity is the same meaning under the same load and different generation days the used initial capacity of the battery is the same based on the sizing of the battery made in Section 4.4.2. For both load estimation scenarios under maximum and minimum generation scenarios the battery charging and discharging rate are different. For instance, as shown in Figure 61 and Figure 62, the power supplied to the load from the battery for the standard efficiency load scenario at 8:00 h is −0.13 kW for the maximum generation scenario and −0.44 kW for the minimum generation scenario. At the peak demand, which is 2.47 kW, the power entering into the battery is 0.77 kW (maximum generation) and 0.34 kW (minimum generation). This implies that the battery is charging at a low rate at a lower generation level as compared to charging at a higher generation meaning the load gets more power from the battery. The discharging is also the same, at the maximum generation scenario the battery is discharging at a lower rate, and at the minimum generation scenario, it discharges at a faster rate.

The result demonstrates that in both generation and load estimation scenarios the sizing of the battery and the PV system is able to supply the load in periods of low generation for the considered days of autonomy. However, the low stored energy results for each scenario indicates that in case of bad weather conditions, such as continuous rain and cloudy weather, different sizing of the battery and PV system may be necessary, depending on worst-case conditions (e.g., the maximum number of days with very small solar radiation).

Comparing it with AC microgrids which require more components, the results obtained in this study are different. Because of the required inverters, there will be additional power losses that lead to a different PV and battery sizing to balance the supply and the demand. This implies that, if the same generation and load estimation scenarios are considered and the system is supposed to be an AC microgrid, the sizing of the battery and the PV system could not supply the load especially in periods of low or no generation for the considered days of autonomy. Therefore, the results presented in Table 1, could be much lower if the same PV and battery sizing are considered. Studies show that DC microgrids are 6–8% more efficient than AC microgrids (Fregosi, et al., 2015), implying that to supply the load estimated in this study, a PV generation higher than the presented generation by 6–8% is required. On the other hand, for lower load demands like the system investigated in this study, DC microgrids are more suited from different perspectives including efficiency, power balance, power quality and cost (SEforALL, 2020).

4.5.3. Cost Analysis

According to IRENA and BNEF, the average cost of a PV system in Africa ranges from US $1.2 to US $4.9/W (IRENA, 2016) and the average cost of lithium-ion batteries is about US $350/kWh (Lockhart, et al., 2019). Considering the fall of the PV cost in the last couple of years US $1.2/W is used in this study. The cost of the system controller is estimated to be US $1000. Based on the given cost scenarios the estimated total system cost required for the load estimation based on standard efficiency is US $33,440 and for the load estimation using high-efficiency appliances is US $16,460. The estimated system cost of the proposed DC microgrid under standard efficiency appliances is higher than the cost of the system under high-efficient appliances by 103.2%. Even if, the cost of high-efficiency appliances is higher (10–40%) than standard efficiency appliances (Phadke, Park, & Abhyankar, 2019), using high-efficiency appliances is still very cost-effective as compared to the cost of the system designed using standard efficiency appliances. Besides, the costs could be much higher with both scenarios if the proposed microgrid was AC microgrids due to the need for additional investment for inverters and other necessary power electronics

CHAPTER FIVE

TECHNO-ECONOMIC ANALYSIS OF HYBRID RENEWABLE ENERGY SYSTEMS FOR RURAL INCLUSIVE ENERGY SERVICES

5.1. Introduction

In this chapter the techno-economic analysis of DC and AC-DC microgrids for different applications including households, health centers and villages were presented. The analysis aims to present a techno-economic analysis of DC and AC-DC microgrids for inclusive rural modern energy services including services of household, agriculture, social and community services including education, health, water supply and shops. The designed microgrids are for a rural health center, household and village applications. In the design, different locations, load estimation, sensitivity variables and renewable energy variabilities were considered.

The rural health center, household and village applications are considered located in different rural areas of Ethiopia whereas for the health center application the simulation was performed for rural locations located in Ethiopia and Burkina Faso. Locations are critical factors for the sizing, cost and design of the system because as the location varies the variability and the availability of renewable energy sources. Therefore, to analyze the impact of locations on the system design and overall system cost, different locations are considered for specific case studies. For instance, for the case study of the health center, two locations, one in Ethiopia (East African country) and the other in Burkina Faso (west African country) were considered and a comparative analysis of the simulation results, as well as the techno-economic analysis, is presented. Furthermore, high-efficiency appliances were considered for load estimations and HOMER software was used for the design and simulation, as well as for the techno-economic analysis of the proposed designed microgrids for the above specified applications.

The lack of modern energy services in Sub-Saharan Africa and other developing countries, particularly in rural areas, impedes social, economic and human development. The lack of access to modern energy services limits economic and more productive agricultural opportunities negatively affects the environment, promotes gender inequality and constrains delivery of social services such as health care delivery system and education. People located in rural areas of Sub-Saharan Africa countries lack more of such services compared with the urban areas. This implies that an inclusive energy solution is critical to address these challenges. In Ethiopia, the second most populous country in Africa, also 80% of about 115 million people are located in rural areas that lack affordable, reliable and sustainable modern energy services. This is identified as the major cause that challenges its sustainable development goals. In order to address the energy problems and improve access to all services and ensure socio-economic development as well as tackle challenges related to the conventional power generation methods, the development of power generation systems based on renewable energy is attracting attention as a suitable sustainable solution (A. H. Mamaghani, 2016).

Renewable energy sources are promising options because of their abundance since they are found locally in rural locations where there is a lack of modern energy services. Despite their intermittence, the potential of renewable energy sources (including solar, wind, hydro) is not fully exploited because of technical and economic barriers. as well as seasonal variability. On the other hand, renewable energy systems have emission-free, environmentally friendly and inexhaustible nature advantages over conventional energy systems and resources. Moreover, millions of people located in rural and remote areas of developing countries like in countries in sub-Saharan Africa have limited or no access to grid electricity. This limited accessibility of energy services is due to geographical locations (far from the grid-inaccessibility), lack of grid infrastructure, the high investment needs to install and connect the rural and distributed poor community with main grid power lines (A.B. Kanase-Patil, 2010; A. H. Mamaghani, 2016; K.Y. Lau, 2010). For such areas, energy generation systems based on several mixes of renewable energy sources systems (hybrid renewable energy systems) are highly regarded as viable cost-effective solutions to address the energy access problems in rural areas of developing countries (P.A. Owusu, 2016; F.A. Rahman, 2017; O.Krishan, 2019).

Nowadays, standalone hybrid renewable energy systems (SHRESs), consisting of two or more renewable energy resources and different energy storage systems, have emerged as a promising technology for electrifying these rural and remote locations (R.K. Rajkumar, 2011; D. Akinyele, 2017). Among the different kinds of renewable energy sources, the combination of wind and solar resources with storage systems, because of their complementary nature, provides a cost-effective and reliable option to form SHRESs to provide energy services in rural and remote areas (M.A.M. Ramli, 2016; O.Krishan, 2019). In these areas without grid connection, the variability of SHRESs requires the support of energy storage systems to balance the variability of and unpredictability of output power from renewable energy sources. On the other hand, energy storage systems are important not only to bust the resilience of the standalone hybrid energy systems but also it enhances the reliability and efficiency of the system (M. Tavakoli, 2018). Many researchers have been done various research in the area of hybrid renewable energy systems by incorporating two or more renewable sources with energy systems for rural electrification applications.

A study made by Chong Li et al. (C. Li, 2013) analyzed the techno-economic potential of autonomous hybrid wind/ PV/battery power system for a household in Urumqi, China, having 11 kWh/day with 5.6 kW of peak demand. For this specific load, 5 kW of PV arrays, a wind turbine with 2.5 kW, and 55.52 kWh of batteries were found to be the optimum sizes. In the optimal case scenario, it was presented that, the PV system accounts for about 72% of total electricity production, whereas wind turbine provides the rest 28% and with the increment in load, solar energy contributes more efficiently than wind energy. Another study made by W. Margaret Amutha and V. Rajini (W.M. Amutha, 2016) for electrification or a rural village called Kadayam in Tamilnadu, India, examined the feasibility of solar/wind/hydro based HRES, with batteries as storage devices and compared with the grid extension using HOMER software. As per their findings, grid extension is not a suitable option for the selected rural location with regard to cost-effectiveness and environmental protection. The results of the study showed that solar/wind/hydro combination provides a complementary effect throughout the year for the selected rural area and can meet the power demand without adversely impacting the environment.

Another study was carried out by Abdullah Al-Sharaf et al. (A. Al-Sharafi, 2017) for different locations in Saudi Arabia, considering six different combinations incorporating PV systems, wind turbines, converter, batteries, electrolyzer, fuel cell, and hydrogen tank. The authors found that the PV/ wind/batteries-based systems are the most cost-effective. However, the Levelized Cost of Electricity (LCOE) is decreased by half, when the batteries are replaced by the arrangement of a fuel cell, hydrogen container and electrolyzer, even if the solution with such configuration is not a viable solution compared with the PV/Wind/batteries configuration. A case study of a nanogrid system, composed of diesel generator (DG), wind, solar, and batteries, for the five neighboring houses in Gwagwalada-Abuja, Nigeria is presented by (D. Akinyele, 2017). The study investigated that among the different possible configurations, hybrid configuration achieves high reliability and better battery performance as compared to single-source configuration due to the complementary characteristics of different sources. The results indicated that the solar/wind/battery nanogrid has the minimum COE among all configurations considered in the study and hence the most cost-effective option to electrify the rural houses considered in the study.

A study by Mehdi Baneshi and Farhad Hadianfard (M. Baneshi, 2016) modeled a hybrid renewable energy system, comprising PV, wind and batteries, using HOMER for a non-residential area in southern Iran having daily average demand and peak demand of 9911 kW h and 725 kW, respectively. In the study, it was concluded that with the addition of batteries to the modeled off-grid system, the COE gets decreased, reliability of the system gets improved besides creating scope for enhanced penetration of the considered renewable energy sources. Another study made by (G. Merei, 2013) on the optimization of an off-grid hybrid system consisting of wind/PV/DG with three different types of batteries including lead-acid battery, lithium-ion battery and vanadium redox-flow battery, was performed for two different locations i.e. Aachen, Germany and Quneitra, Syria. The main finding of the study was that with the use of batteries, the proposed off-grid system performs in a more economic, effective and ecological way. From the results, it is observed that the use of a single type of battery provides a more feasible option than using the two or more different types of batteries. With a vanadium redox-flow battery, the system has the least COE of 0.65 €/kWh and 0.34 €/kWh for Aachen and Quneitra locations, respectively. Similarly, a techno-economic analysis of wind/solar hybrid system, for an area located in the west coast area of Saudi Arabia, was performed with respect to total electricity production and COE (M.A.M. Ramli, 2016). The authors investigated that if the combination of PV and wind with their power contribution being 63% and 37%, respectively, is used then the unmet electric demand is the lowest.

A study made by (A. A. Kebede, 2021) analyzed the techno-economic feasibility of lithium-ion and lead-acid batteries integrated with Photovoltaic Grid-connected systems using HOMER and MATLAB. The authors concluded that the system with Li-ion battery resulted in a Levelized Cost of Energy (LCOE) of 0.32 €/kWh compared with the system with lead-acid battery with LCOE of 0.34 €/kWh. Besides, the Net Present Cost (NPC) of the system with Li-ion batteries was found to be €14,399 while the system with the lead-acid battery resulted in a NPC of €15,106. The results indicated that Li-ion batteries are techno-economically more viable than lead-acid batteries under the considered specifications and application profile. In another study by (K. Gebrehiwot, 2019), a standalone off-grid system was modeled and analyzed for the rural village called Golbo II village in Adaa district, Oromia Region, Ethiopia using HOMER software. The authors concluded that among the different configurations considered in the study, a hybrid energy system consisting of solar PV, wind, battery and a diesel generator is the viable option from an economic perspective with COE 0.207 $/kWh and NPC $ 82,734.

In most of the available previous studies, the main issue addressed in the studies is either the sizing of the system and economic analysis of the system on a specific application or on combining different renewable energy sources and their feasibility. On the other hand, most of the previous studies are only focused on electrification such as lighting, entertainment and refrigeration (in some cases), which has a limited purpose. However, the energy services required in rural areas are beyond electrification, and include clean cooking services, clean water supply, cost-effective irrigation and productive agriculture. Moreover, most of the available studies are focused on AC microgrids. The previous studies clearly indicate that little attention is given to the development and model of standalone hybrid renewable energy systems for inclusive energy services (including lighting, cooking, irrigation, and water supply loads), as well as on the techno-economic analysis of DC microgrids. Therefore, this part of the thesis aims to fulfill this gap by analyzing the techno-economic feasibility of DC microgrids for different case studies and inclusive energy access. Furthermore, in this study high energy efficiency appliances are considered which is not yet addressed in many previous studies. Additionally, it presented the comparative techno-economic analysis of DC and AC-DC microgrids for rural village energy access applications. In this part of the study, the following three case studies are presented.

1. Techno-economic analysis of standalone DC microgrid to electrify rural households: this case study is considered to fulfill the energy demand of a single household with five family members (which is the average family size of most of sub-Saharan Africa) located in the Afar region of Ethiopia.
2. Techno-economic analysis of standalone DC microgrid for a rural health center in Sub-Saharan Africa: A case of Ethiopia and Burkina Faso: this case study analyzed the techno-economic analysis of DC microgrid to fulfill the energy demand of a typical rural health center in two different locations of sub-Saharan Africa. The one is in North Gondar, Ethiopia and the other is in West Africa i.e Bèna, Burkina Faso
3. Techno-economic Analysis of Standalone hybrid renewable energy system for inclusive energy services of a rural Village: Comparative analysis of DC and AC-DC microgrids: this case study is focused on the techno-economic analysis of DC and AC-DC microgrids to supply the residential, community and agricultural energy demands of rural area in North Gondar, Ethiopia with a population of 1000 (about 200 households).

For the study, HOMER software is used to investigate the technical and economic aspects with respect to COE, NPC, total load served, electricity production, renewable energy penetration level. Different sensitivity conditions are considered related to interest rate, PV lifetime and derating factor, battery lifetime and SoC, nominal discount rate, project lifetime, inflation rate, etc.

5.2. System Description and Methodology

5.2.1. Sites Description

This study considered four sites located in Ethiopia and Burkina Faso. The site considered for the proposed standalone DC microgrid for household application is located at 12°11.4'N, 40°29.1'E in the rural area of the Afar region, Ethiopia. As with most rural areas of Ethiopia, the economy is dependent on agriculture in the specified area with a household having 5 family members on average. In this area, there is no grid connection to supply the household energy demand where setting up a standalone energy solution based on renewable energy sources is considered a viable solution. Therefore, a standalone DC microgrid composed of solar PV and battery is proposed to supply the energy demand of a single household in the specified location, which will be used as a model for other households in the surrounding. The other case study is the techno-economic analysis of a standalone DC microgrid for rural health centers in Ethiopia and Burkin Faso. The sites considered for the proposed standalone DC microgrid for health center applications are located at 12°22.7'N, 38°8.5'E and 12°4.5'N, 4°11.4'W, in East Belesa, North Gondar, Ethiopia and Bèna, Burkina Faso, respectively. Services like healthcare services are limited in both selected locations due to the lack of access to electricity. The other case study considered in this work is analyzing the techno-economic feasibility of DC and AC-DC microgrid for inclusive energy service of a village located in Ethiopia. The selected site for this case study is located in 12°22.6'N, 37°39.9'E, a village called Cushiranga Villag in North Gondar of Ethiopia. The case study considered about 200 households with average family members of 5 which implies the designed microgrid could supply energy demand for about 1000 inhabitants.

5.2.2. Load Estimation

In the design and modeling of power systems, load estimation is a critical task, particularly for distributed energy systems. Due to the variability of renewable energy sources estimating loads is important for efficient utilization of renewable energy sources, as well as for designing cost-effective power systems. Load demand determines the sizing of the system and the over cost of the system. Therefore, for each case study, the load demand was estimated based on the high efficiency appliances reported by Global LEAP Awards (Awards, 2019). The loads are for households, health centers and for villages. In the case of the village, all possible loads are considered to supply inclusive energy services including lighting, cooking, irrigation, clean water supply, shop energy services (lighting, refrigerator), etc.

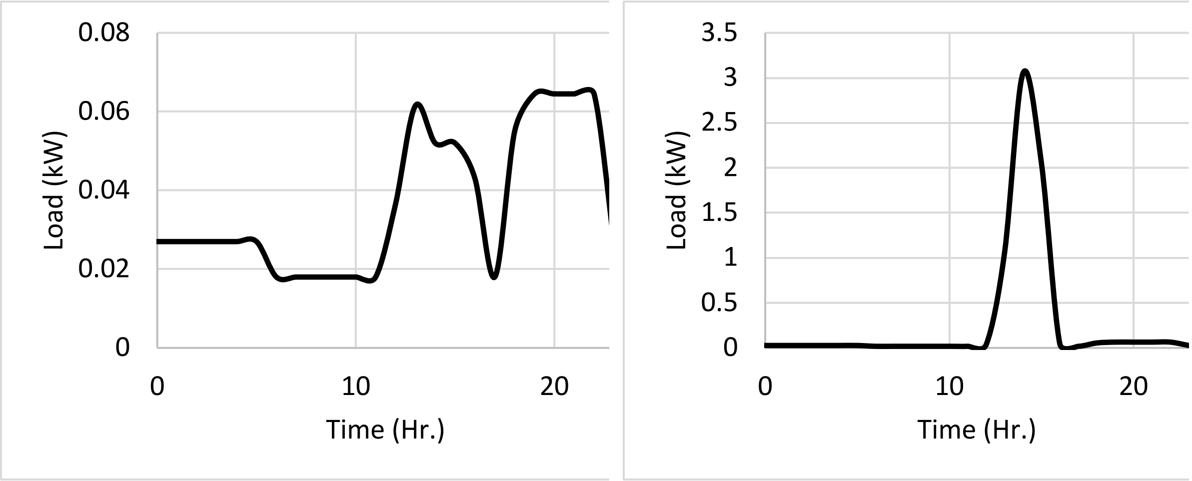
For the case of the proposed DC microgrid for household application, the common loads of most households are lighting, cooking, refrigerator, fan (depending on the location/season), TV and mobile charging. Table 13 Load estimation for a single household presents the load estimation of the household for the case of DC microgrid design for household application.

The estimated household load over one day gives a total energy consumption of 4.2 kWh and a peak load of about 3.1 kW. The load demand was estimated taking into account highly efficient household appliances including 5 lamps in total (4 inside the house and one outside the house), cooking services (Injera baking which is the most common food in Ethiopia and pressure cookers considering emerging energy efficient cooking appliances), ceiling fan, TV, refrigerator and mobile charging. In the case of cooking, Injera baking is usually performed once per three days, therefore, the load estimation considers this case.

Figure 63 (a and b) presents the daily power consumption of the household over 24h, based on the load estimation presented in Table 13. The loads are distributed based on the hours of the day when the appliances are used, which is for inside lighting from 19 h to 23 h, for outside lighting from 19h to 6h, for a refrigerator for 24 hrs, for TV from 12h to 18h and from 19h to 22h and for other services including cooking, fans, mobile charging the loads are distributed from 12h to 18h. The load profiles present a similar fashion for every working day over the year, as presented in Figure 63. The profile presented in Figure 63 (a) is the load profile without cooking services. As presented in Table 13 the cooking loads are much higher than other loads making the loads concentrated in between 12h to 15h, as shown in Figure 63 –(b). It is assumed that such cooking activities are performed in the day where there is much sun rather than at the night which demands high energy, implying the need for high storage facilities. The two load profiles are presented to show the load profile with cooking and without cooking. Most household loads are concentrated in the evening hours, the daily load profile without cooking services also presents it.

Table 13 Load estimation for a single household

Appliances/Services		**Specification**	**Power (W)**	**Daily Use (Hr/day)**	**Energy Consumption (Wh/day)**
Lighting	Inside	7 W × 4	28	5	140
	Outside	9 W × 1	9	12	108
Cooking	Mitad/Injera Baking	2000 W × 1	2000	2 Hr/3 days*	1333
	Pressure cooker	1000 W × 1	1000	2	2000
Celing Fan		25 W × 1	25	4	100
TV		9.5 W × 1	9.5	6	57
Refrigerator		17.8 W × 1	17.8	24	427.2
Mobile charging		3 W × 3	9	4	36
Total			4100		4202



a) Daily load profile without the cooking load b) Daily load profile with the cooking load

Figure 63 Daily load profile of the household

For the case of the proposed DC microgrid for health center applications, the basic loads in health centers are loads required to give basic health services like simple blood and urine analysis, lighting, freezer and refrigerator to store pharmaceutical products and samples, computers and printers, water pump, microscopes. As per a health worker who has experience in rural health centers in Ethiopia, the health center in rural locations is supposed to have about 8 rooms (considered in this study) and about 19 staff including nurses, doctors, pharmacists and security officers. The eight rooms are supposed to be one pharmacy room, one delivery room, one reception room, one antenatal care and family planning room, one lab, one emergency room, one triage room and one Outpatient Department. In each room, there is lighting service, as well as all the necessary equipment in respected rooms including deep freeze, refrigerator, centrifuge, CD4, ultrasound, sterilizer, computer, printer, etc. Table 14 presents the basic services with its load estimation based on the high efficiency appliances. The estimation implies that it is required about 1.4 kW of power to supply the energy demand of the rural health center in the selected location with an energy consumption of 6 kWh per day.

Figure 64 presents the considered daily power consumption of the health center over 24 h, based on the load estimation presented in Table 13. The loads are distributed based on the hours of the day when the appliances are typically used. The health center is supposed to work mainly in the day hours, which the loads are mostly distributed between 9h and 16h that gives the advantage of using solar energy at its full potential. The inside lighting is supposed to be used in the day and sometimes at night in the case of emergency cases, whereas the security and outside lighting services are going on in the nighttime. Other services related to laboratory examination are supposed to be used in the daytime when necessary, since most rural people come from far to health centers and the lab test is going to be analyzed in the daytime. Therefore, services like blood and urine analysis are going to be used from 9 h to 12 h and 13 h to 16 h, CD4 from 10 h to 14 h, water pump from 10 h to 16 h, centrifuge from 11 h to 15 h, TV is mostly used in the day when patients came to the health center, fans are used in afternoon times when the penetration of the sun is believed to be high and refrigerator and deep freeze are going to be used whenever necessary.

For the case of the proposed DC microgrid for village application, the analysis aims to supply inclusive energy services including community and residential loads such as primary school, health center, irrigation and clean water supply, household loads, shop, sewing and milling loads. The school, household and health center loads presented above are considered as loads in the village load. For the household loads, particularly the cooking loads are much higher than other loads, therefore the cooking loads are distributed by considering groups of houses, which is very critical to minimize the overall cost, efficiency and size of the system. As it is presented above, 200 households are considered in the study, and therefore the houses are grouped into six groups; 25 households are supposed to cook from 8 h to 10 h, 40 households are supposed to cook from 10 h to 12 h, 40 households are supposed to cook from 12 h to 14 h, 40 households are supposed to cook from 14 h to 16 h, 40 households are supposed to cook from 16 h to 18 h and 15 households are supposed to cook from 18 h to 20 h. The other household loads, school and health center loads are distributed based on the daily load distribution presented in Figure 63, Figure 52 and Figure 64, respectively. The sewing and milling loads are distributed in the day from 9 h to 18 h and the shop loads are also supposed to work in the day as well as for 24 hrs in the case of refrigeration services. The irrigation loads are supposed to use solar water pumps which are emerging technologies for rural farmers and are supposed to function from 12 h to 17 h. Loads including irrigation, clean water supply, school, shop, health center loads are considered as community and commercial loads in this study. Figure 65 presents the daily load profile of the village distributed over 24 h. The loads are distributed based on the time of use of the appliances over a day and present about 140 kW of peak load and 1452 kWh energy consumption per day.

Table 14 Load estimation and services required for rural health center

Appliances/Services		**Specification**	**Power (W)**	**Daily Use (Hr/day)**	**Energy Consumption (Wh/day)**
Lighting	Office	9 W × 8	81	11	891
	Security	9 W × 1	9	5	45
	Outside	11 W × 2	22	12	264
Ultrasound		28 W × 1	28	2	56
Deep freeze		36 W × 1	36	12	432
Refrigerator		18 W × 1	18	11	198
Centrifuge		25 W × 1	25	4	100
Blood sample analyzer		45 W × 1	45	4	180
Urine analyzer		30 W × 1	30	4	120
Sterilizer		500 W × 1	500	2	1000
CD4		200 W × 1	200	4	800
Suction App		24 W × 1	24	7	168
Computer		20 W × 4	80	4	320
Printer		65 W × 1	65	4	260
LED Microscope		70 W × 1	70	2	140
Water Pump		100 W × 1	100	6	600
TV		9.5 W × 1	9.5	8	76
Ceiling Fan		25 W × 3	75	4	300
Total			1417.5		5950

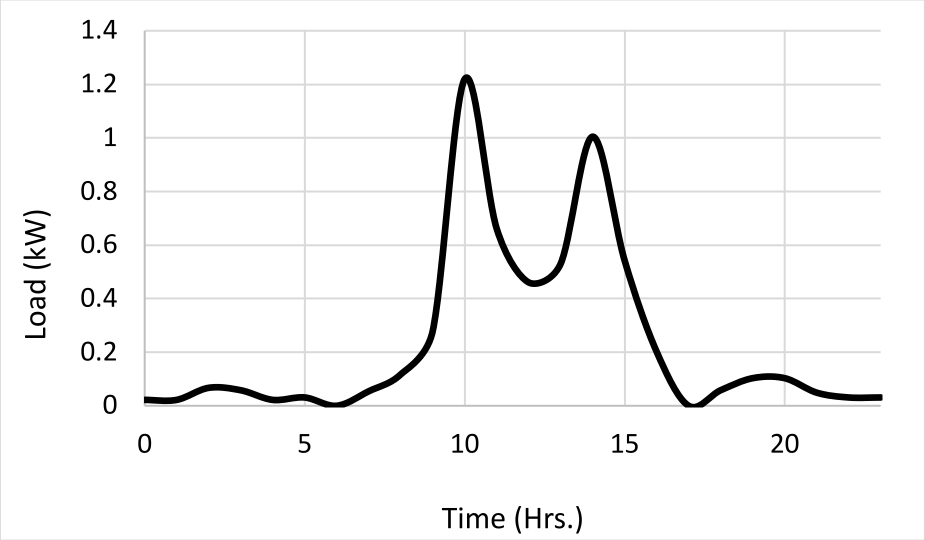


Figure 64 Daily load profile for the health center

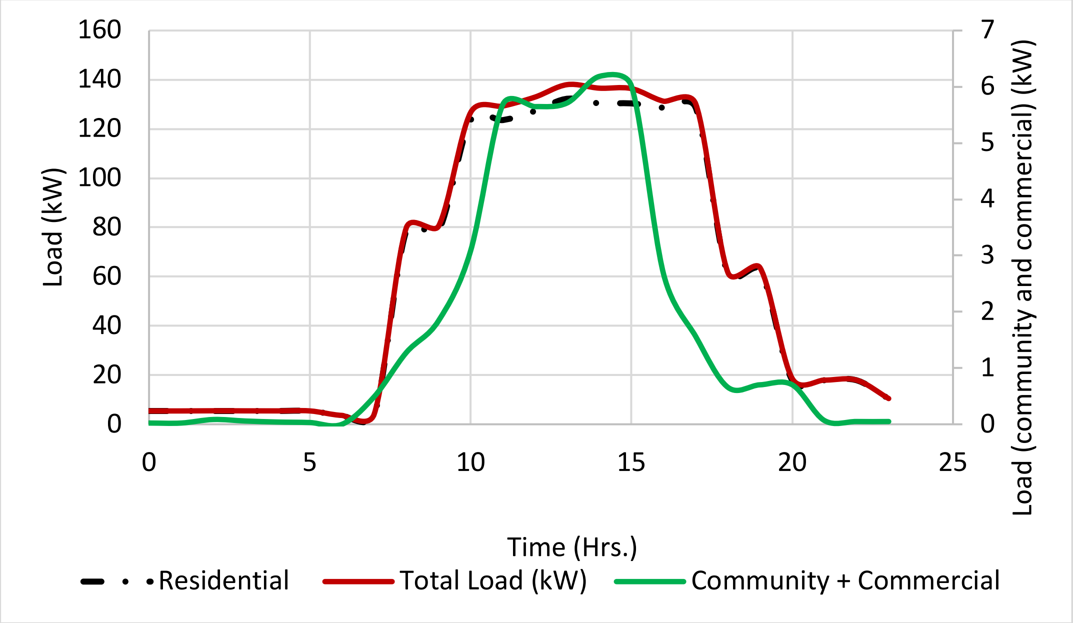


Figure 65 Daily load profile of the village

5.3. System Modeling and Components

5.3.1. System Modeling

Hybrid Optimization of Multiple Energy Resources (HOMER) software developed by NREL (National Renewable Energy Laboratory, USA) has been utilized for optimal designing and to assess the techno-economic feasibility of the renewable energy sources based power systems. The software is a powerful tool for the optimal designing, sizing, and planning of hybrid renewable energy systems by carrying out techno-economic analysis for off-grid and grid-connected power systems. It takes inputs such as location, electric or heating loads and generate renewable energy sources for the selected location to perform simulations based on different system configurations or the hybrid combinations of components and generates the optimized system configurations sorted in term of investment cost, COE and NPC.

Optimization of system design configurations is performed by minimizing the objective function to the constraints. The objective function in this analysis is NPC, which is the present cost of the system excluding the sum of revenues. The constraints are charging and discharging of batteries, power balance and other technical constraints. HOMER simulates the system configurations by making energy balance for each hour and takes the electric or thermal loads per hour that a system can supply (M. K. Shahzad, 2017).

The software is helpful to demonstrate the impact of renewable penetration and storage and other sensitivity variables including inflation and discount rates on the COE and NPC. In HOMER, three tasks can be performed such as: running simulations, performing sensitivity analysis and optimizing the simulated system (A. Ghasemi, 2013; K. Murugaperumal, 2019). Before performing the HOMER based analysis for the hybrid renewable energy systems a Pre-HOMER analysis was performed by making an assessment of the load requirements for each case study, including household, health center and village. After that, the demand data was fed into the software interface and an assessment was performed for the DC and AC-DC microgrids proposed for household, health center and village applications. Loads, renewable energy components, storage and converter with it is respective sensitivity variables are the main inputs of techno-economic analysis of microgrids using HOMER. In this study, the loads include the electric load, and the components include PV, wind, batteries and converter and the sensitivity variables were inserted in the system. Figure 66 presents the steps followed for the techno-economic analysis of proposed microgrids using HOMER.

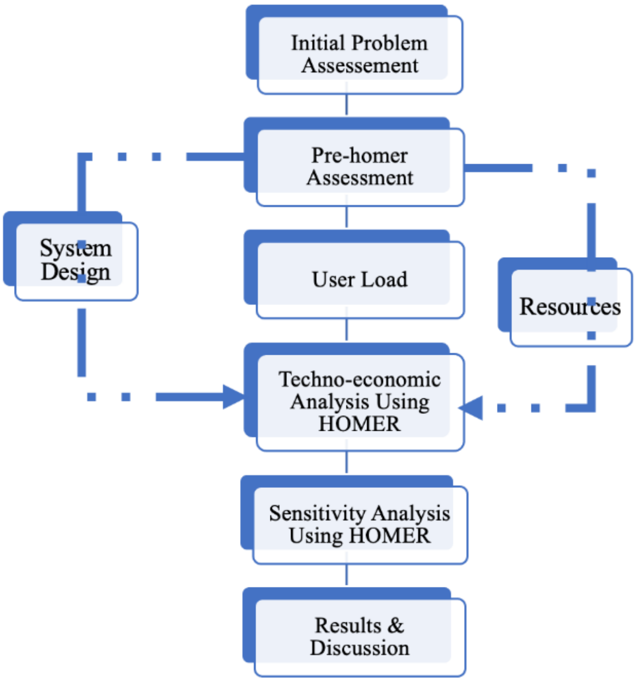


Figure 66 The methodology followed for techno-economic analysis of proposed microgrids using HOMER

The optimization process, built in the simulations with objective functions to minimize total life cycle cost and COE, computes the optimum size of the components proposed for the systems such as the

PV array, wind turbines, batteries and converters, so that all energy demands can be supplied at all the time.

As per (O.Krishan, 2019) and (A. A. Kebede, 2021) the total life cycle cost of the proposed systems, which includes initial investment and installation cost, replacement cost, and O&M costs, is characterized by NPC which is computed as per Equation 8:

$$NPC = \frac{C_{ann,tot}}{CRF\ (i,N)} \qquad 8$$

Where,
Cann,tot is the total annual cost ($/year), *i* is the annual real interest rate (%), *N* is the project lifetime (years), and *CRF (i, N)* is the capital recovery factor which can be expressed as follows in Equation 9:

$$CRF\ (i, N) = \frac{i\ (1+i)^N}{i\ (1+i)^N+1} \qquad 9$$

Where, i is the interest rate. And the *COE ($/kWh)* is calculated by dividing *Cann,tot* ($/year) to total annual load served (E_{serve}) in kWh/year by the microgrid as per Equation 10:

$$COE = \frac{C_{ann,tot}}{E_{serve}} \qquad 10$$

5.3.2. Renewable Energy Resource Assessment

HOMER software allows the evaluation of the solar and wind potential of the selected location for the proposed off-grid systems. Solar radiation and wind speed data were obtained by using HOMER software for each location selected for this study. The solar radiation data for the selected location called “Sedeha Melefu” in Afar region of Ethiopia of 12°11.4'N latitude and 40°29.1'E longitude from “NASA surface meteorology and Solar Energy Database”, indicates that the annual scaled average solar radiations were found to be 5.77 kWh/m^2/day and the maximum and minimum solar radiation were found to be 6.46 kWh/m^2/day in the month of May and 5.1 kWh/m^2/day in the month of January, respectively. Figure 67 presents the average daily solar radiation and clearness index of the selected location in the Afar region of Ethiopia.

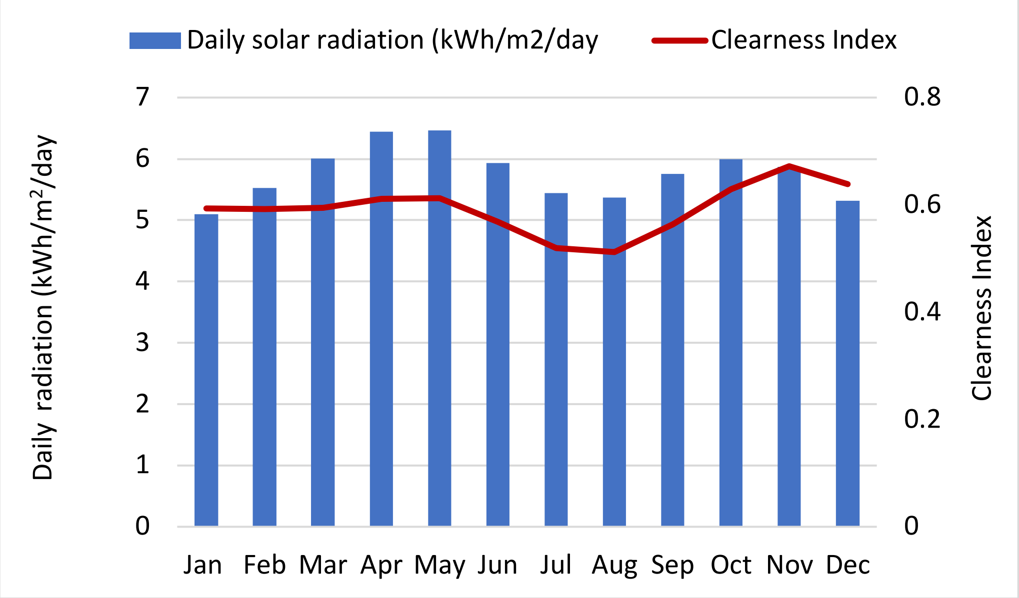


Figure 67 Average daily solar radiation in the selected location

The daily average solar radiation and clearness index in the selected locations of Ethiopia and Burkina Faso are presented in Figure 68 and Figure 69. The annual average solar radiation data in the other location of East Belasa of North Gondar of Ethiopia with 12°22.7'N latitude and 38°8.5'E longitude were found to be 6.25 kWh/m^2/day and the maximum and minimum average solar radiation were found to be 6.82 kWh/m^2/day in the month of April and 5.62 kWh/m^2/day in the month of June, respectively. The annual average solar radiation data in the location of Bèna, Burkina Faso with 12°4.5'N of latitude and 4°11.4'W longitude were found to be 5.79 kWh/m^2/day and the maximum and minimum average solar radiation were found to be 6.24 kWh/m^2/day in the month of April and 5.35 kWh/m^2/day in the month of August, respectively.

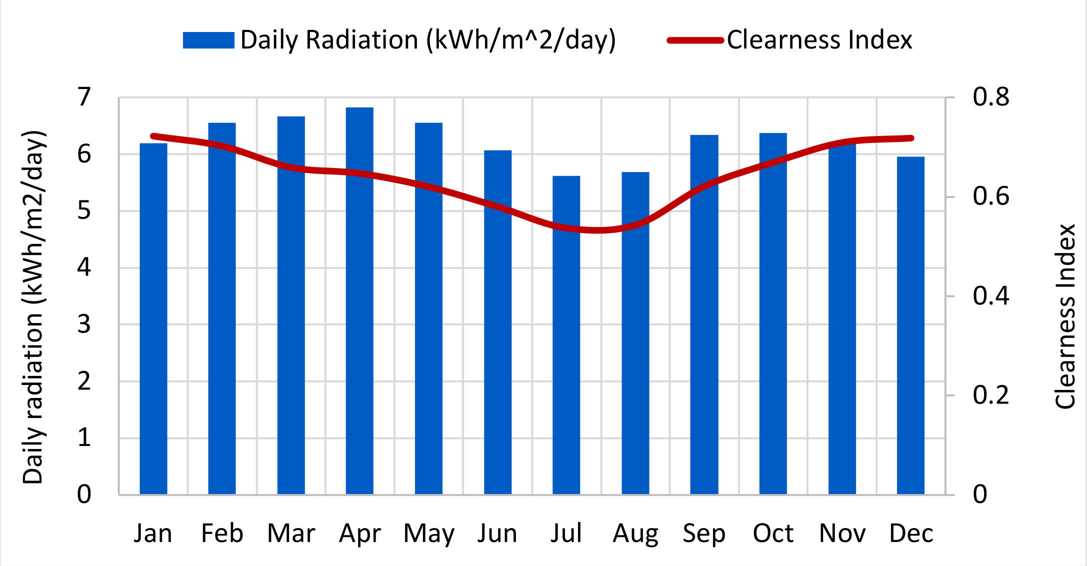


Figure 68 Average daily solar radiation in the selected location (Ethiopia)

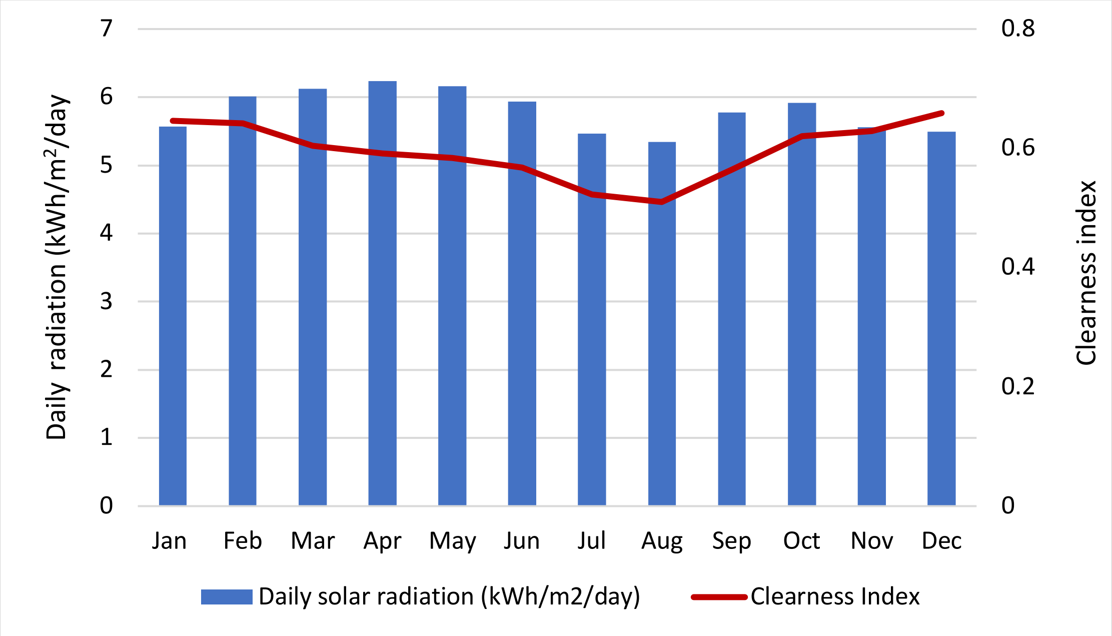


Figure 69 Daily average solar radiation of the selected site (Burkina Faso)

For the village application, the HOMER analysis indicates that a microgrid composed of wind turbines, solar PV and battery storage is a viable solution. Figure 70 presents the average daily solar radiation and clearness index of the selected site. The annual average solar radiation data in the other location of Cushiranga Village, Ethiopia with 12°22.6'N latitude and 37°39.9'E longitude were found to be 6.12 kWh/m^2/day and the maximum and minimum average solar radiation were found to be 6.86 kWh/m^2/day in the month of April and 5.27 kWh/m^2/day in the month of July, respectively. The average daily wind speed in the selected location is 3.48 m/s as presented in Figure 71.

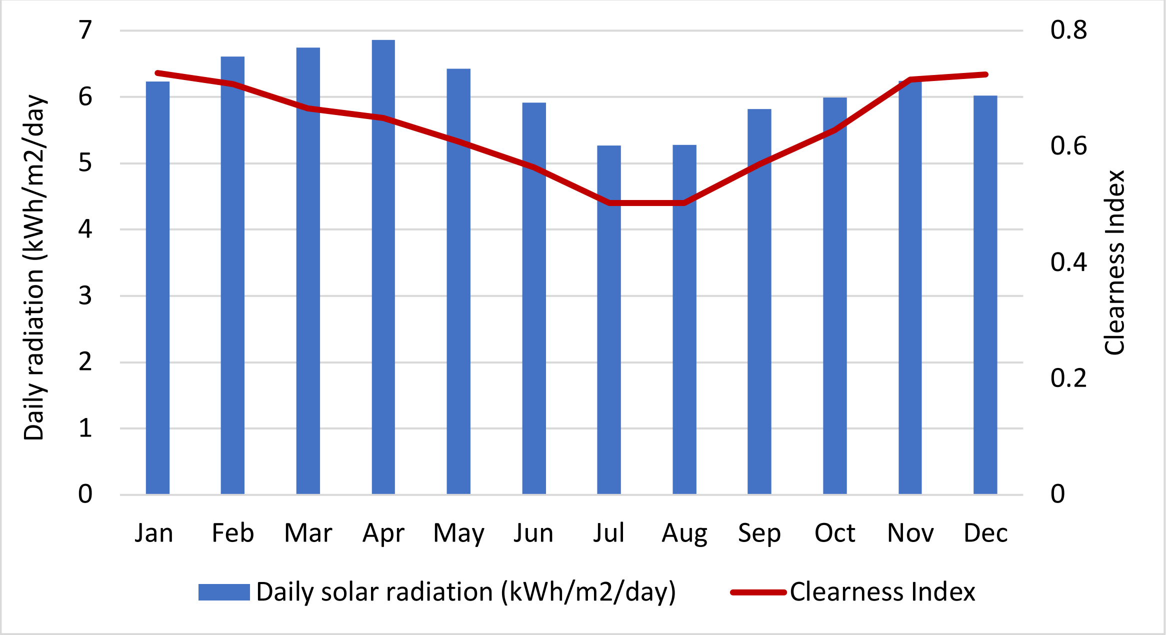


Figure 70 Average solar radiation of the selected site

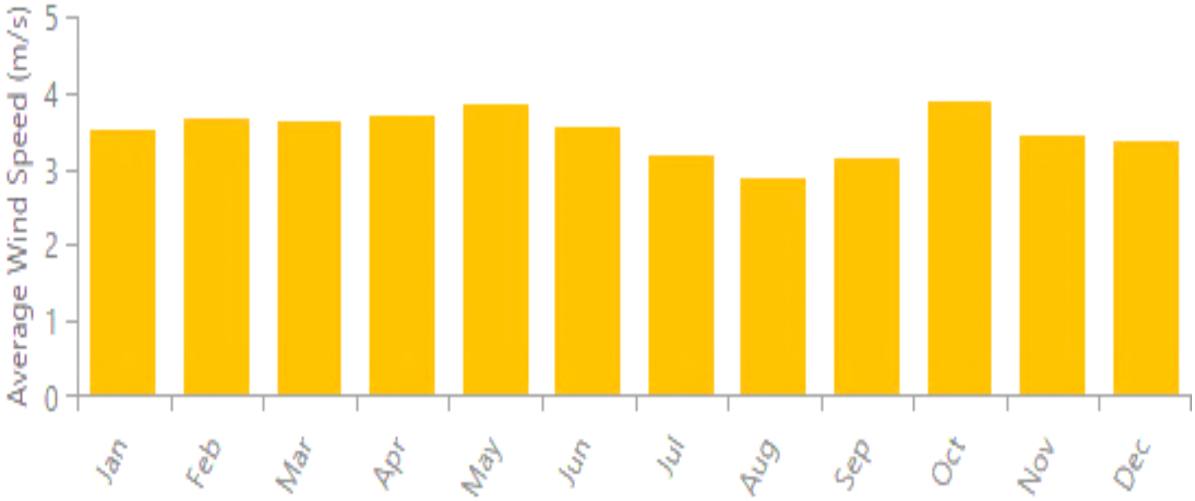


Figure 71 Average wind speed (m/s) in the selected site

Table 15 shows the cost details of the components used in the techno-economic analysis of the proposed microgrids. The cost is the current cost of each component in the Ethiopian market off-grid components market. For the PV the cost in Ethiopia ranges from 50 to 70 Ethiopian birr (ETB) per W which is equivalent to \$1.6/W with a 20% of inflation rate (the market is so volatile). Similar market assessments were made for the battery and the converter and the costs are estimated based on the local market and the inflation rate. These cost details were used as inputs for the simulation of all the systems proposed under each different scenario and case study.

Table 15 Cost details of the components used in the proposed microgrids

Parameters	PV (Generic flat plate)	Battery		Wind	Converter
		Li-Ion	Lead Acid		
Capital ($)	1600/kW	350/kWh	250/kWh	7000/kW	250/kW
Replacement ($)	1600/kW	350/kWh	250/kWh	7000/kW	250/kW
O & M ($/year)	10	20	20	70	10

5.3.3. Sensitivity Variables

One of the tasks implemented by the HOMER software is a sensitivity analysis. For such analysis, it is required to define sensitivity variables or constraints that are factors that affect the system performance, as well as the operating cost of the system. Therefore, for this study four scenarios were proposed based on the defined sensitivity variables as presented in *Table* 16. The variables are related to components including PV, Battery, Wind, converter and economics (project lifetime, inflation rate, discount rate). The variables used in the analysis were based on the components of each microgrid. For instance, in the case of DC microgrid analysis for household application, the variables related to converter and wind were not used. For the AC-DC analysis for village energy supply application, all the sensitivity variables presented in Table 16 were used as inputs and the techno-economic analysis was performed using the variables, as well as the loads and renewable energy resources.

Table 16 Sensitivity variables related to components of the microgrid and economics

Variables		Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV	Derating	%	80	80	90	90
	Lifetime	years	20	25	20	25
Battery	Lifetime	years	10	8	8	10
	Initial SoC	%	100	90	90	100
	Minimum SoC	%	20	30	20	30
	Throughput	kWh	2000	2000	2000	2000
Wind	Hub Height	m	10	25	10	25
	Lifetime	years	15	20	15	20
Converter	Lifetime	years	10	15	10	15
	Inverter efficiency	%	80	90	90	80
	Rectifier efficiency	%	90	95	95	90
Economics	Nominal discount rate	%	10	12	10	12
	Inflation rate	%	5	10	10	5
	O&M	$/years	0	500	0	500
	Project lifetime	years	20	25	20	25

5.4. Results

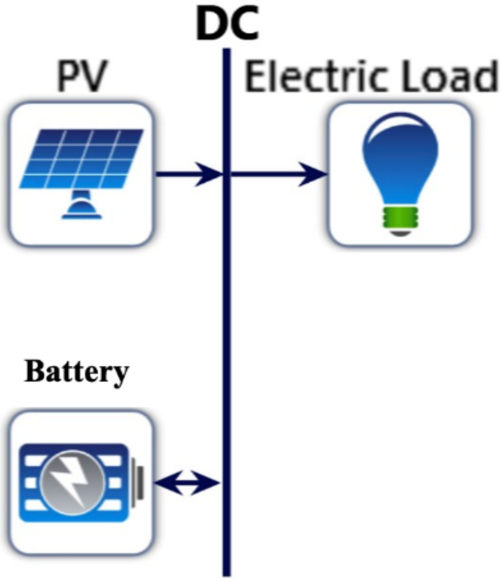
In this study, 3 DC and 1 AC-DC microgrid systems were designed to supply the energy needs of households, health centers and villages. The 2 DC microgrids are for household and health center application whereas the DC and AC-DC microgrids are for village application, ensuring a comparative analysis of the DC and AC-DC microgrids. These proposed systems were simulated by using HOMER software to optimize the designed system configuration according to the load profile and the results obtained are presented in this section. The system was analyzed and optimized by considering different sensitivity variables including PV and battery lifetimes, project lifetime, interest and discount rates. HOMER while simulating the system also optimizes based on the specific parameters given as input so as to provide the best combination scheme resulting in the best performance in respect of economic and technical aspects.

Figure 72 presents the modeled microgrid systems for different applications. The modeled systems are a combination of PV and battery for household and health center applications. For village application, the modeled microgrids contain PV, wind turbine, battery and converter in the case of AC-DC model. Whereas the case of the DC microgrid model for village application, contains wind, PV and battery storage. The input data presented in the load estimation section and the inputs in Table 15 were used in the simulation. Additionally, the sensitivity variables presented in Table 16 were used accordingly in the simulations.

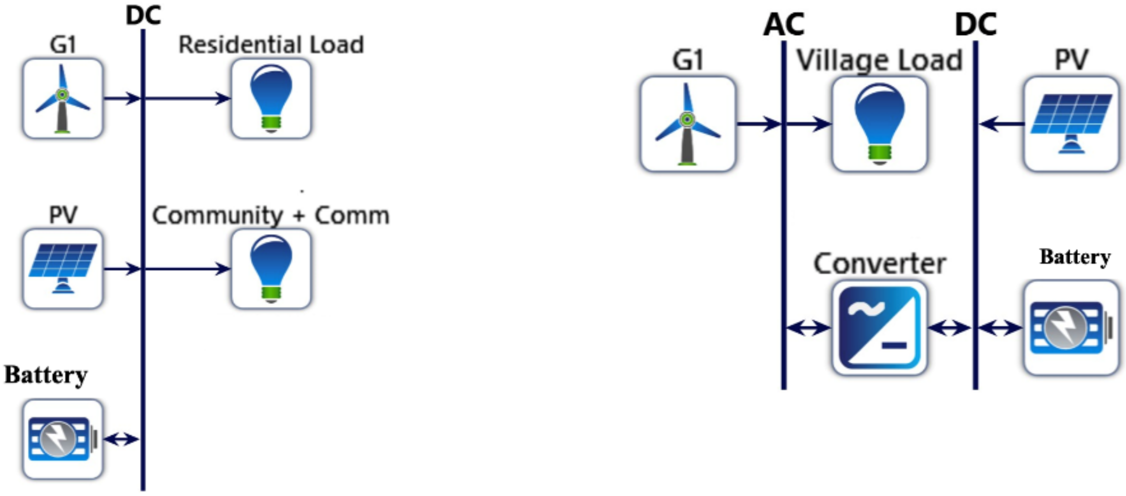
Simulations were performed for the following combinations under four scenarios (Table 16) on an hourly basis and NPC and COE were determined for each case studies:

- PV/battery storage system - for household and health center energy supply system
- PV/wind/battery storage system – for village energy supply system
- PV/wind/battery/converter – for village energy supply system

Table 17 presents the simulation result details of the DC microgrid model for household application under four scenarios. The results also indicate the simulation result details when the battery storage system is different, i.e considering lithium-ion and lead-acid batteries. The results show as best configurations with lithium-ion batteries 4.25 kW of PV with 10kWh battery capacity, 4.78 kW of PV with 10 kWh battery capacity, 2.48 kW of PV with 14 kWh battery capacity and 5 kW of PV with 8 kWh battery capacity for scenario 1, scenario 2, scenario 3 and scenario 4, respectively. Whereas in the case of lead-acid batteries, the results show as best configurations 3.93 kW of PV with 17 kWh battery capacity, 3.93 kW of PV with 17 kWh battery capacity, 2.3 kW of PV with 19 kWh battery capacity and 3.5 kW of PV with 17 kWh battery capacity for scenario 1, scenario, 2, scenario 3 and scenario 4, respectively.



a) DC microgrid for Household and Health Center



b) DC microgrid for village

c) AC - DC microgrid for Village

Figure 72 schematic configuration of the proposed microgrids ((a) DC microgrid for household application, b) DC microgrid for health center application, c) DC microgrid application for village application and d) AC-DC microgrid application for village application) modeled using HOMER

In each scenario and case, there is a much higher monthly electric generation than the load demand, which implies the system can supply the load demand of the household without the need for backup. For instance, in the case of scenario 1 of the system, the annual electricity generation is higher than the annual load demand by 65%, whereas in the case of scenario 4 the electricity generation is much higher than the load demand compared with the other scenarios, which is higher than 74% compared with the annual load demand. On the other hand, in the case of scenario 3, the annual electricity generation is higher than the annual load demand, but the difference is much lower compared with the other scenarios, which is about 47%. Therefore, in most of the scenarios, if there is no extreme weather scenario, there is no need for backup, especially in the case of scenario 4.

Table 17 Simulation results of the DC microgrid for household application under different scenarios

Case studies	**Parameters**	**Unit**	**Scenarios**			
			1	**2**	**3**	**4**
Lithium-Ion	PV	kW	4.25	4.78	2.48	5
	Battery	kWh	10	10	14	8
	DC load	kWh/year	2507	2507	2507	2507
	Electricity production	kWh/year	7317	8218	4799	9670
	Unmet load	%	0	0	0	0
Lead Acid	PV	kW	3.93	3.93	2.30	3.50
	Battery	kWh	17	17	19	17
	DC load	kWh/year	2507	2507	2507	2507
	Electricity production	kWh/year	6763	6763	4453	6775
	Unmet load	%	0	0	0	0

Comparing the two cases studies (lead-acid and lithium-ion batteries), the yearly electric generation in each scenario in the case of the system composed of PV and lithium-ion batteries is higher than the system with lead-acid batteries. For instance, in scenario 1, in the case of the system that contains lithium-ion batteries the annual electricity generation of the system is 7317 kWh/year and in the case of the system that contains the lead-acid batteries is 6763 kWh/year, which implies that the system with the lithium-ion batteries has higher generation by about 554 kWh/year. Whereas, in the case of scenario 4 where higher generation of electricity is recorded in both cases, the generation in the case of the lead-acid battery is lower than the generation in the case of lithium-ion battery by 2895 kWh/year, implies that the case of lithium-ion battery has higher generation which is enough to supply the annual load demand. The difference between the annual generations is due to the simulated size of the PV system, since, in the case of the lithium-ion battery scenario 4, the simulated size of the PV system is 5 kW and for the case of the lead-acid battery the simulated size of the PV system is 3.5 kW.

Figure 73 and Figure 74 present the simulation results for the monthly electric generation under scenarios 3 and 4 (where lower and higher annual generation resulted in both case studies, respectively) for the case of the system containing PV and lithium-ion batteries for the household energy supply application. The results show higher electricity generation in the months of March, April, May, October and November which corresponds to the daily solar radiation presented in *Figure* 67 in both case studies. Whereas, the months of June, July and August are the months where minimum monthly electricity generation was recorded.

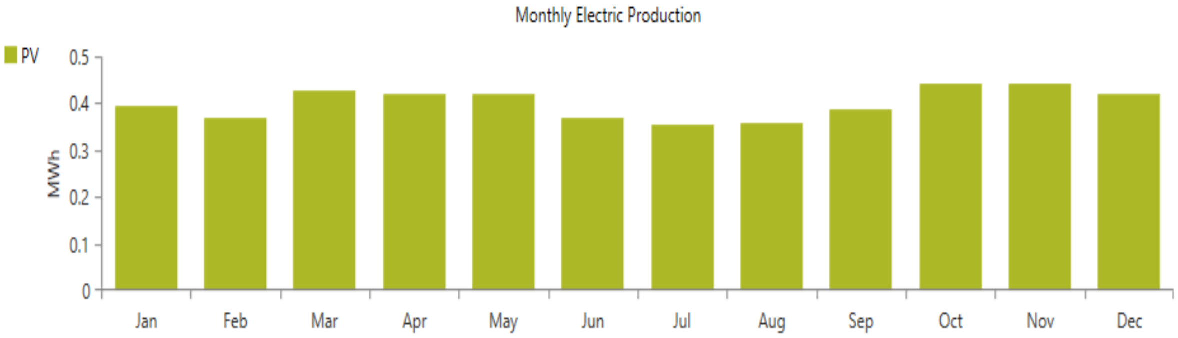


Figure 73 Monthly electric production for the case of scenario 3 of Lithium-ion battery

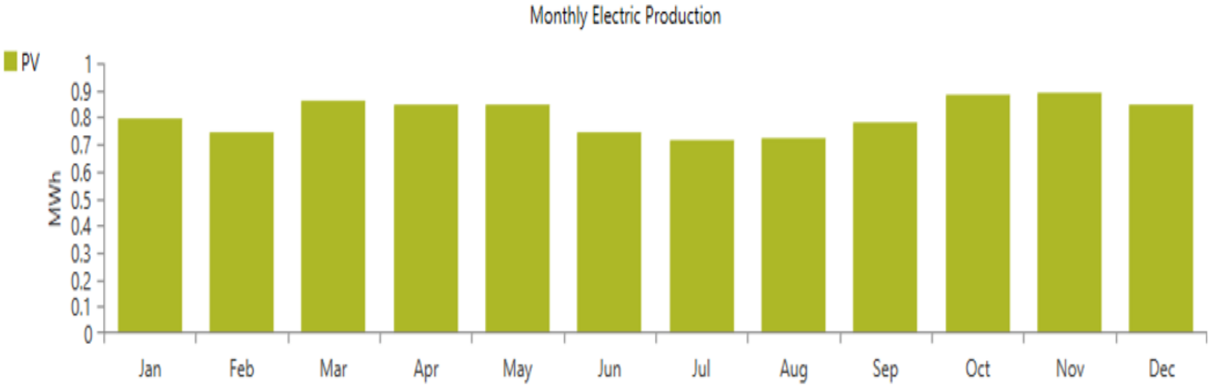


Figure 74 Monthly electric production for the case of scenario 4 of Lithium-ion battery

Figure 75 shows the NPC and COE for the DC microgrid for household application under different sensitivity scenarios and battery options. The result indicates that the NPC in the case of the system composed of PV and lithium-ion batteries has lower values than the system composed of PV and lead-acid batteries. Compared with other scenarios, scenario 4 in the case of the system that contains PV and lithium-ion batteries presents a total NPC of $15,274.39 which has better economic benefit only considering the NPC and in terms of COE scenario 1 and scenario 3 presented better economic benefit with US$ 0.49/kWh in both cases. On the other hand, Whereas scenario 3 resulted in a higher NPC value of $24,244.31 compared with all the other scenarios analyzed.

In the case of the system composed of PV and lead-acid battery, scenario 4 resulted in a better economical configuration considering NPC as compared with other scenarios with a total NPC of $17,472.53. However, considering the COE, scenario 3 demonstrated better economic benefit with US$ 0.56/kWh compared with all the other scenarios considering. In both lithium-ion and lead-acid batteries, scenario 4 was found to be the most economical configuration among other scenarios comparing the NPC of each scenarios. The NPC and COE values for scenario 4 in the case of lithium-ion batteries are lower than the NPC and COE values for scenario 4 in the case of the system containing lead-acid batteries by $2.198.14 and 0.073 $/kWh. This implies that the system with lithium-ion batteries is the most cost-effective as compared to the system with lead-acid batteries. Therefore, it is concluded that systems with lithium-ion batteries have better economic benefits when compared with the system proposed with lead-acid batteries. As a result, for the other case studies in this work (including health center and village application), lithium-ion batteries are used instead of lead-acid batteries.

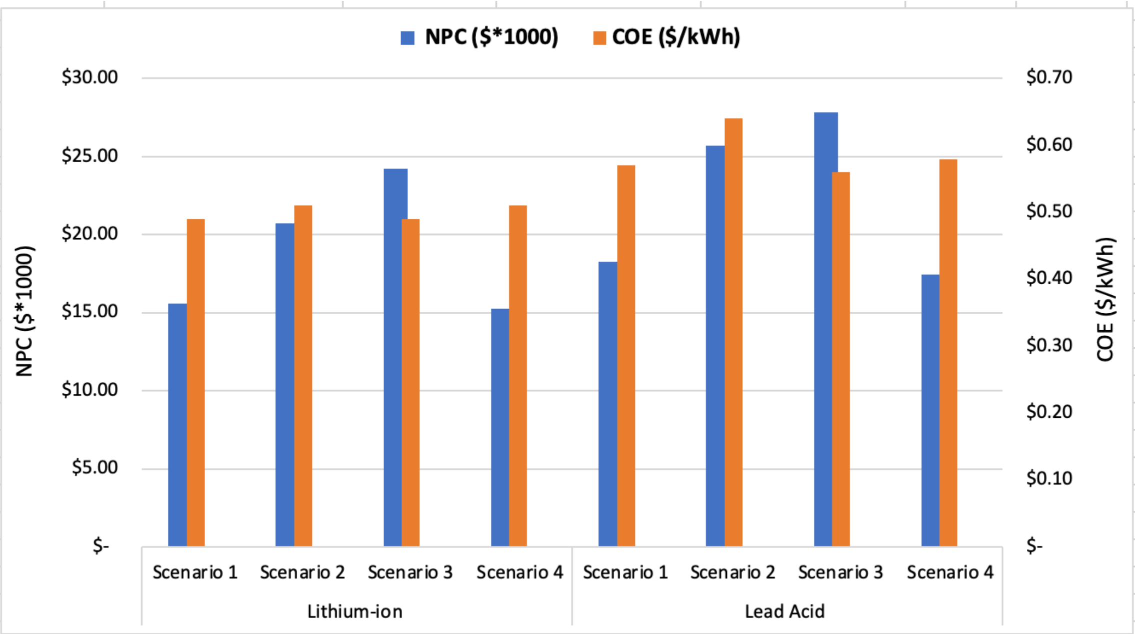


Figure 75 NPC and COE values of DC microgrid for household application under different scenarios and battery options

Figure 76 and Figure 77 presents the cost and cash flow summary of the system using lithium-ion and lead-acid batteries, respectively. In both cases, scenario 3 shows higher installation cost which is costly compared with the other possible scenarios. Whereas scenario 4 presents less cost compared with the other possible proposed configurations.

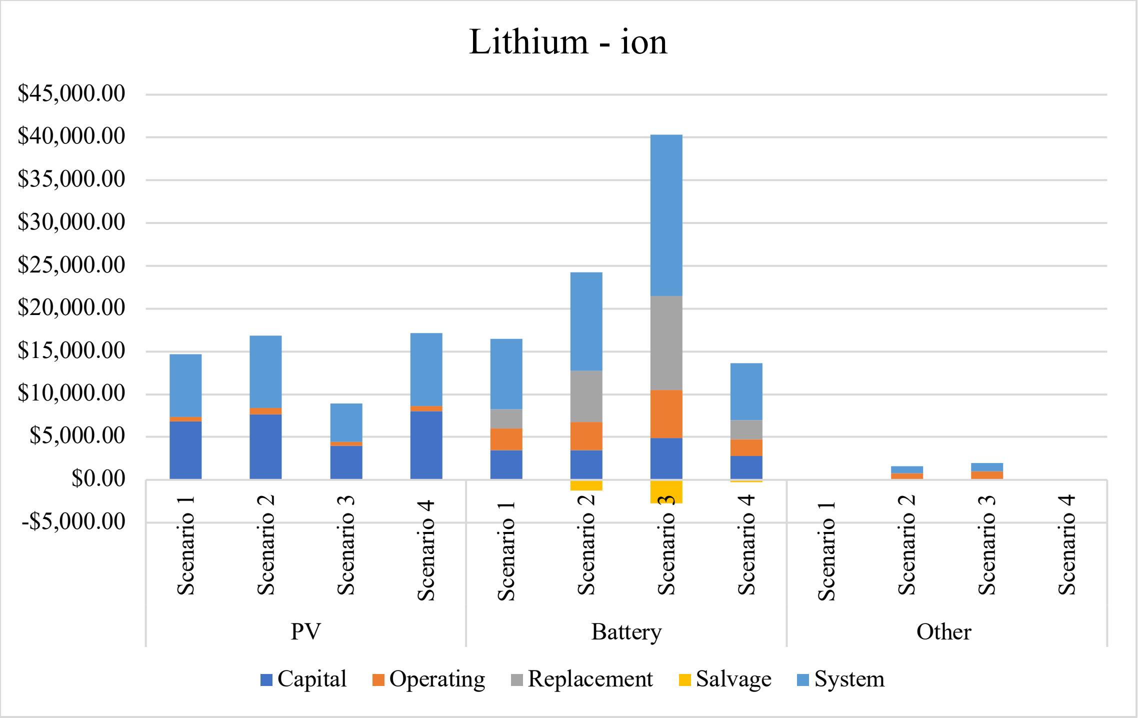


Figure 76 Cost summary and cash flow of the proposed DC microgrid under different scenarios for the case with lithium-ion batteries

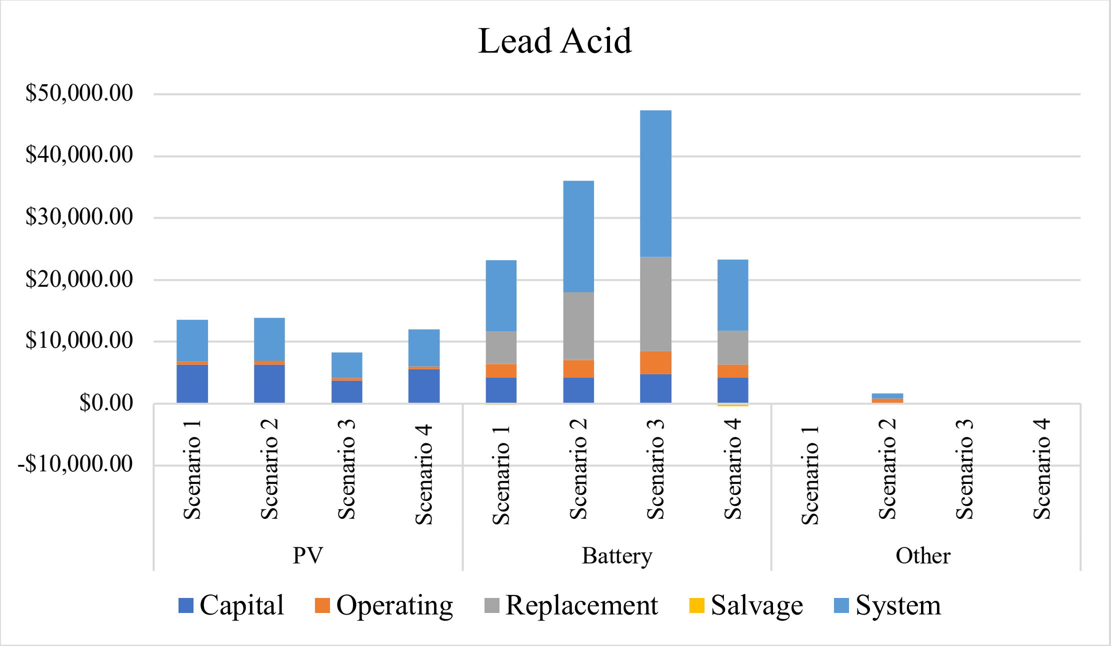


Figure 77 Cost summary and cash flow of the proposed DC microgrid under different scenarios for the case of lead-acid batteries

Figure 78 and Figure 79 present the NPC and COE values of the system for the health center and village applications, respectively. The system for the health center application was analyzed in different locations, one in Ethiopia and the other in Burkina Faso with the same input except for renewable energy resources (since its potential depend on the location). Whereas in the case of proposed systems for village applications, the inputs are the same and the location is the same, but two different systems are compared, namely DC and AC-DC microgrids. For the case of the AC-DC microgrid, a converter was added to the system.

The techno-economic analysis indicates that the health center system designed for the Ethiopian case presented lower NPC values as compared to the system in Burkina Faso in all 4 scenarios. However, the difference between the NPC values is not significant. For instance, in both cases, scenario 4 presents lower NPC values compared with the other 3 scenarios with values of $11,035.76 for the Ethiopian case and $11,986.82 for the Burkina Faso case. The NPC value in the case of Burkina Faso is higher than the NPC value in the Ethiopia case by a value of about $951. The lower cost of the system in the Ethiopian case could be from the simulated size of the PV which is 2.5 kW and for the Burkina Faso case the simulated PV size is 3 kW (Appendix B). Therefore, it is concluded that the modeled system for health center application indicates that the system in the Ethiopian context has a lower net present cost compared with the system in Burkina Faso with the same inputs except for the location difference under all scenarios. Considering the COE of the 4 scenarios analyzed in both Ethiopia and Burkina Faso, scenario 3 of Burkina Faso presented lower value with a value of US$ 0.39/kWh. The size of the system is due to the solar radiation penetration difference in the selected locations. As presented in Figure 68 and Figure 69, the average solar radiation in Ethiopia (6.25 kWh/m^2/day) is higher than the average solar radiation in the selected site of Burkina Faso which is 5.79 kWh/m^2/day that leads to the system requiring larger PV sizes which resulted in the higher system costs.

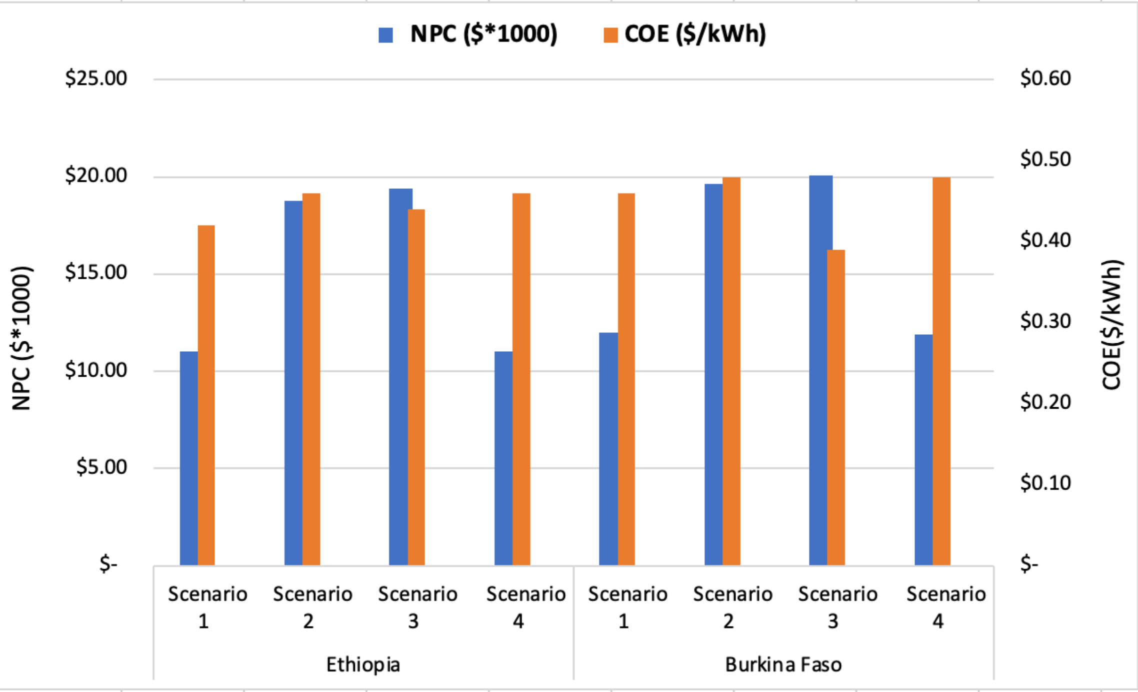


Figure 78 NPC and COE values of DC microgrid for the health center application under different scenarios

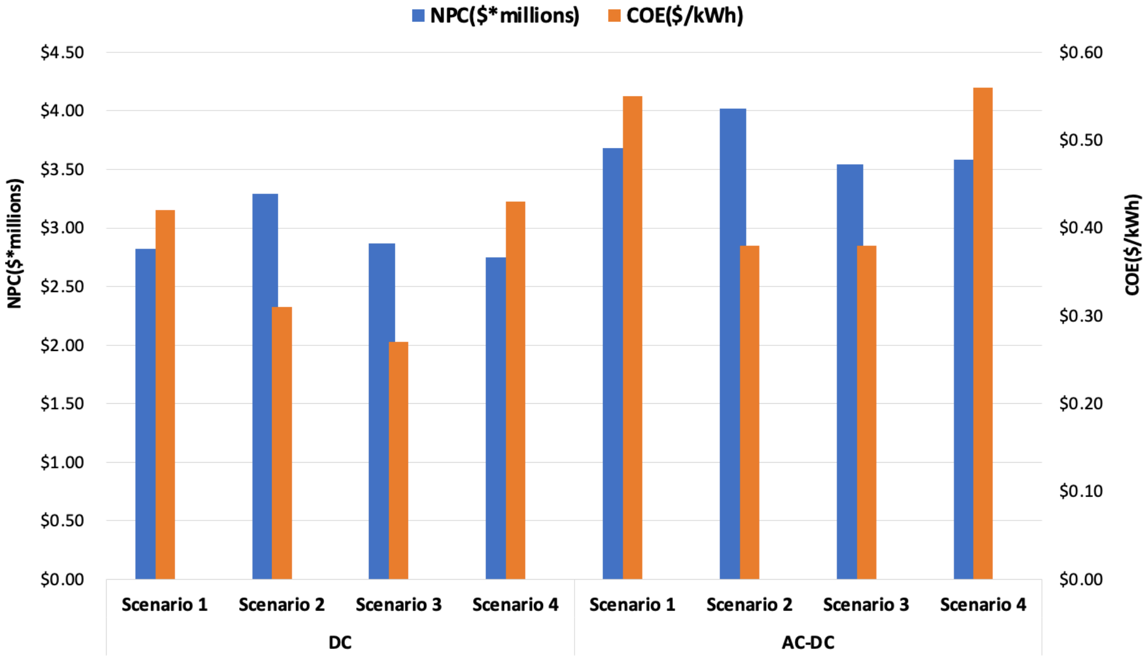


Figure 79 NPC and COE values of DC and AC-DC microgrid for village application under different scenarios

For the village application, the DC microgrid presents lower NPC and COE values when the results are compared with the AC-DC system under all scenarios. Among all scenarios analyzed, scenario 4 is the most cost-effective configuration in the case of DC considering the NPC results with NPC value of $2.75 million and scenario 3 is the most cost-effective configuration in the case of AC-DC microgrid systems with NPC of $3.54 million. Considering the simulated results of COE, NPC 3 of the DC microgrid presented lower COE with a value of US$ 0.27/kWh, which makes it the most cost-effective configuration among all the scenarios considered and cases studied i.e DC and AC-DC microgrids. Whereas scenario 2 of the AC-DC microgrid presented the highest NPC value when compared with all the other scenarios in the case of DC and AC-DC microgrid systems with a value of $4.02 million. On the other hand, scenario 4 and scenario 3 of the DC microgrid presented a lower NPC and COE values with values of US$ 2.75 million and US$ 0.27/kWh, respectively, that demonstrates the proposed DC microgrid for village application is more cost-effective than the proposed AC-DC microgrid with savings of over $0.8 million.

Figure 80 and Figure 81 present the power flows of the load, PV system and the battery for the DC microgrid system for village application under maximum generation and minimum generation scenarios, respectively. The presented power flow curves are for the first week of April, which is the month of maximum solar radiation and for the first week of July which is the month of solar radiation as presented in Figure 70. The simulation output shows that the model gives the anticipated result which is when there is enough generation to supply the demand the load gets power from the PV system and the battery charges as well as when there is less generation to supply the demand the battery supplies power to the load.

Furthermore, other details of the simulation of all case studies are presented in Appendix A (simulation result details of the system proposed for household application), Appendix B (simulation result details of the system proposed for health center application), Appendix C (simulation result details of the system proposed for Village application (DC microgrid)) and Appendix D (simulation result details of the system proposed for Village application (AC-DC microgrid)). The simulation result details include monthly electricity production curves, power flow curves, techno-economic analysis results under different scenarios and case studies, battery charging and discharging curves, cash flow and cost summary curves.

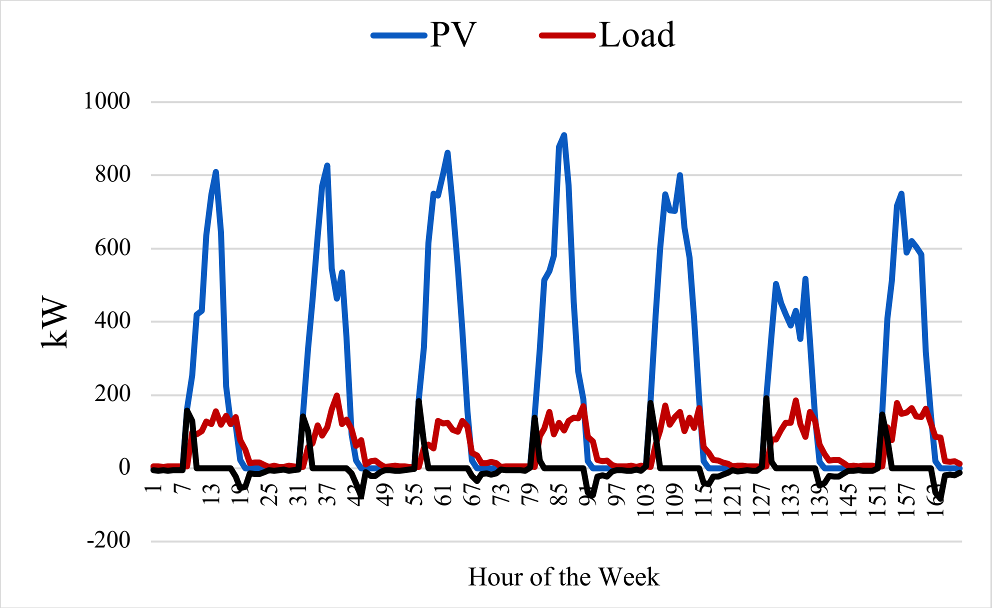


Figure 80 Power flow of Load, PV and Battery for the 1st week of April (month of maximum solar radiation)

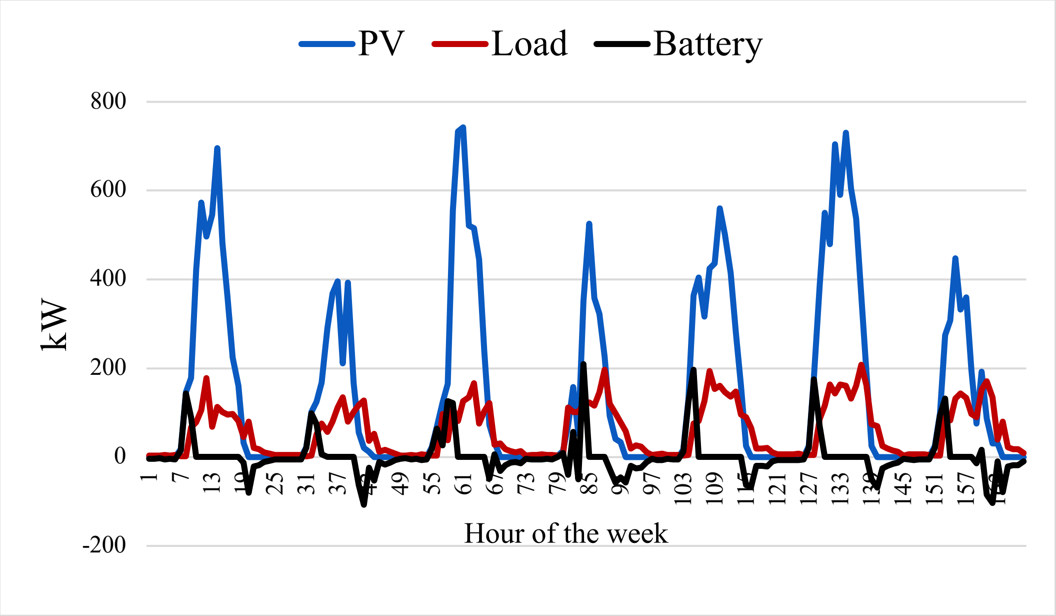


Figure 81 Power flow of Load, PV and Battery for the 1st week of July (month of minimum solar radiation)

CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

6.1. Conclusion

This PhD thesis aimed at finding sustainable energy means to improve energy access in rural developing countries, in particular in Sub-Saharan Africa, a region with very limited modern energy services. Many developing countries including countries in Sub-Saharan African countries (where the majority of the population is located in rural areas) face many challenges to achieve their socio-economic development plans. One of the many challenges is energy access, where over 70% of the population lacks reliable access to modern energy services including lighting, cooking, heating and cooling, information technologies, entertainment and so on. On the other hand, energy access is essential to improve socio-economic development in the region where the majority of the population sector lives under a high poverty level, as well as without adequate social services. Lack of access to modern energy services limits economic and more productive agricultural opportunities, negatively affects the environment, promotes gender inequality and constrains delivery of social services such as health care delivery system and education. People located in rural areas of Sub-Saharan Africa countries lack more services than the people in the urban areas.

Increasing energy access through off-grid solutions could improve socio-economic development, which by itself can be a large developmental challenge in Sub-Saharan Africa. Sub-Saharan Africa is richly endowed with renewable energy resources such as biomass, wind, solar, hydropower and geothermal, which largely remain unexploited. Additionally, renewable energy resources are widely available throughout the region unlike the conventional fossil-based resources, which are concentrated within very few countries. Therefore, finding effective and pragmatic solutions to increase energy access using such resources is critical. In this regard, this PhD thesis fills the gap by finding and presenting inclusive energy solutions for rural areas of Sub-Saharan Africa. As presented, this work analyzed sustainable energy access solutions from different perspectives including:

- Energy-efficient appliances, particularly clean cooking solutions were analyzed, which is a major challenge in rural and semi-urban areas of the region from different aspects such as the impact of inefficient cooking systems on the environment and gender equality, as well as the advantage of clean cooking solutions from energy saving, emission minimization, gender empowerment, life cycle cost, were analyzed and presented.
- DC microgrids were designed and modeled using MATLAB and HOMER software and the techno-economic analysis were performed for different applications including rural primary school, rural health center, rural household and villages for rural sites mostly located in Ethiopia and Burkina Faso in the case of health center.
- DC and AC-DC microgrids were designed and comparative analyses were made.
- The impact of energy-efficient appliances on improving energy access, as well as on the lifecycle cost of a system was also analyzed.

Cooking is the most energy-intensive end-use in the residential sector in rural and remote areas of Sub-Saharan Africa. In the study, an experimental evaluation was carried out using different electric cookstoves, considering Ethiopian food types, with the objective of selecting the technologies with higher benefits for rural areas of developing countries, with low access to clean cooking options and low-income levels. The temperatures at different parts of the cookstoves body and cookware were monitored, as well as the energy consumption during the cooking test.

The investigation indicates that the cooking time for the same amount of rice ranges from 12 to 20 minutes for TEIH and IPPC, respectively, whereas for Shiro cooking the minimum cooking time recorded was for IPPC (60 minutes) and the maximum cooking time was for SHP (130 minutes), while LEIH and LMEC took about 70 minutes. Therefore, in terms of time saving, TEIH is a better option for rice cooking and IPPC for Shiro cooking. On the other hand, the heating transfer behaviors of each cookstove and cookware were analyzed, and the results indicate that LMEC had a high change in temperature values on the surface of the cookstove and the body of the cookware, which implies that it has higher heat losses. The output thermal energy of each cooking technology was calculated and LMEC presented higher variation within the output and the input energy for both rice and Shiro cooking compared with the other technologies. In the case of boiling water, the energy efficiencies of 32.6%, 70.5%, 67.5% and 78.8% were recorded for LMEC, TEIH, SHP and IPPC, respectively. This indicates that IPPC presents the highest efficiency, while LMEC presents the lowest energy efficiency for boiling water. Furthermore, the energy costs analysis indicates that LMEC had higher energy costs and IPPC has lower energy costs and the shift between the two options can lead to 59.4% of savings. The NPC results indicate that IPPC had higher costs (US$ 225.39) followed by TEIH (US$ 137.31), LMEC (US$ 133.05) and SHP (US$ 91.22) over the given lifespan. Although, the investment cost of LMEC is lower than LEIH by 69%, the higher energy, maintenance and repair costs resulted in a lower cost-benefit ratio (US$ 4.26) as compared to LEIH.

Moreover, the adoption and promotion of clean cooking technologies require policies and strategies that should be implemented. As a result, it is necessary to involve governmental agencies at every level in the implementation of the proposed policies and strategies including the development of a clean cooking policy and strategy. It is also necessary to enhance supply and demand by following different strategies like educational and training campaigns on the benefits of clean cooking solutions for customers and the business sector. Energy efficiency, emissions, safety standards and gender equality are also important components of the policy framework that should be taken under consideration for the effective adoption and promotion of clean cooking solutions in rural areas of developing countries.

The other dimension of the study was to design and model DC microgrids using locally available renewable energy sources for rural energy solutions. In this regard, the study designed, modeled and assessed four DC microgrids and one AC-DC microgrid. The four DC microgrids were for applications in schools, households, health centers and villages, whereas the AC-DC microgrid was designed for village applications to make a comparative analysis with DC microgrids. The design and analysis were performed using MATLAB Simulink and HOMER software. The study also considered energy-efficient appliances as a main aspect of the analysis, as well as load estimation scenarios and their impact on energy access, and the assessment analyzed life-cycle cost and load demand minimization aspects.

One of the studies designed and modeled a DC-microgrid system composed of solar PV, controller and battery storage system for a primary school in the rural sub-Saharan region, using Ethiopia as a case study. For the design of the DC-microgrid two load estimation and two scenarios of generation profiles were considered. The first scenario was the estimation of daily load based on standard efficiency appliances and the second scenario was the estimation of the daily load based on emerging high-efficiency appliances, which is one of the novel aspects of this study. On the other hand, the average maximum generation and average minimum generation days were considered to assess the system performance in both scenarios.

Taking into account the estimated loads for both cases and generation scenarios the PV and the battery were sized at 3.7 kWp and 80 kWh, and 1.8 kWp and 38 kWh for standard efficiency and high-efficiency appliances, respectively. The proposed DC microgrid was designed and simulated for both load and generation scenarios using MATLAB/Simulink. The simulation results show that the proposed and designed DC-microgrid can supply the required demand with the support of a battery storage system using standard or high-efficiency appliances in both generation options under the presented conditions. The stored energy in each load and generation scenario at the end of the day was enough to supply the demand for two days. Severe weather conditions with several days without sunshine are very uncommon in Ethiopia during school months. A small additional investment (increasing the solar PV capacity by 50%) can be used to make the system more robust concerning longer periods of reduced solar radiation. On the other hand, the system cost was assessed, and the result indicates that the system with standard efficiency appliances more than doubles the cost with the option with high-efficiency appliances, proving the high impact of the selected appliances on the cost-effectiveness of the solution.

The other studies were techno-economic analyses of DC and AC-DC microgrids for applications in rural households, health centers and villages using HOMER software. The studies considered different locations in Ethiopia and Burkina Faso and different scenarios based on sensitivity variables. The consideration of different locations and the scenarios based on sensitivity variables was aimed to analyze the impact of the variability of renewable energy resources on the overall performance and the cost of the system. The sensitivity variables/constraints are related to economics (inflation rate, discount rate, project lifetime) and components constraints such as lifetime and derating factor for PV, lifetime, minimum and maximum State of Charge for the case of battery and hub height and lifetime for the case of wind turbines. Based on such factors, four scenarios were proposed and the technical-economic analysis of DC and AC-DC microgrids for household, health center and village applications were performed using HOMER software. Based on all the scenarios and composed of different components, different system configurations of hybrid renewable energy systems were analyzed in HOMER by simulating a dynamic hybrid model.

On the other hand, energy-efficient appliances were considered for the load demand assessment of each case studies, since it is proved that energy-efficient appliances presented higher cost-effectiveness in the analysis of DC microgrids for primary school applications. Assessments of residential, community and commercial, as well as a health center and school loads and resources of the selected location, were done, which are inputs for the simulation of the system. Additionally, capital cost, O&M cost, and replacement cost of different components were used in the model along with different sensitivity variables like project lifetime, components lifetime, inflation and discount rates as the inputs. Then, simulations were performed for the proposed DC and AC-DC microgrid system, as well as the technical-economic analysis and optimum sizing of different components of the systems using HOMER.

In the case of DC microgrid for household energy supply system, among the four different scenarios and configurations analyzed in this work, scenario 4 (a project lifetime of 25 years, inflation rate of 5%, nominal discount rate of 12%, PV derating factor of 90% and 25 years lifetime, battery minimum SoC of 30% and maximum SoC of 100%) is found to be the most cost-effective configuration considering NPC with a value of $15,274.39 and NPC of $17,472.53 in the case of the system composed of PV and lithium-ion batteries and the system of composed of PV and lead-acid batteries, respectively. This implies that the system with lithium-ion batteries is the most cost-effective compared with the system with lead-acid batteries. Whereas, considering COE scenario 1 and scenario 3 of the system composed of PV and Lithium-ion batteries presented better economic benefit with US$ 0.49/kWh.

The study also presented the techno-economic analysis of a DC microgrid composed of PV and lithium-ion batteries in two different locations i.e., in rural areas of Ethiopia and Burkina Faso. The results indicated that the system designed for the Ethiopian case presented lower NPC values as compared to the system in Burkina Faso in all four scenarios. As in the case of the household, scenario four presents lower NPC compared with the other three scenarios with values of $11,035.76 for the Ethiopian case and $11,986.82 for the Burkina Faso case, respectively. Considering the COE values of all the scenarios and case studies considered, scenario 3 of Burkina Faso presented lower COE with a value of US$ 0.39/kWh. This implies that for the DC microgrid proposed for health center application scenario 3 is the most cost-effective scenario, even if the NPC values is the highest compared with all the other scenarios analyzed with a value of US$ 20, 100. Whereas in the case of the systems analyzed for village application where inclusive energy supply was considered, among all scenarios, scenario four is found to be the most cost-effective configuration in the case of DC with NPC and COE values of $2.75 million and 0.43 $/kWh and scenario three is the most cost-effective configuration in the case of AC-DC microgrid systems considering only with NPC value of $3.54 million. Whereas scenario two of the AC-DC microgrid presented the highest NPC value compared with all the other scenarios in the case of DC and AC-DC microgrid systems with a value of $4.02 million. On the other hand, scenario 3 of the DC microgrid presented a lower COE value compared with all other scenarios in both case studies with a value of US$ 0.27/kWh. For the analysis, it is concluded that the proposed DC microgrid for village application is more cost-effective than the proposed AC-DC microgrid with savings of over $0.8 million.

The results obtained in this study are multi-dimensional and can have a key role to promote large-scale energy access in rural areas of Sub-Saharan Africa, as well as improving the socio-economic wellbeing of the underserved people who lack the multiple benefits of modern energy services. The implementation of the studies' outcome would have a significant impact on promoting clean cooking, minimizing household air pollution and promoting gender equality, as well as averts the impact of inefficient cooking systems on health and the environment. Furthermore, the studies implementation would have a huge impact on promoting education, increasing quality education, health care services, increasing quality health care services, to attract teachers and health care workers in rural areas which is a challenge in many areas due to lack of energy access and increasing the number of children attending schools, as well as healthy generation. On the other hand, the implementation of the studies can have a significant impact on business creation, agricultural productivity, and creating a sustainable environment, as well as sustainable socio-economic development. If there is electricity in the nearby primary school, families could send their children (that increases the number of children attending classes) to get mutual benefit including to charge their mobile phone and lighting appliances which avoid long travels to charge the mobile phone, as well as to save money that could be paid for charging. Additionally, if there is electricity in the nearby health center, safe baby delivery is possible, children get vaccinated for polio and other early childcare vaccination, residents in the area get medication and family planning services can be provided.

Apart from promoting such benefits, inclusive rural energy access has a fundamental impact on the level of awareness of the community, raising self-confidence, increasing income-generation opportunities, and empowering women by increasing the number of girls attending the schools and increasing the number of girls promoted to secondary and higher education. The study also applies to many sub-Saharan countries in the region with very low energy access rates and abundant solar energy, thus giving a large contribution to achieve the United Nations Sustainable Development Goals including Good Health and Well-being (SDG 3), Quality Education (SDG 4), Gender Equality (SDG 5), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG7), Decent Work and Economic Growth (SDG 8) and Climate action (SDG 13).

6.2. Future Work

Like many other studies, this thesis work had some limitations. One limitation of this study is that due to the global pandemic and limited resources available, travel for interviews to analyze the social aspects of the study was impeded. Particularly, in the analysis of clean cooking technologies, it was supposed to speak with women in the group on the impact of conventional cooking systems from their perspective and the acceptance of the proposed clean cooking systems. Additionally, in the techno-economic analysis of proposed DC and AC-DC microgrids, since the cooking loads are much higher than other loads, it is considered that to include several houses in clusters to make the cooking at different hours. However, this needs to be analyzed whether it has social acceptance by the community. These issues could be considered for continuing this research work in the future by considering the social factors of promoting clean cooking access and analyzing emerging cooking technologies like solar cooking technologies, as well as cluster cooking options, which are important for load shifting and management.

Practical implementation of microgrids and analysis of the real data is crucial for off-grid systems to be implemented and to further modify it, if necessary. Therefore, another dimension of future work would be on practical implementation and analysis of at least one of the designed and modeled microgrids as a pilot project in the selected area. This future research dimension should be focused on the analysis of the system on the ground and will further analyze the measures that can be implemented to balance the supply and demand. Furthermore, in this part of the study, the development of remote monitoring and control strategies of the proposed microgrids would be another aspect that requires investigation.

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Appendix A

Techno-economic Analysis of Standalone DC microgrid for Rural Household in Sub-Saharan Africa: A case of Ethiopia

System Simulation Report (Under Scenario 1)

PV + Lead Acid

Location: Sedeha Melefu, Afar, Ethiopia (12°11.4'N, 40°29.1'E)

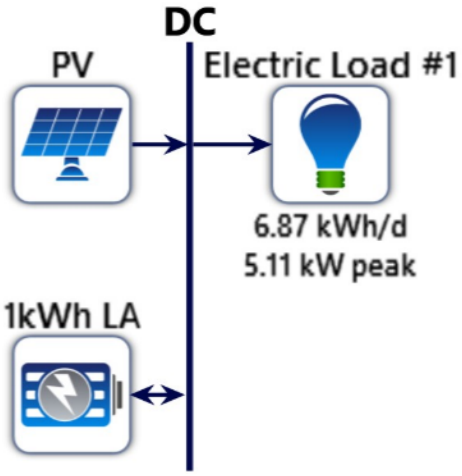
Total Net Present Cost: $18,246.01

Levelized Cost of Energy ($/kWh): $0.572

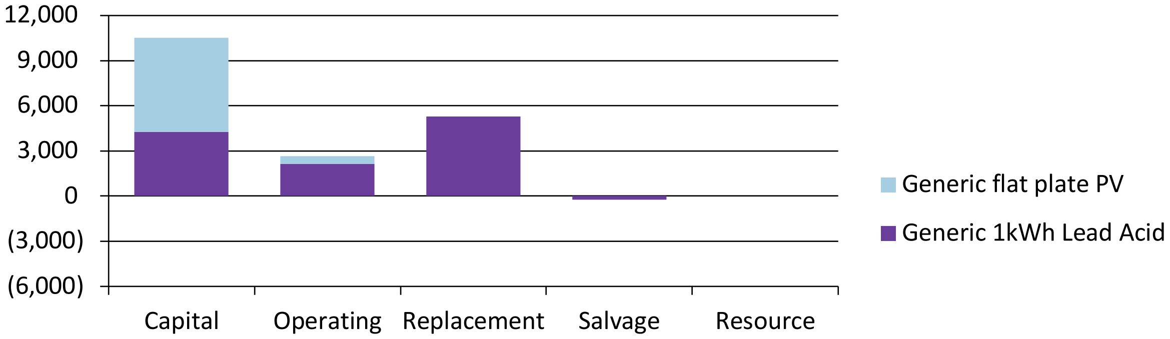
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	3.93	kW
Storage	Generic 1kWh Lead Acid	17	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



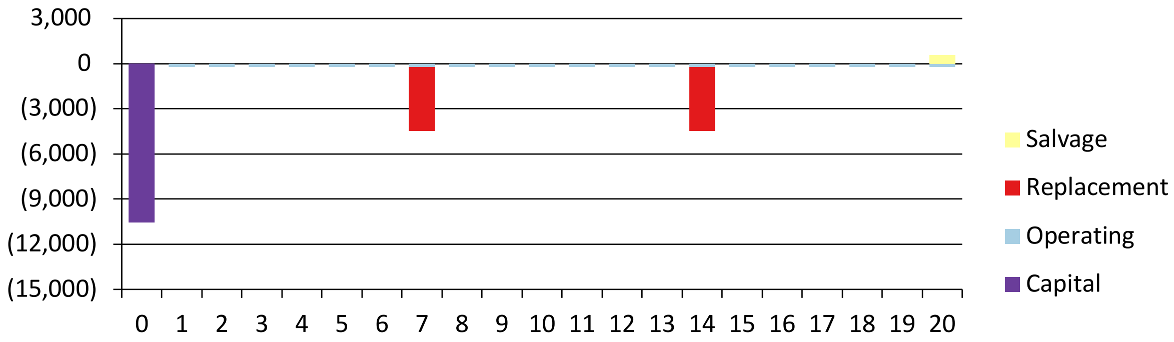
Net Present Costs

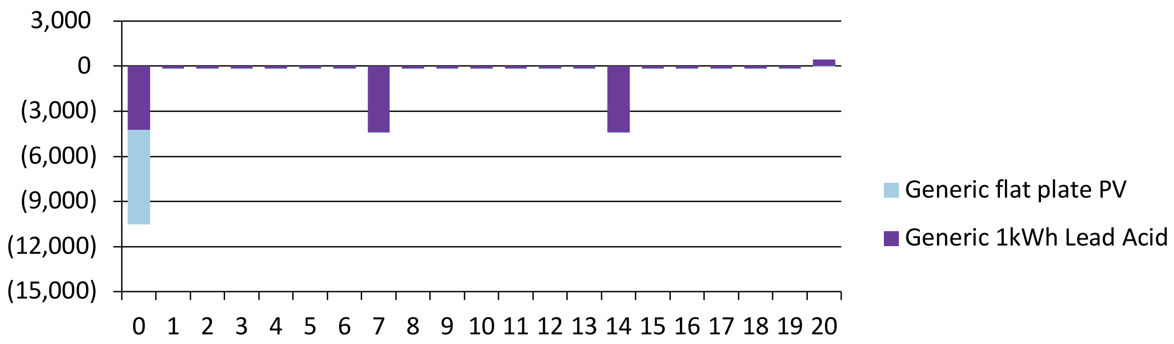
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$4,250	$2,162	$5,285	-$239.45	$0.00	$11,457
Generic flat plate PV	$6,289	$499.88	$0.00	$0.00	$0.00	$6,789
System	$10,539	$2,662	$5,285	-$239.45	$0.00	$18,246

Annualized Costs

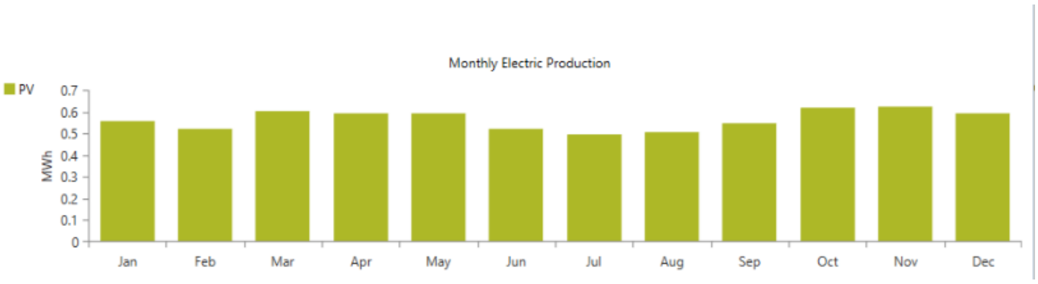
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$334.18	$170.00	$415.53	-$18.83	$0.00	$900.89
Generic flat plate PV	$494.50	$39.31	$0.00	$0.00	$0.00	$533.81
System	$828.68	$209.31	$415.53	-$18.83	$0.00	$1,435

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	4,059	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.50	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	6,763	100
Total	6,763	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,509	100
Deferrable Load	0	0
Total	2,509	100

PV: Generic flat plate PV

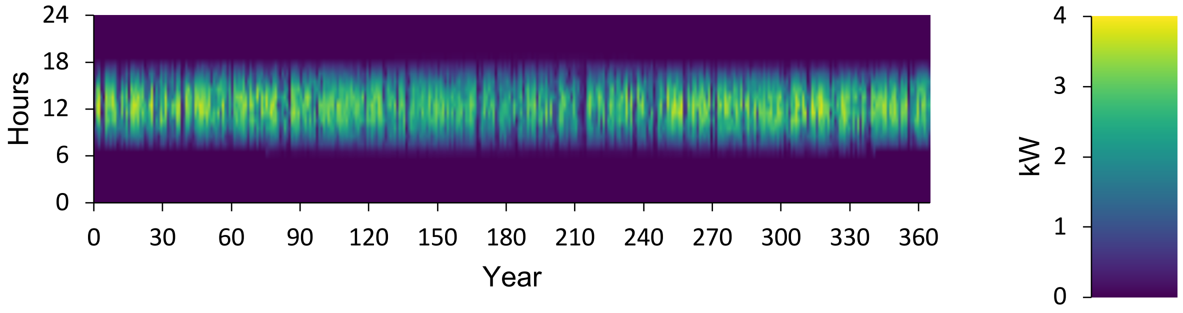
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	3.81	kW
PV Penetration	270	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0789	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	3.93	kW
Mean Output	0.772	kW
Mean Output	18.5	kWh/d
Capacity Factor	19.6	%
Total Production	6,763	kWh/yr

Generic flat plate PV Output (kW)



Storage: Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	17.0	qty.
String Size	1.00	batteries
Strings in Parallel	17.0	strings
Bus Voltage	12.0	V

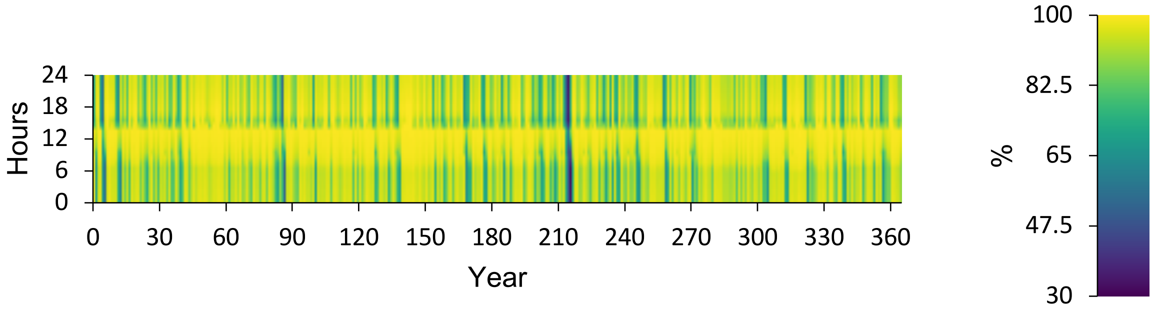
Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	988	kWh/yr
Energy Out	792	kWh/yr
Storage Depletion	1.87	kWh/yr
Losses	198	kWh/yr
Annual Throughput	885	kWh/yr

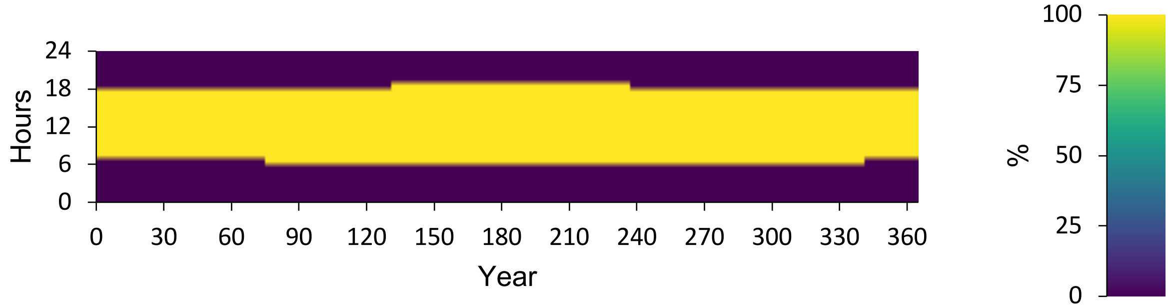
Lead Acid Statistics

Quantity	Value	Units
Autonomy	47.5	hr
Storage Wear Cost	0.140	$/kWh
Nominal Capacity	17.0	kWh
Usable Nominal Capacity	13.6	kWh
Lifetime Throughput	6,197	kWh
Expected Life	7.00	yr

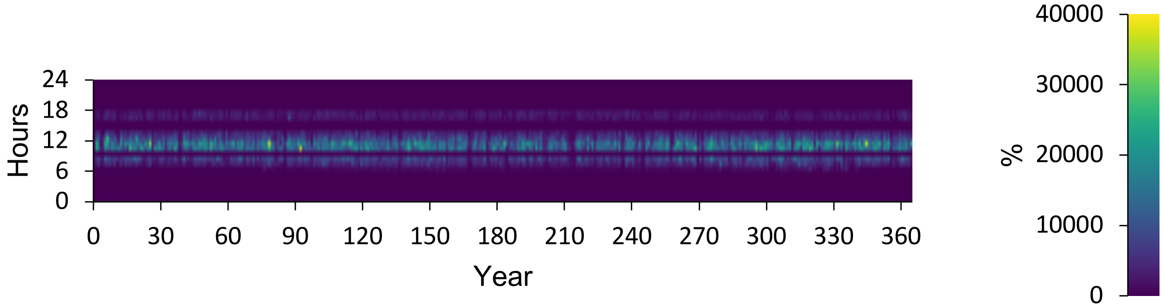
Lead Acid State of Charge (%)



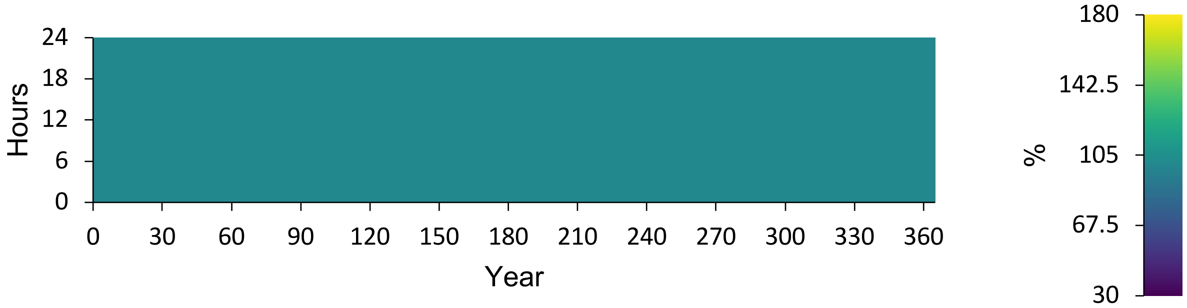
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System cost
Net Present Cost	$18,246
CAPEX	$10,539
OPEX	$606.01
LCOE (per kWh)	$0.572
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2)

PV + Lead Acid

Location: Sedeha Melefu, Ethiopia (12°11.4'N, 40°29.1'E)

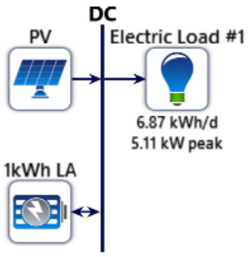
Total Net Present Cost: $25,733.97

Levelized Cost of Energy ($/kWh): $0.636

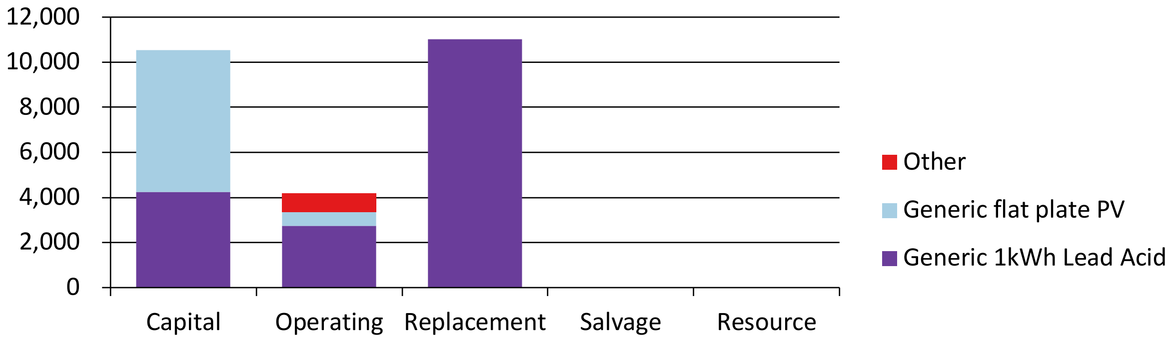
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	3.93	kW
Storage	Generic 1kWh Lead Acid	17	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



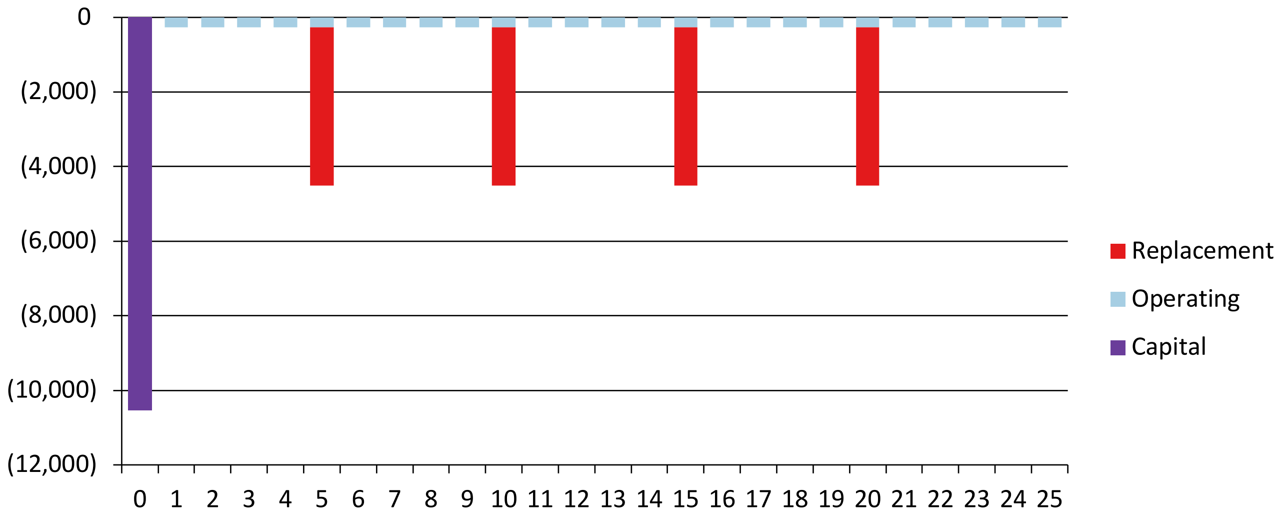
Net Present Costs

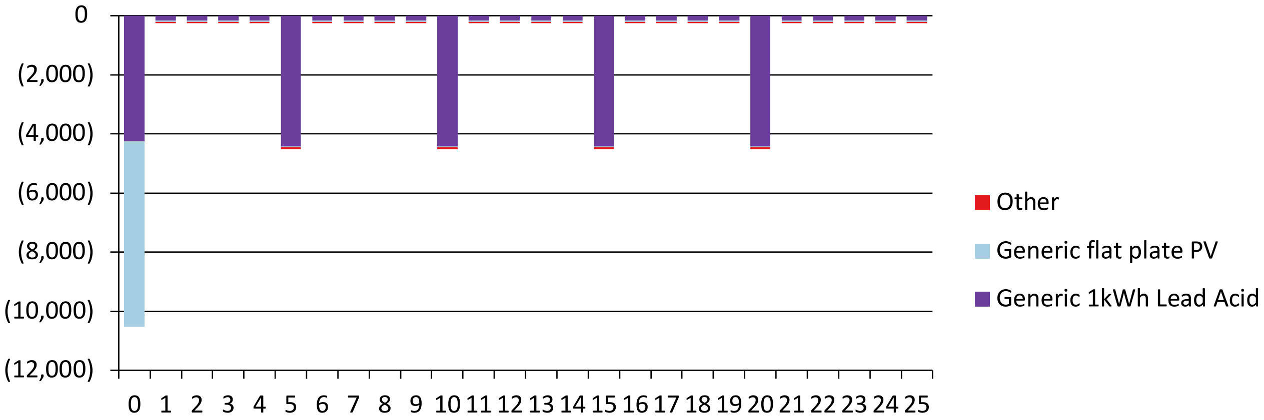
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$4,250	$2,741	$11,014	$0.00	$0.00	$18,005
Generic flat plate PV	$6,289	$633.73	$0.00	$0.00	$0.00	$6,923
Other	$0.00	$806.15	$0.00	$0.00	$0.00	$806.15
System	$10,539	$4,181	$11,014	$0.00	$0.00	$25,734

Annualized Costs

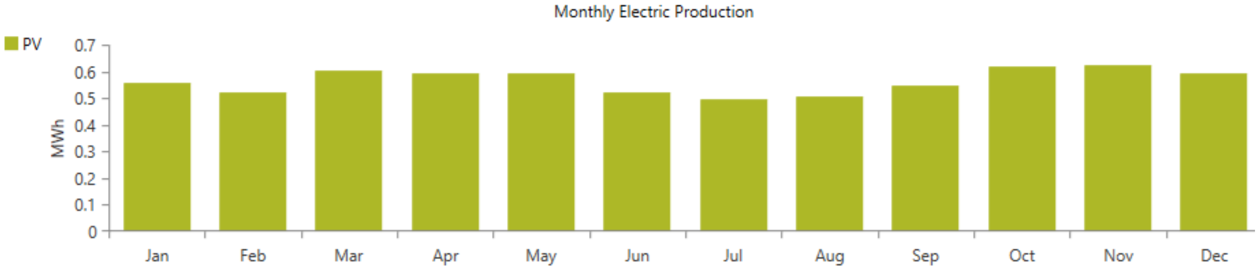
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$263.60	$170.00	$683.14	$0.00	$0.00	$1,117
Generic flat plate PV	$390.06	$39.31	$0.00	$0.00	$0.00	$429.37
Other	$0.00	$50.00	$0.00	$0.00	$0.00	$50.00
System	$653.66	$259.31	$683.14	$0.00	$0.00	$1,596

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	4,057	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.50	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	6,763	100
Total	6,763	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,509	100
Deferrable Load	0	0
Total	2,509	100

PV: Generic flat plate PV

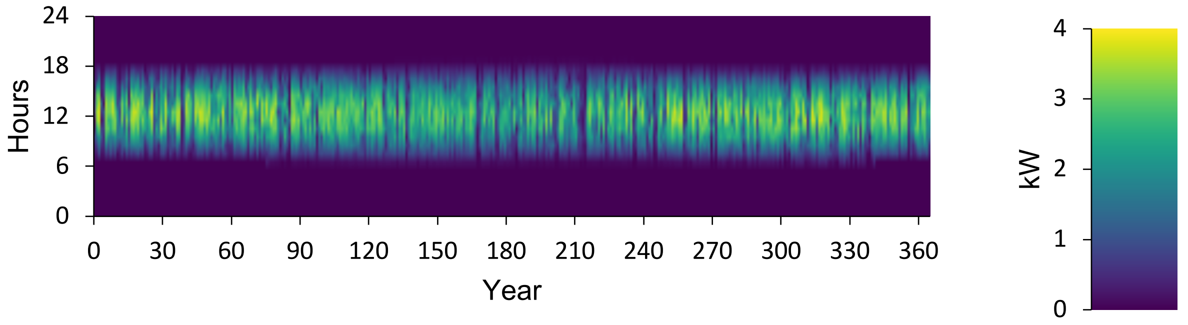
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	3.81	kW
PV Penetration	270	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0635	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	3.93	kW
Mean Output	0.772	kW
Mean Output	18.5	kWh/d
Capacity Factor	19.6	%
Total Production	6,763	kWh/yr

Generic flat plate PV Output (kW)



Storage: Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	17.0	qty.
String Size	1.00	batteries
Strings in Parallel	17.0	strings
Bus Voltage	12.0	V

Generic 1kWh Lead Acid Result Data

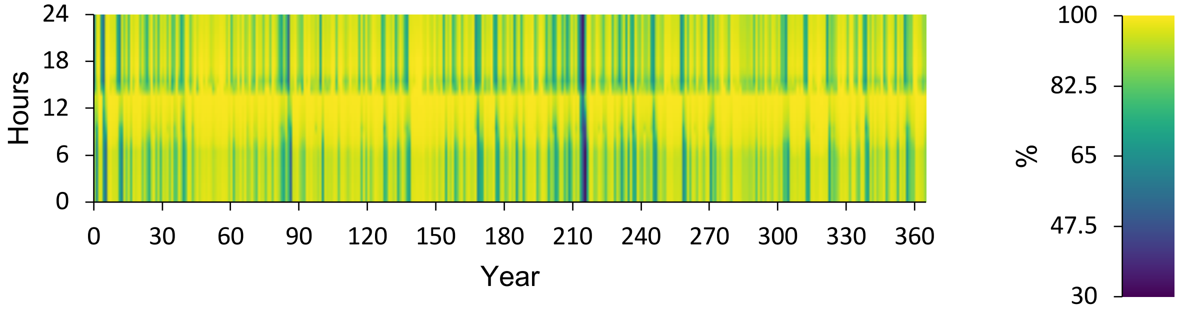
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	990	kWh/yr
Energy Out	792	kWh/yr
Storage Depletion	0.164	kWh/yr
Losses	198	kWh/yr
Annual Throughput	885	kWh/yr

Generic 1kWh Lead Acid Statistics

Quantity	Value	Units
Autonomy	41.6	hr

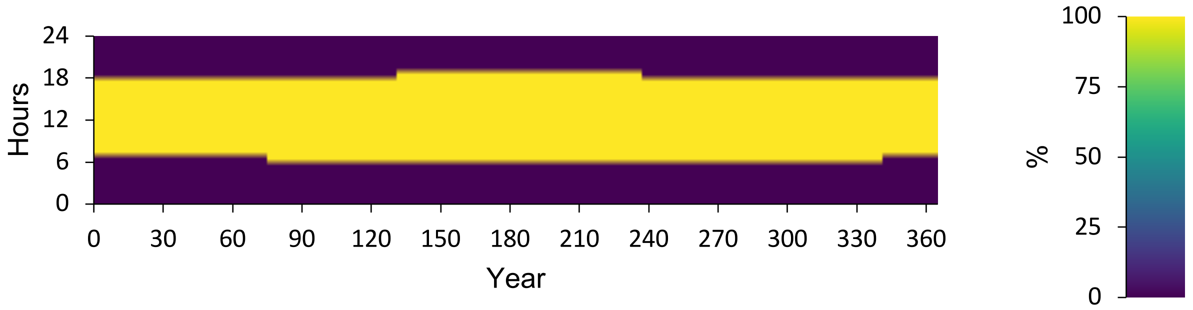
Storage Wear Cost	0.0932	$/kWh
Nominal Capacity	17.0	kWh
Usable Nominal Capacity	11.9	kWh
Lifetime Throughput	4,427	kWh
Expected Life	5.00	yr

Generic 1kWh Lead Acid State of Charge (%)

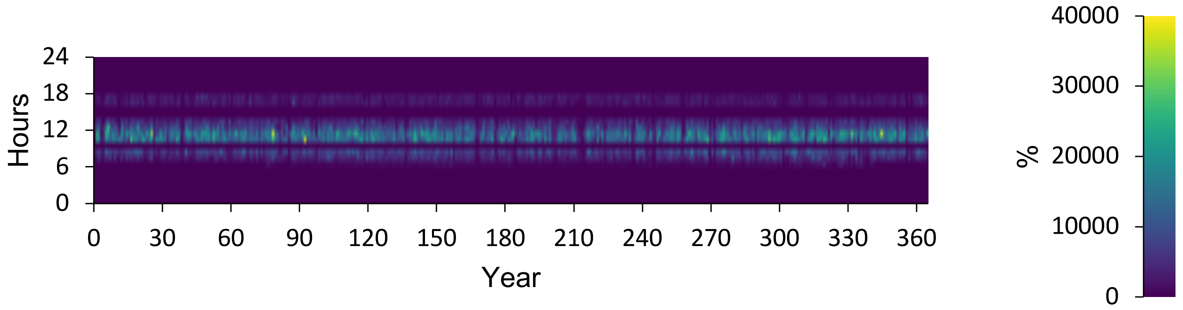


Renewable Summary

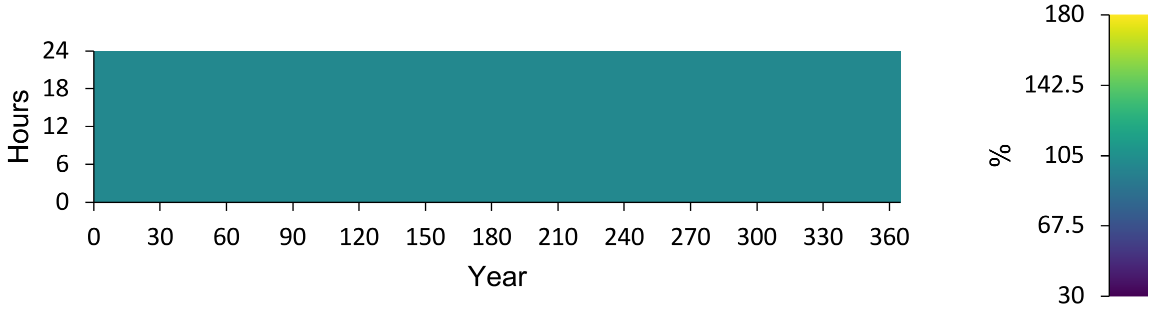
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System cost
Net Present Cost	$25,734
CAPEX	$10,539
OPEX	$942.44
LCOE (per kWh)	$0.636
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 3)

PV + Lead Acid

Location: Sedeha Melefu, Ethiopia (12°11.4'N, 40°29.1'E)

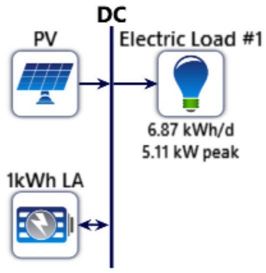
Total Net Present Cost: $27,848.00

Levelized Cost of Energy ($/kWh): $0.559

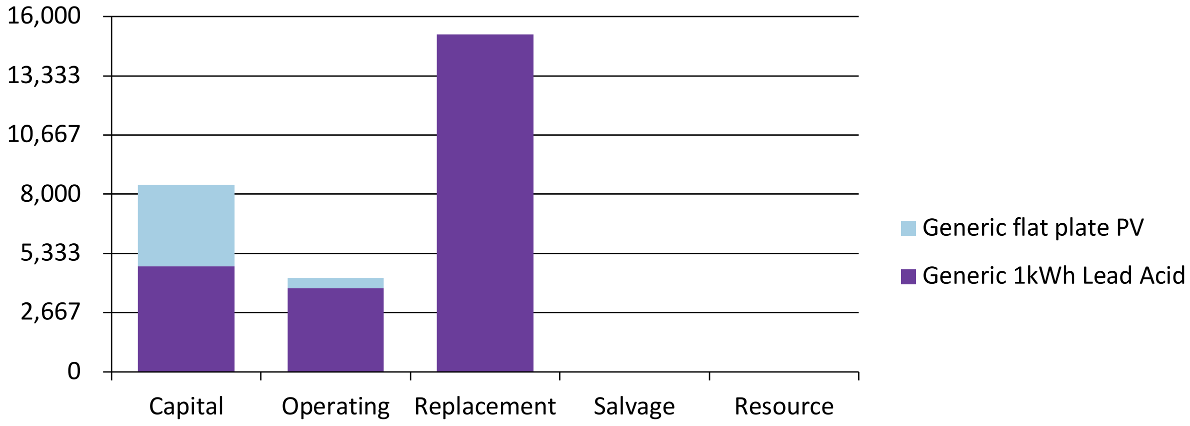
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.30	kW
Storage	Generic 1kWh Lead Acid	19	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



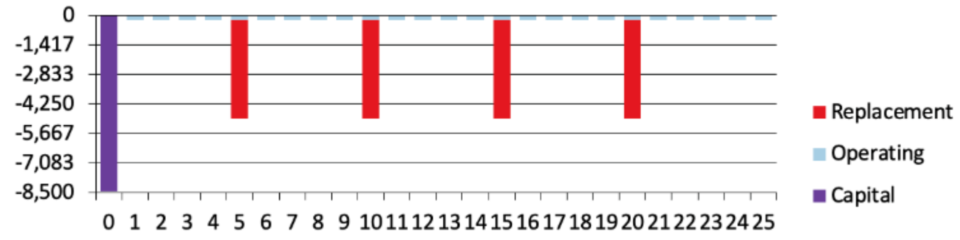
Net Present Costs

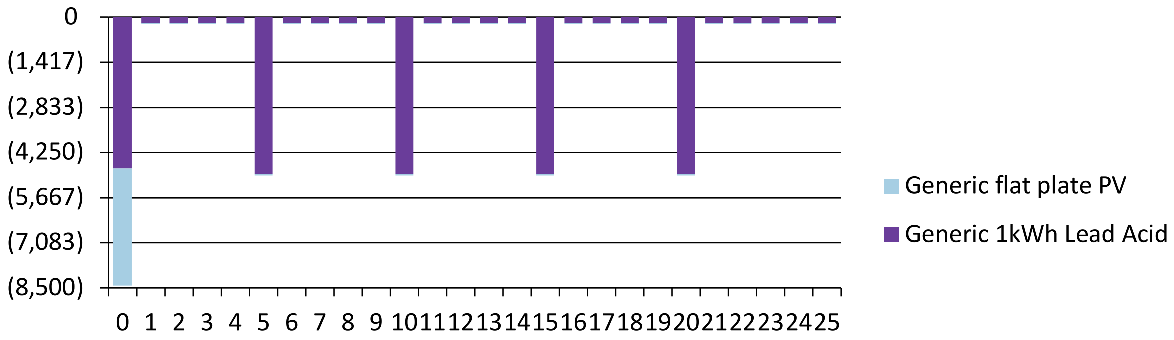
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$4,750	$3,775	$15,185	$0.00	$0.00	$23,710
Generic flat plate PV	$3,681	$457.05	$0.00	$0.00	$0.00	$4,138
System	$8,431	$4,232	$15,185	$0.00	$0.00	$27,848

Annualized Costs

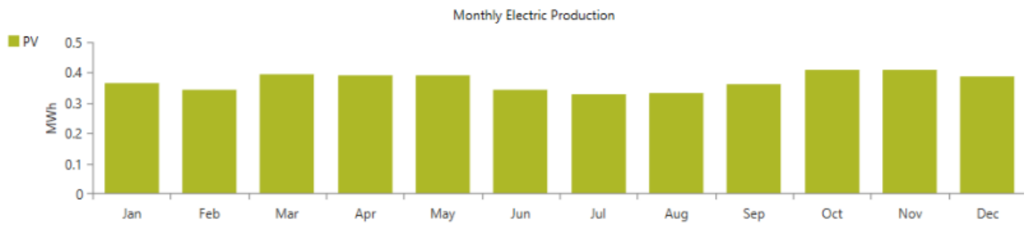
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$239.09	$190.00	$764.34	$0.00	$0.00	$1,193
Generic flat plate PV	$185.27	$23.01	$0.00	$0.00	$0.00	$208.28
System	$424.36	$213.01	$764.34	$0.00	$0.00	$1,402

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,645	kWh/yr
Unmet Electric Load	1.36	kWh/yr
Capacity Shortage	2.47	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,453	100
Total	4,453	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,507	100
Deferrable Load	0	0
Total	2,507	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

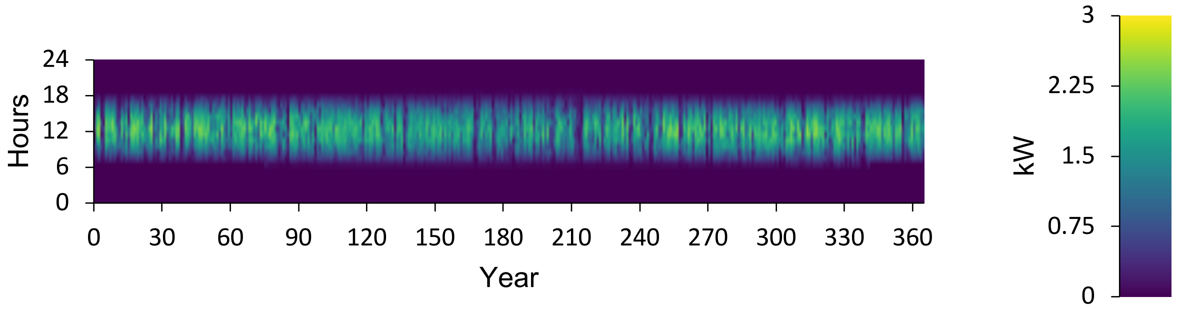
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	2.51	kW
PV Penetration	178	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0468	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.30	kW
Mean Output	0.508	kW
Mean Output	12.2	kWh/d
Capacity Factor	22.1	%
Total Production	4,453	kWh/yr

Generic flat plate PV Output (kW)



Storage: Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	19.0	qty.
String Size	1.00	batteries

Strings in Parallel	19.0	strings
Bus Voltage	12.0	V

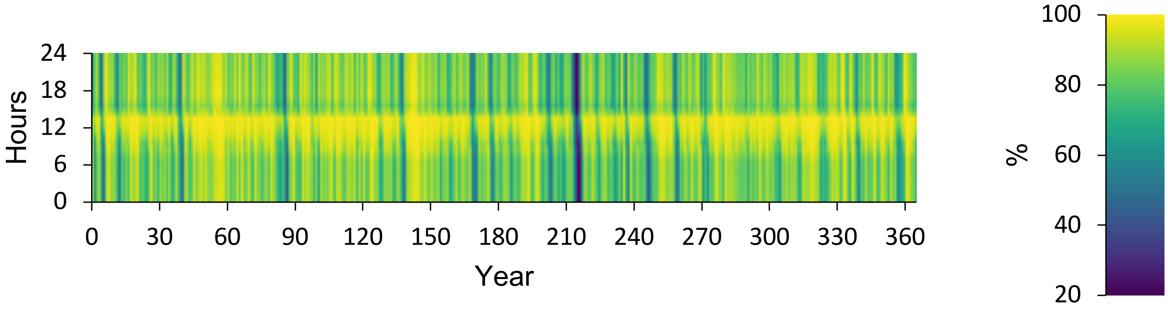
Generic 1kWh Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	1,513	kWh/yr
Energy Out	1,213	kWh/yr
Storage Depletion	2.27	kWh/yr
Losses	303	kWh/yr
Annual Throughput	1,356	kWh/yr

Generic 1kWh Lead Acid Statistics

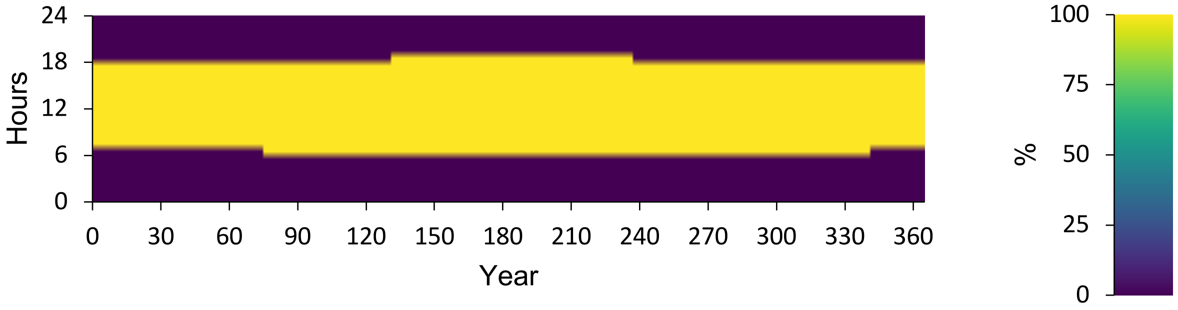
Quantity	Value	Units
Autonomy	53.1	hr
Storage Wear Cost	0.140	$/kWh
Nominal Capacity	19.0	kWh
Usable Nominal Capacity	15.2	kWh
Lifetime Throughput	6,778	kWh
Expected Life	5.00	yr

Generic 1kWh Lead Acid State of Charge (%)

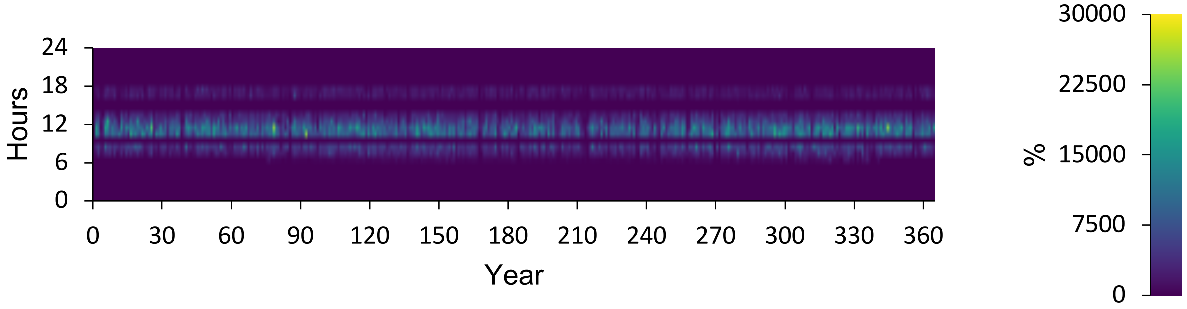


Renewable Summary

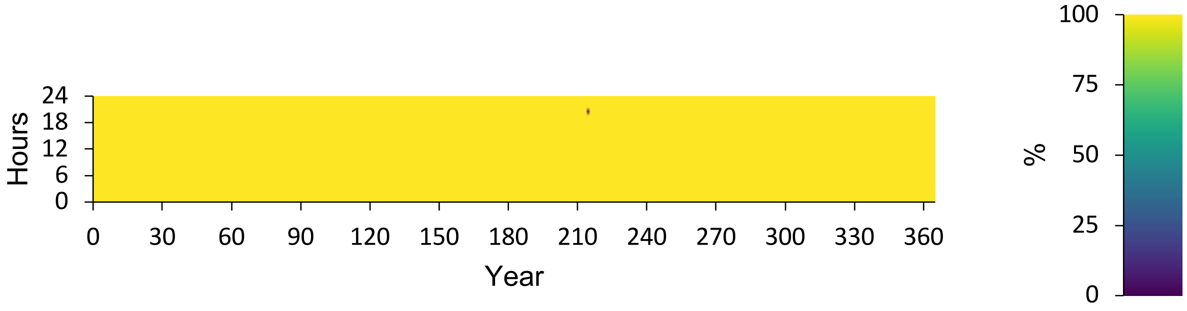
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$27,848
CAPEX	$8,431
OPEX	$977.34
LCOE (per kWh)	$0.559
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4)

PV + Lead Acid

Location: Sedeha Melefu, Afar, Ethiopia (12°11.4'N, 40°29.1'E)

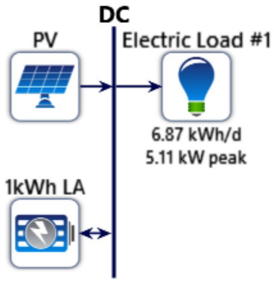
Total Net Present Cost: $17,472.53

Levelized Cost of Energy ($/kWh): $0.580

System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	3.50	kW
Storage	Generic 1kWh Lead Acid	17	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary

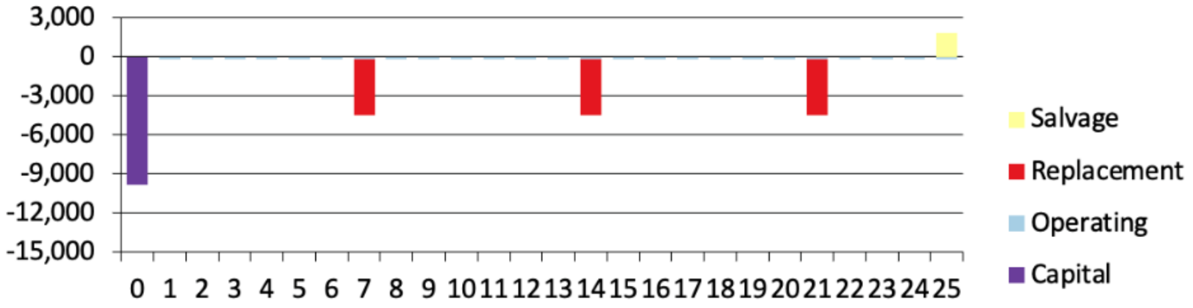
Net Present Costs

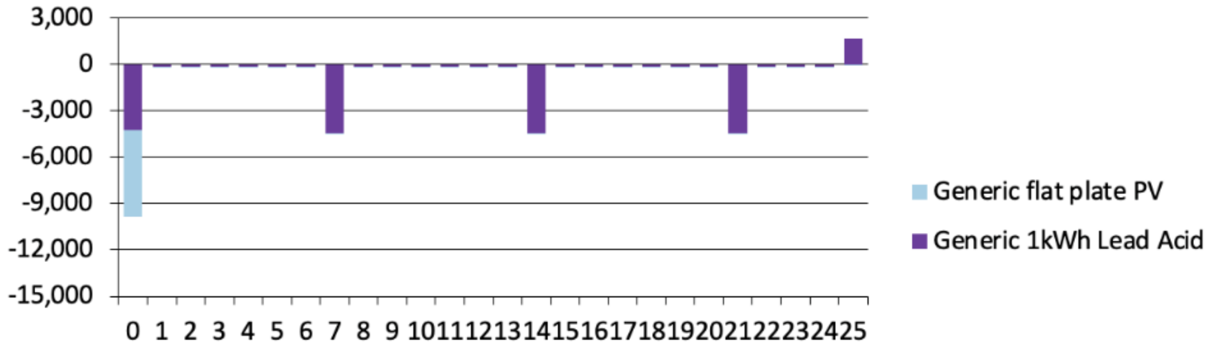
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$4,250	$2,042	$5,523	-$362.82	$0.00	$11,452
Generic flat plate PV	$5,600	$420.42	$0.00	$0.00	$0.00	$6,020
System	$9,850	$2,462	$5,523	-$362.82	$0.00	$17,473

Annualized Costs

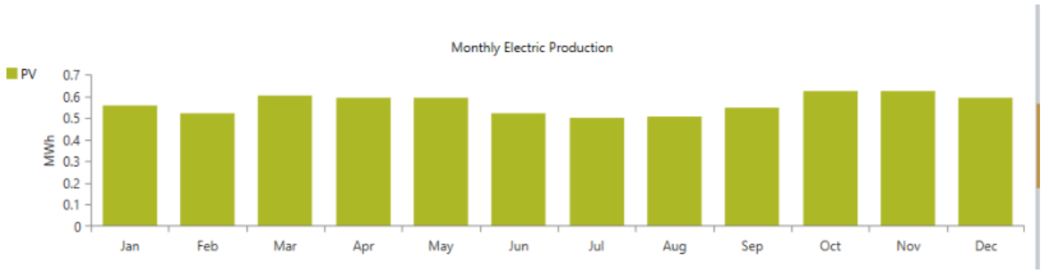
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Lead Acid	$353.81	$170.00	$459.78	-$30.20	$0.00	$953.38
Generic flat plate PV	$466.20	$35.00	$0.00	$0.00	$0.00	$501.20
System	$820.01	$205.00	$459.78	-$30.20	$0.00	$1,455

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	4,071	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.49	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	6,775	100
Total	6,775	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,509	100
Deferrable Load	0	0
Total	2,509	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

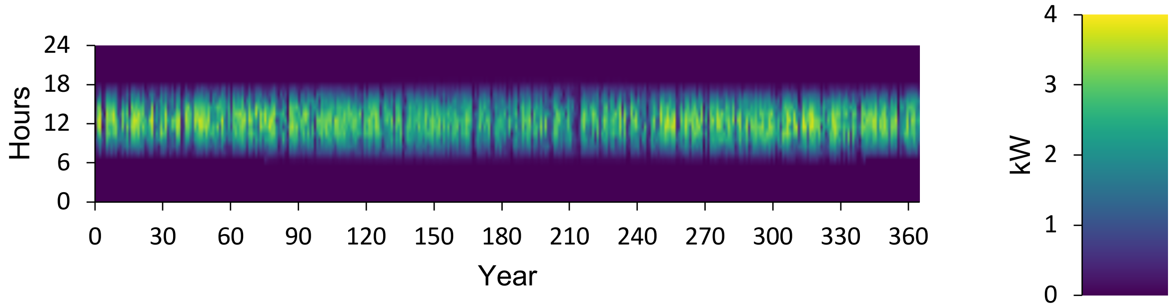
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	3.81	kW
PV Penetration	270	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0740	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	3.50	kW
Mean Output	0.773	kW
Mean Output	18.6	kWh/d
Capacity Factor	22.1	%
Total Production	6,775	kWh/yr

Generic flat plate PV Output (kW)



Storage: Lead Acid

Generic 1kWh Lead Acid Properties

Quantity	Value	Units
Batteries	17.0	qty.
String Size	1.00	batteries
Strings in Parallel	17.0	strings
Bus Voltage	12.0	V

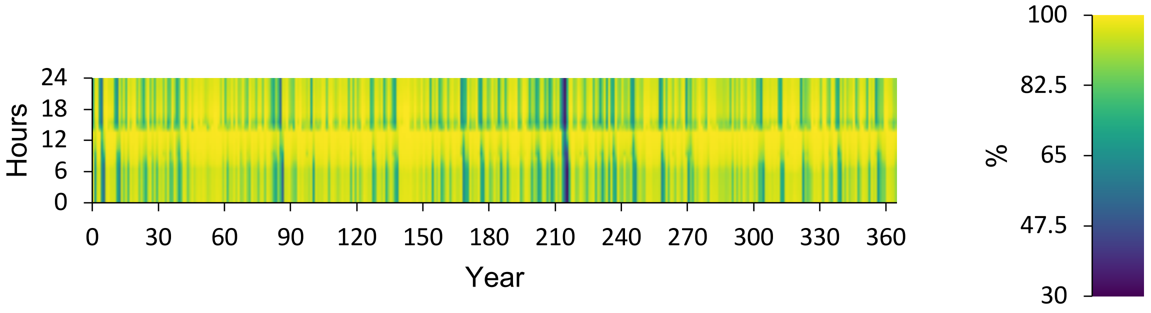
Generic 1kWh Lead Acid Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	986	kWh/yr
Energy Out	790	kWh/yr
Storage Depletion	1.86	kWh/yr
Losses	197	kWh/yr
Annual Throughput	883	kWh/yr

Generic 1kWh Lead Acid Statistics

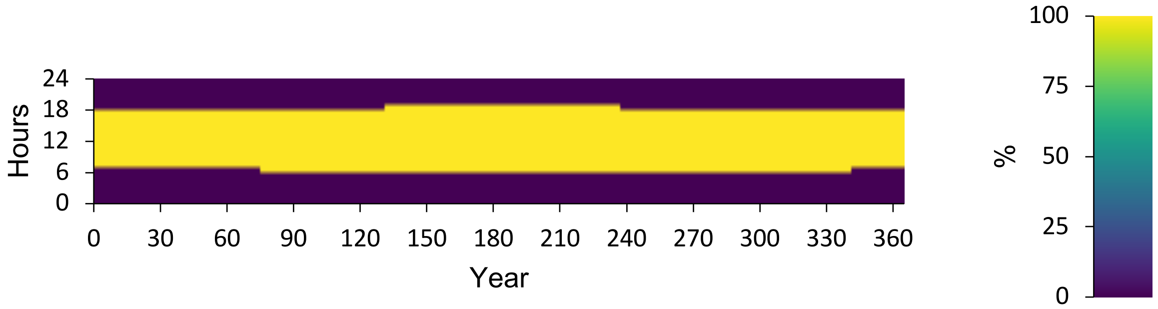
Quantity	Value	Units
Autonomy	41.6	hr
Storage Wear Cost	0.140	$/kWh
Nominal Capacity	17.0	kWh
Usable Nominal Capacity	11.9	kWh
Lifetime Throughput	6,183	kWh
Expected Life	7.00	yr

Generic 1kWh Lead Acid State of Charge (%)

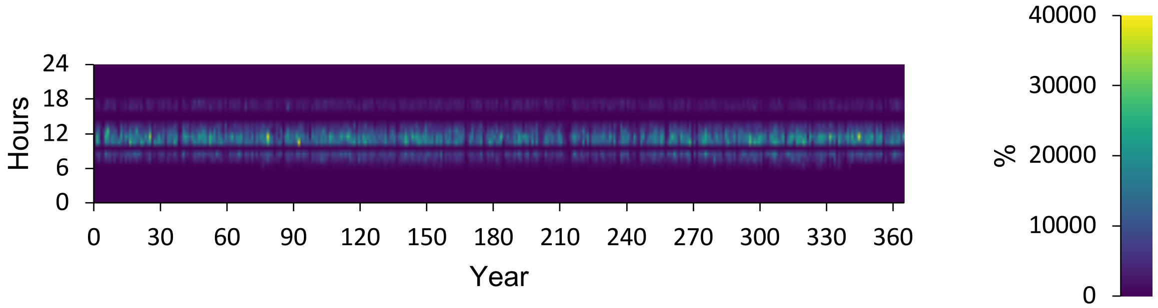


Renewable Summary

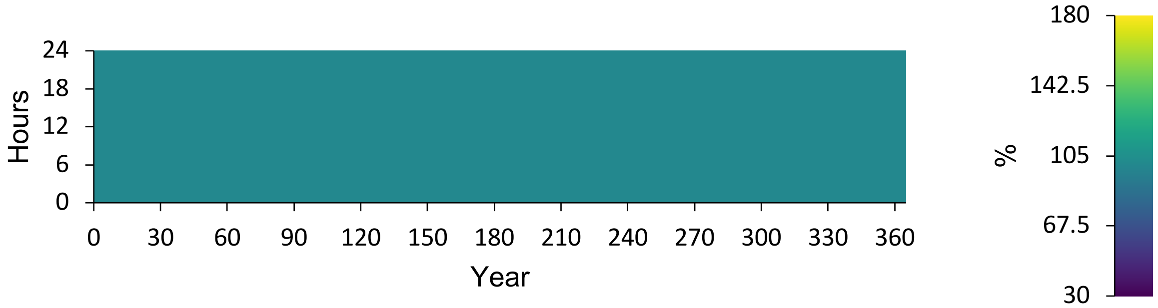
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$17,473
CAPEX	$9,850
OPEX	$634.57
LCOE (per kWh)	$0.580
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 1)

PV + Lithium-ion

Location: Sedeha Melefu, Afar, Ethiopia (12°11.4'N, 40°29.1'E)

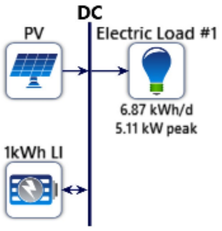
Total Net Present Cost: $15,585.88

Levelized Cost of Energy ($/kWh): $0.489

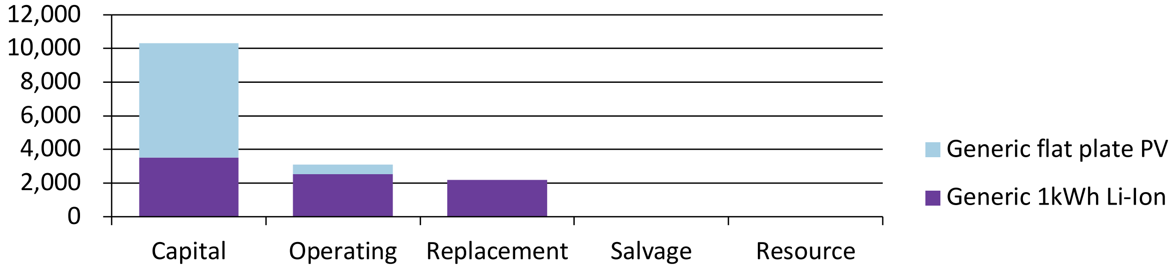
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	4.25	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



Net Present Costs

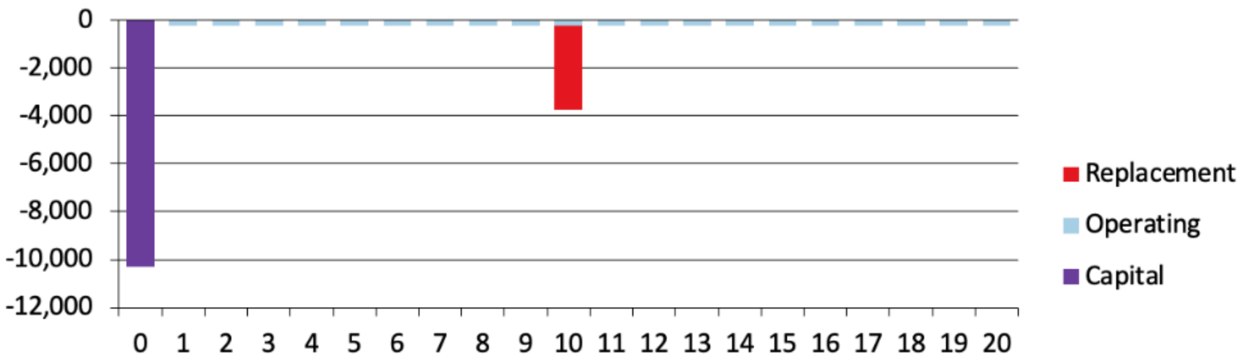
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$2,544	$2,198	$0.00	$0.00	$8,242

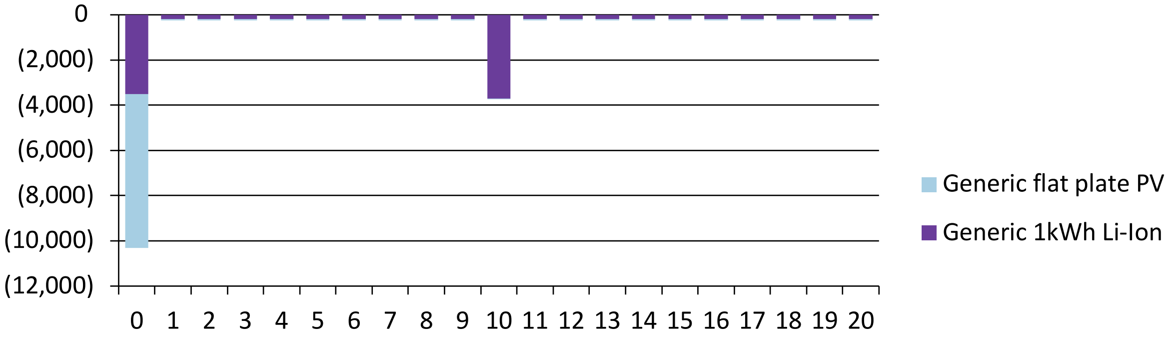
Generic flat plate PV	$6,804	$540.78	$0.00	$0.00	$0.00	$7,344
System	$10,304	$3,084	$2,198	$0.00	$0.00	$15,586

Annualized Costs

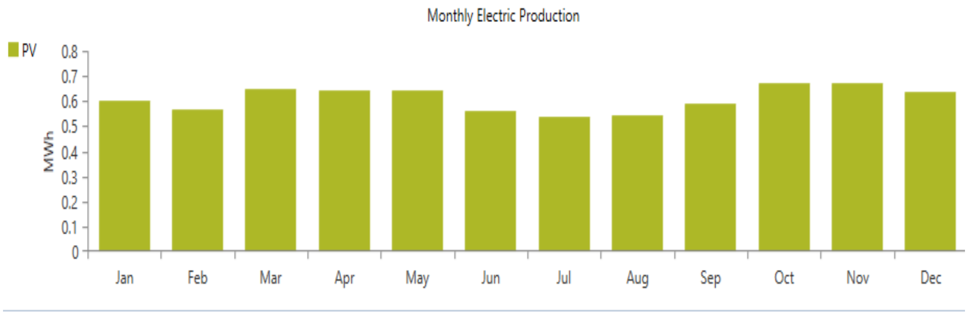
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$275.21	$200.00	$172.83	$0.00	$0.00	$648.04
Generic flat plate PV	$534.97	$42.52	$0.00	$0.00	$0.00	$577.49
System	$810.17	$242.52	$172.83	$0.00	$0.00	$1,226

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	4,732	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.49	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	7,317	100
Total	7,317	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,507	100
Deferrable Load	0	0
Total	2,507	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

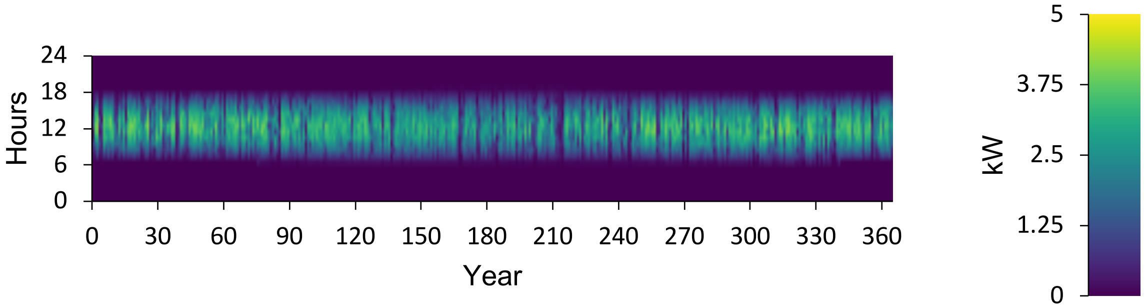
Quantity	Value	Units

Minimum Output	0	kW
Maximum Output	4.12	kW
PV Penetration	292	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0789	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	4.25	kW
Mean Output	0.835	kW
Mean Output	20.0	kWh/d
Capacity Factor	19.6	%
Total Production	7,317	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

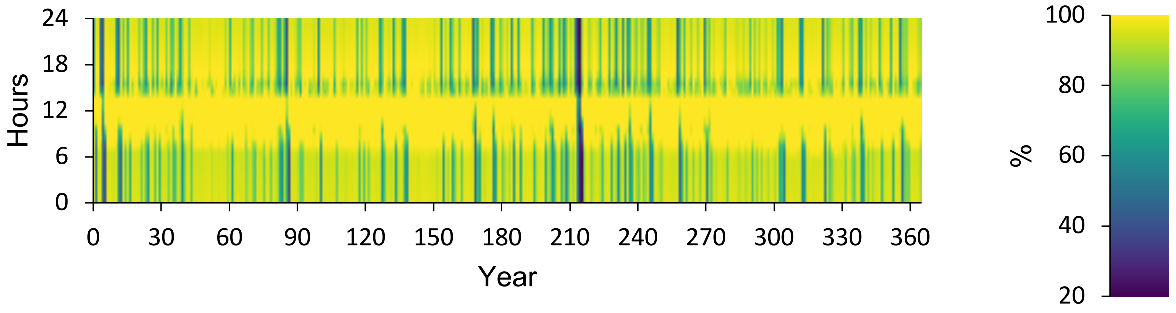
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	789	kWh/yr
Energy Out	711	kWh/yr
Storage Depletion	1.10	kWh/yr
Losses	79.0	kWh/yr
Annual Throughput	750	kWh/yr

Generic 1kWh Li-Ion Statistics

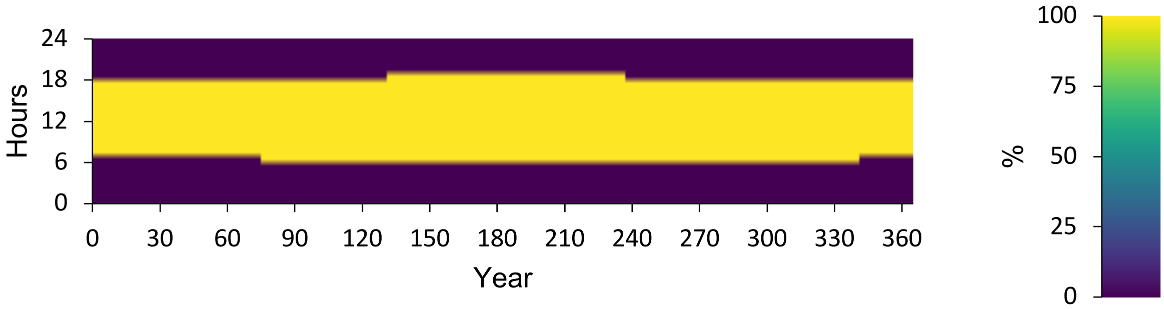
Quantity	Value	Units
Autonomy	27.9	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	8.00	kWh
Lifetime Throughput	7,496	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

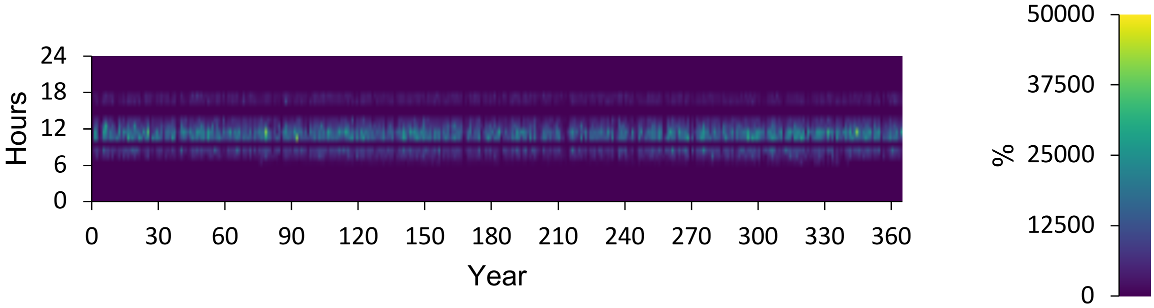


Renewable Summary

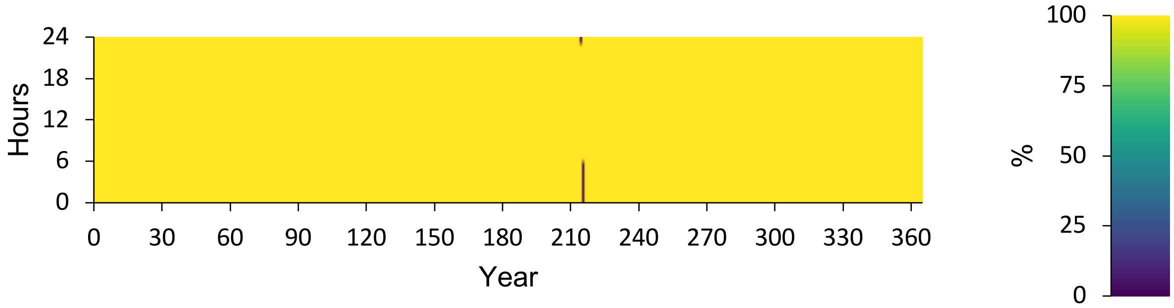
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$15,586
CAPEX	$10,304
OPEX	$415.35
LCOE (per kWh)	$0.489
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2)

PV + Lithium-ion

Location: Sedeha Melefu, Afar, Ethiopia (12°11.4'N, 40°29.1'E)

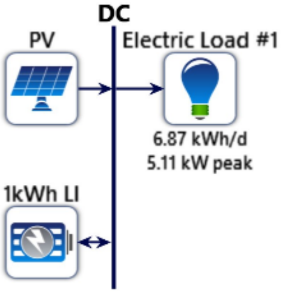
Total Net Present Cost: $20,743.36

Levelized Cost of Energy ($/kWh): $0.513

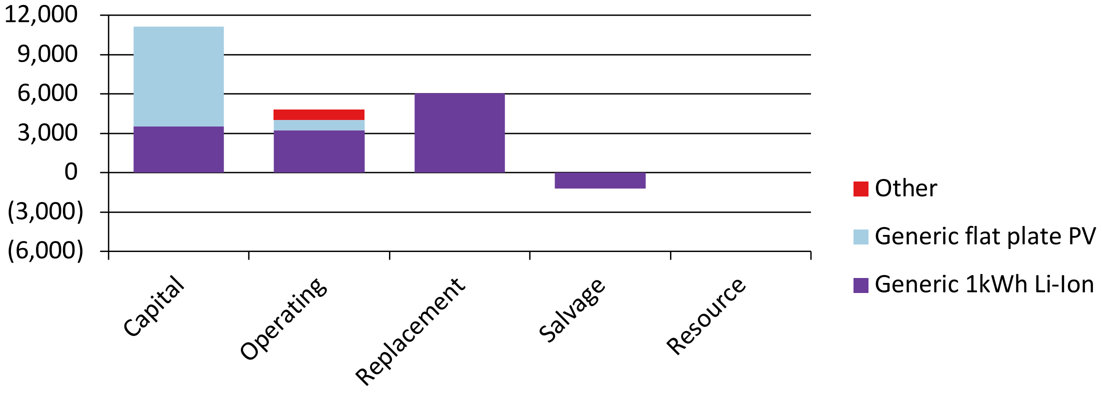
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	4.78	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



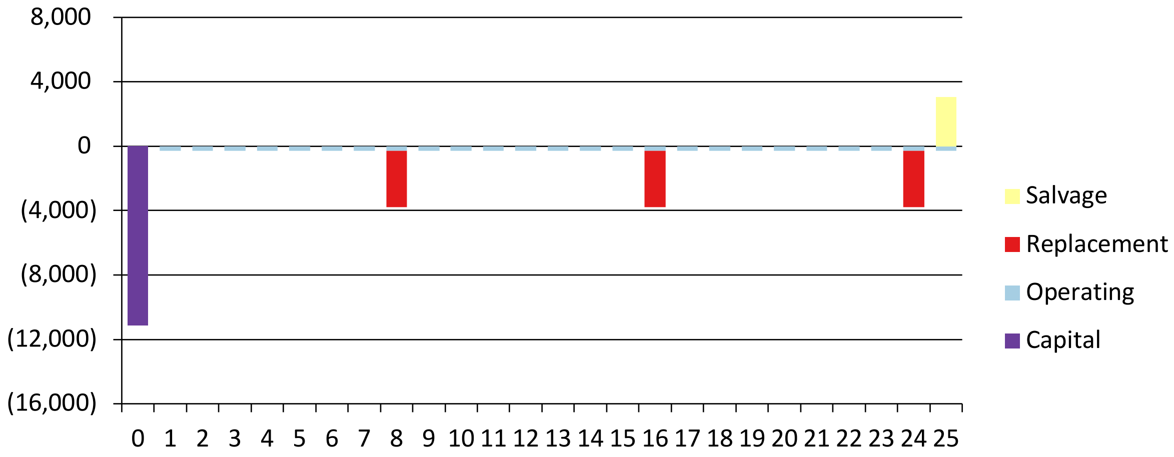
Net Present Costs

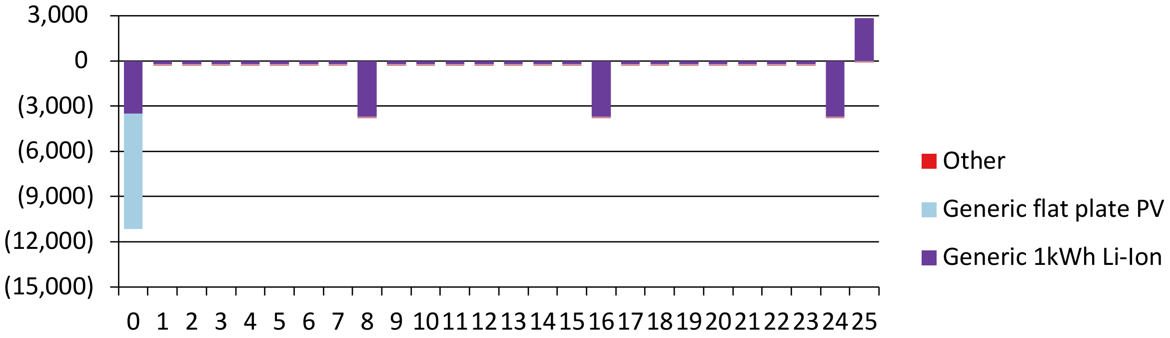
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$3,225	$6,035	-$1,234	$0.00	$11,525
Generic flat plate PV	$7,642	$770.04	$0.00	$0.00	$0.00	$8,412
Other	$0.00	$806.15	$0.00	$0.00	$0.00	$806.15
System	$11,142	$4,801	$6,035	-$1,234	$0.00	$20,743

Annualized Costs

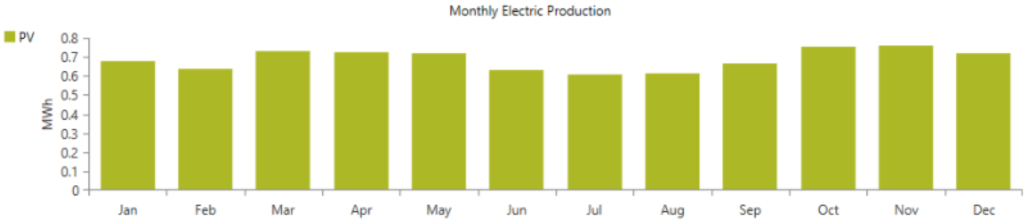
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$217.08	$200.00	$374.28	-$76.52	$0.00	$714.85
Generic flat plate PV	$473.96	$47.76	$0.00	$0.00	$0.00	$521.72
Other	$0.00	$50.00	$0.00	$0.00	$0.00	$50.00
System	$691.04	$297.76	$374.28	-$76.52	$0.00	$1,287

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	5,643	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.47	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	8,218	100
Total	8,218	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent

AC Primary Load	0	0
DC Primary Load	2,508	100
Deferrable Load	0	0
Total	2,508	100

PV: Generic flat plate PV

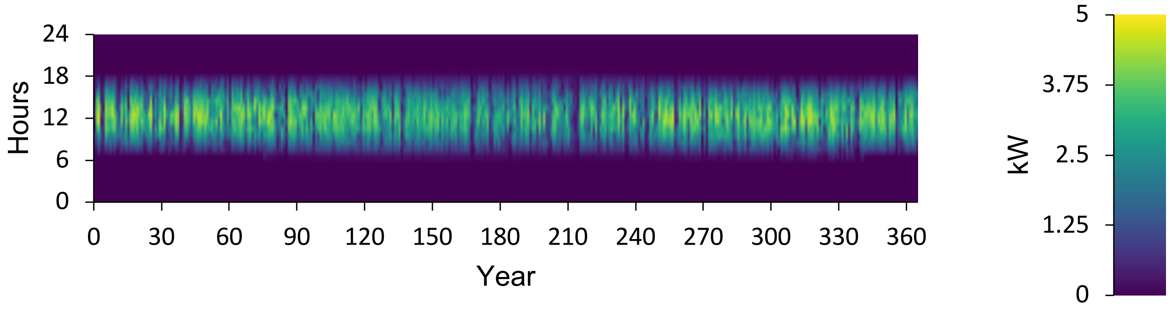
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	4.62	kW
PV Penetration	328	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0635	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	4.78	kW
Mean Output	0.938	kW
Mean Output	22.5	kWh/d
Capacity Factor	19.6	%
Total Production	8,218	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

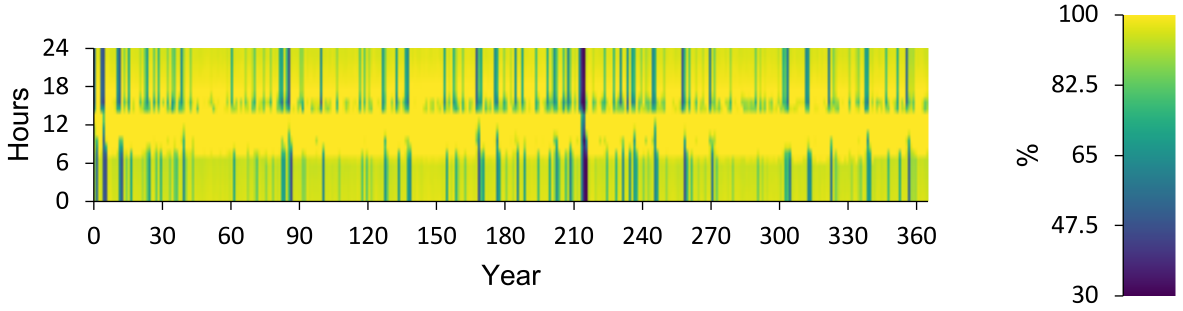
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	673	kWh/yr
Energy Out	605	kWh/yr
Storage Depletion	-0.492	kWh/yr
Losses	67.3	kWh/yr
Annual Throughput	638	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	24.4	hr

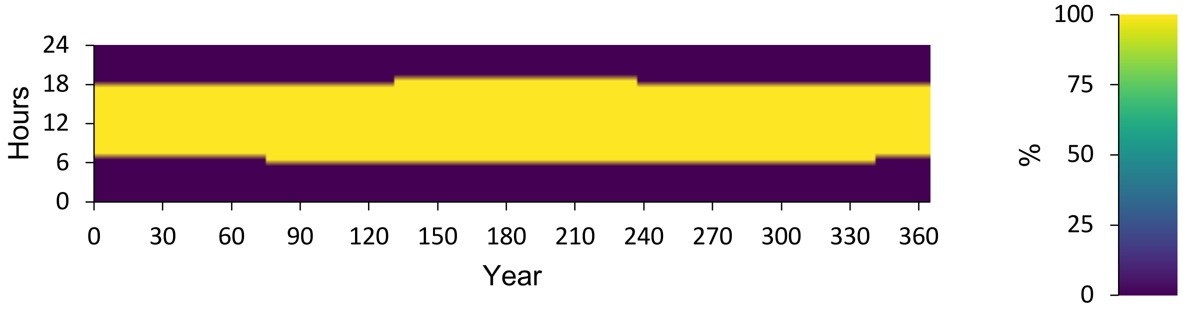
Storage Wear Cost	0.123	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	7.00	kWh
Lifetime Throughput	5,104	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

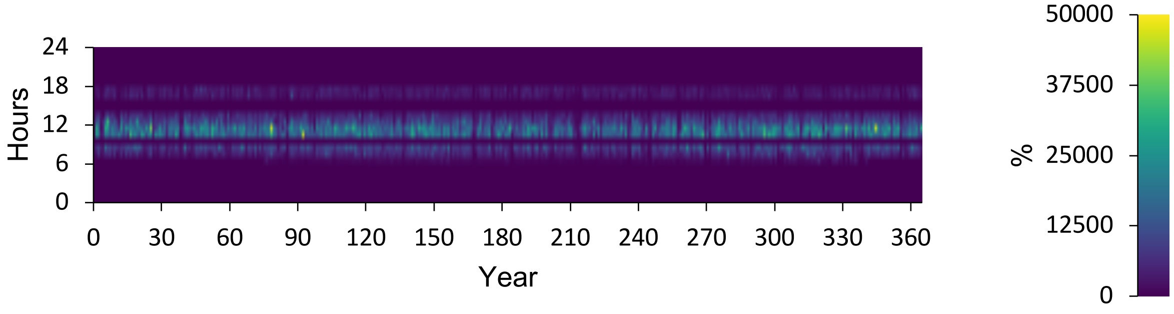


Renewable Summary

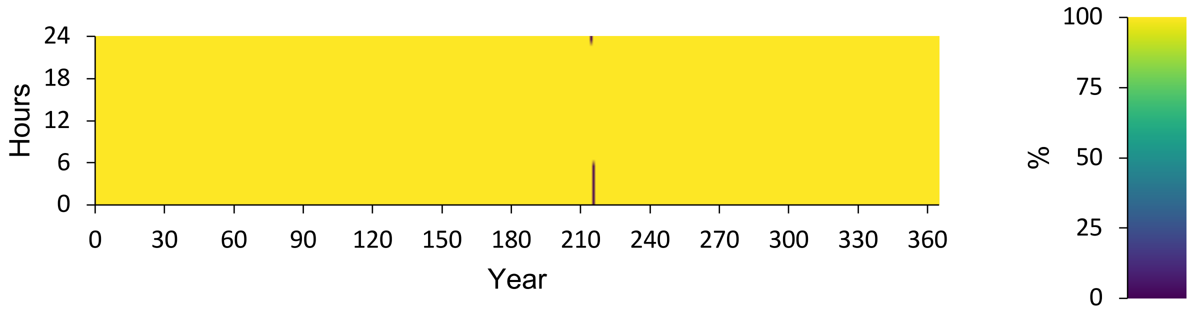
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$20,743
CAPEX	$11,142
OPEX	$595.53
LCOE (per kWh)	$0.513
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 3)

PV + Lithium-ion

Location: Sedeha Melefu, Afar, Ethiopia (12°11.4'N, 40°29.1'E)

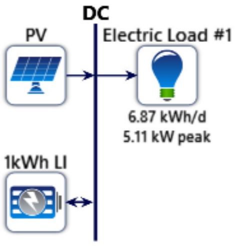
Total Net Present Cost: $24,244.31

Levelized Cost of Energy ($/kWh): $0.487

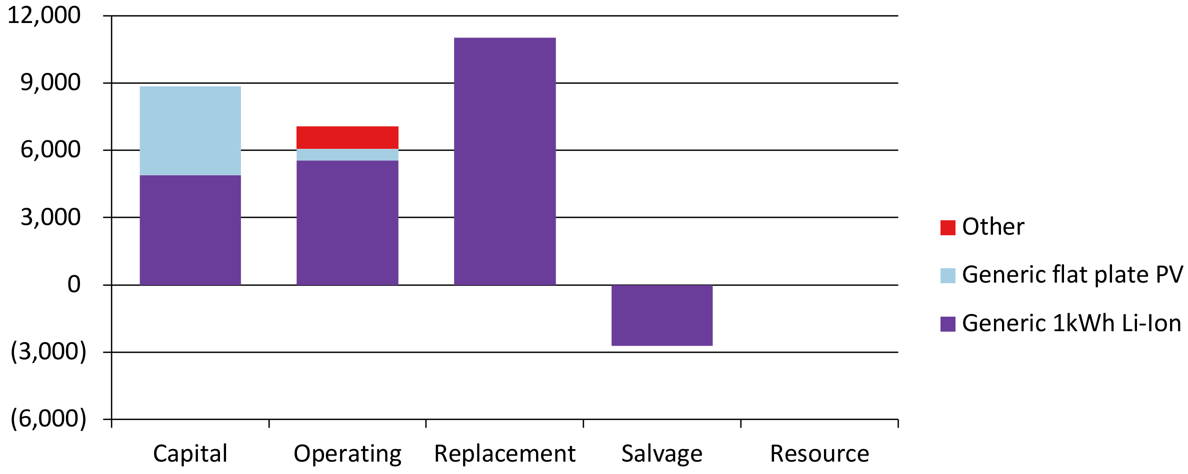
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.48	kW
Storage	Generic 1kWh Li-Ion	7	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



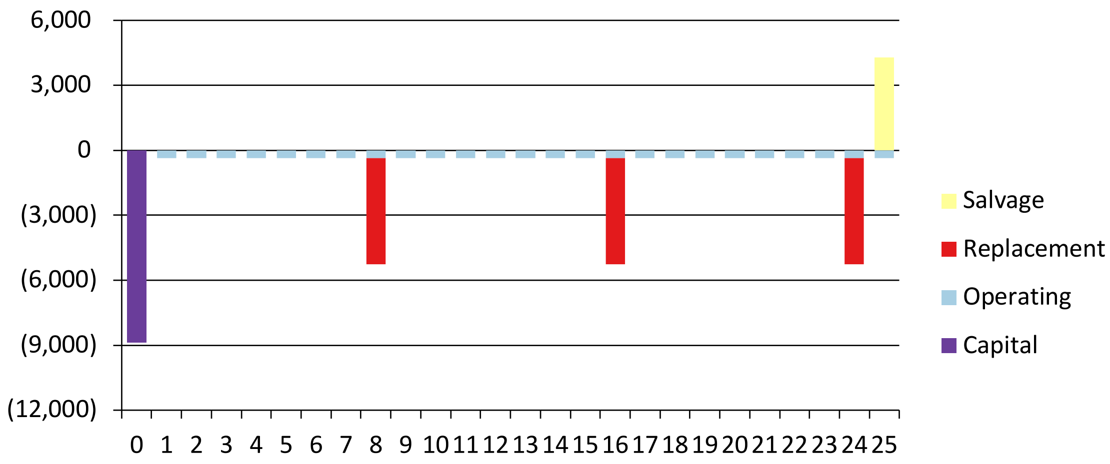
Net Present Costs

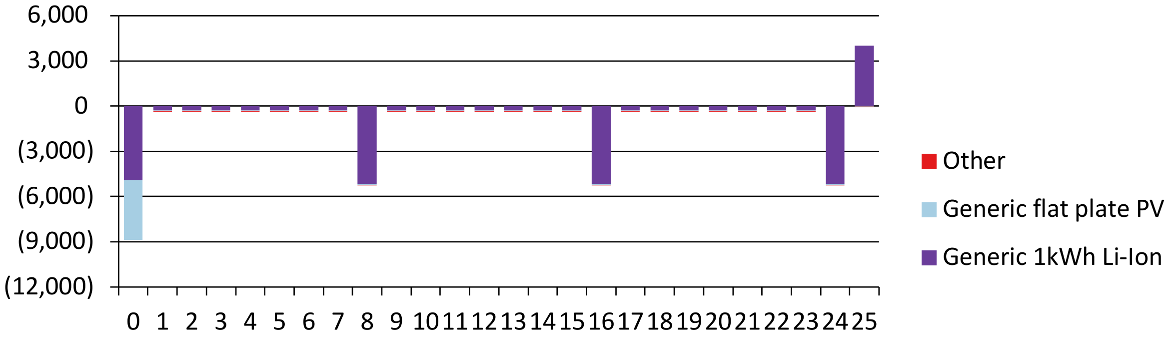
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$4,900	$5,563	$11,039	-$2,710	$0.00	$18,792
Generic flat plate PV	$3,967	$492.54	$0.00	$0.00	$0.00	$4,459
Other	$0.00	$993.37	$0.00	$0.00	$0.00	$993.37
System	$8,867	$7,049	$11,039	-$2,710	$0.00	$24,244

Annualized Costs

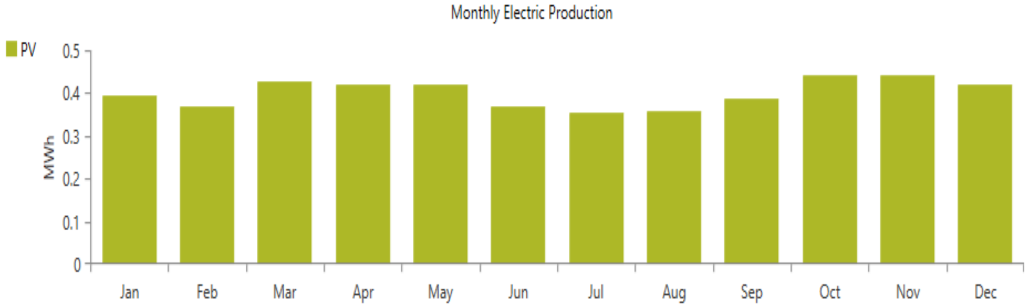
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$246.64	$280.00	$555.63	-$136.41	$0.00	$945.86
Generic flat plate PV	$199.66	$24.79	$0.00	$0.00	$0.00	$224.45
Other	$0.00	$50.00	$0.00	$0.00	$0.00	$50.00
System	$446.29	$354.79	$555.63	-$136.41	$0.00	$1,220

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,167	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.46	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,799	100
Total	4,799	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,507	100
Deferrable Load	0	0
Total	2,507	100

PV: Generic flat plate PV

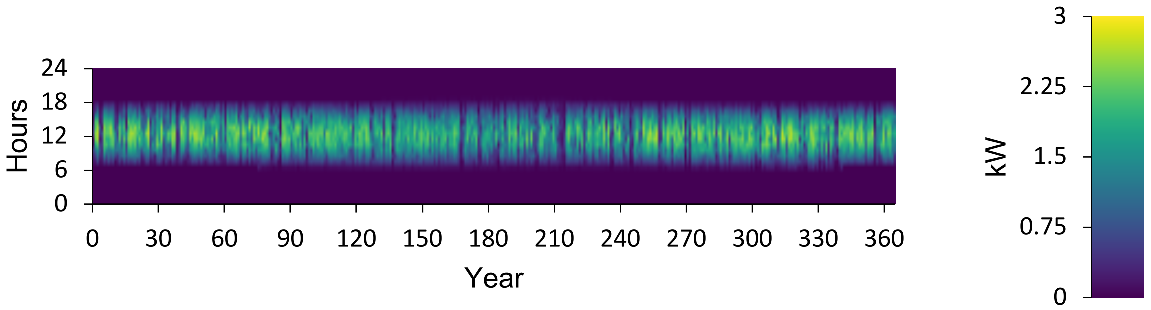
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	2.70	kW
PV Penetration	191	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0468	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.48	kW
Mean Output	0.548	kW
Mean Output	13.1	kWh/d
Capacity Factor	22.1	%
Total Production	4,799	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units

Batteries	14.0	qty.
String Size	2.00	batteries
Strings in Parallel	7.00	strings
Bus Voltage	12.0	V

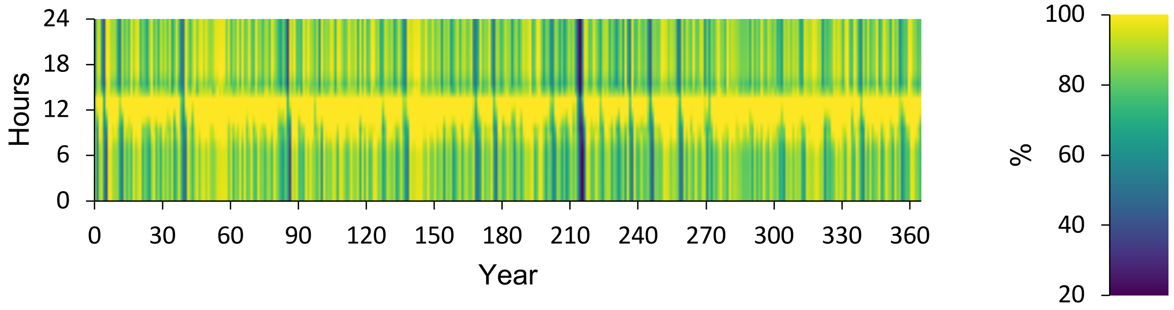
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	1,266	kWh/yr
Energy Out	1,140	kWh/yr
Storage Depletion	1.36	kWh/yr
Losses	127	kWh/yr
Annual Throughput	1,202	kWh/yr

Generic 1kWh Li-Ion Statistics

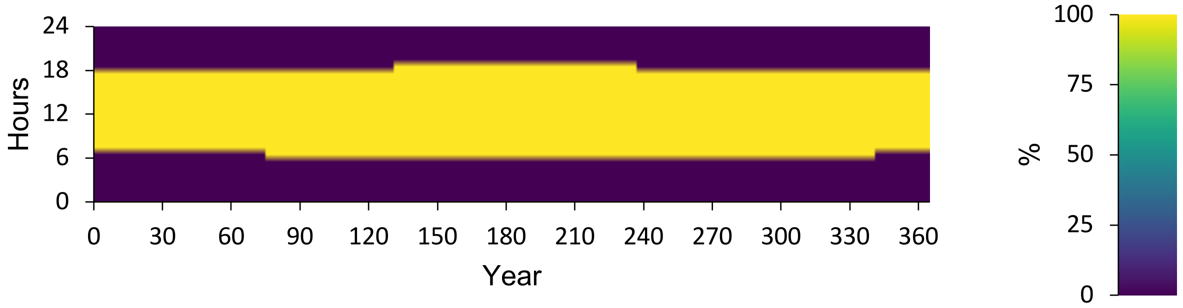
Quantity	Value	Units
Autonomy	39.1	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	14.0	kWh
Usable Nominal Capacity	11.2	kWh
Lifetime Throughput	9,617	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

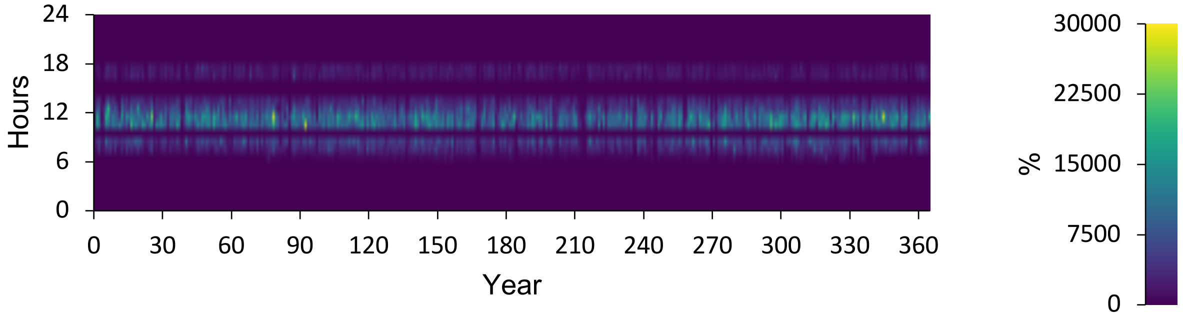


Renewable Summary

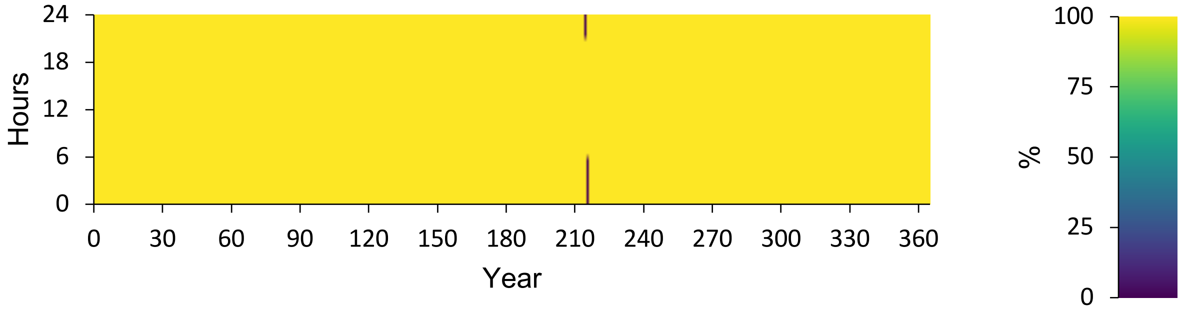
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$24,244
CAPEX	$8,867
OPEX	$774.02
LCOE (per kWh)	$0.487
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4)

PV + Lithium-ion

Location: Sedeha Melefu, Ethiopia (12°11.4'N, 40°29.1'E)

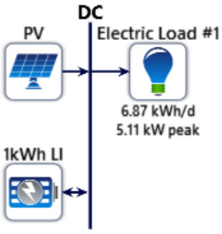
Total Net Present Cost: $15,274.39

Levelized Cost of Energy ($/kWh): $0.507

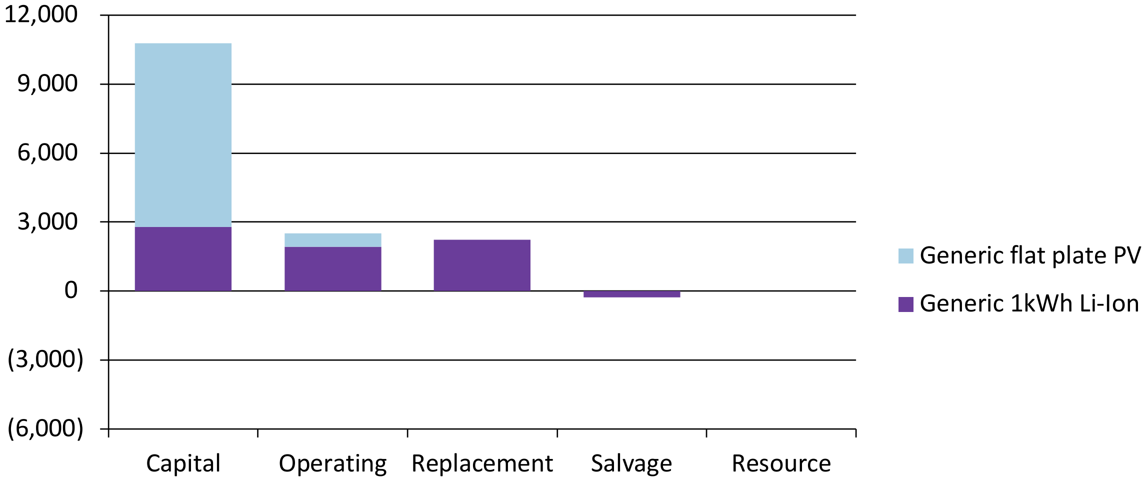
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	5.00	kW
Storage	Generic 1kWh Li-Ion	4	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



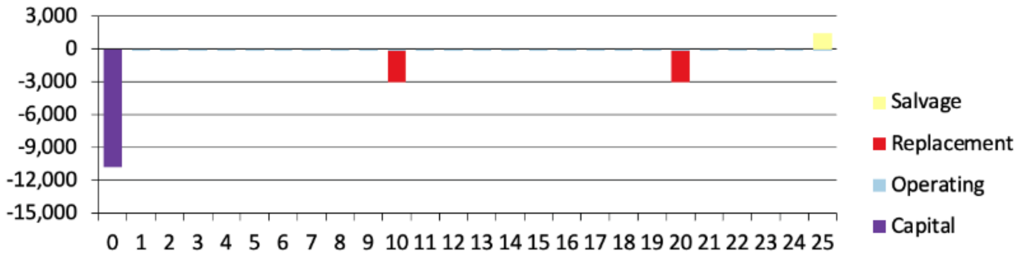
Net Present Costs

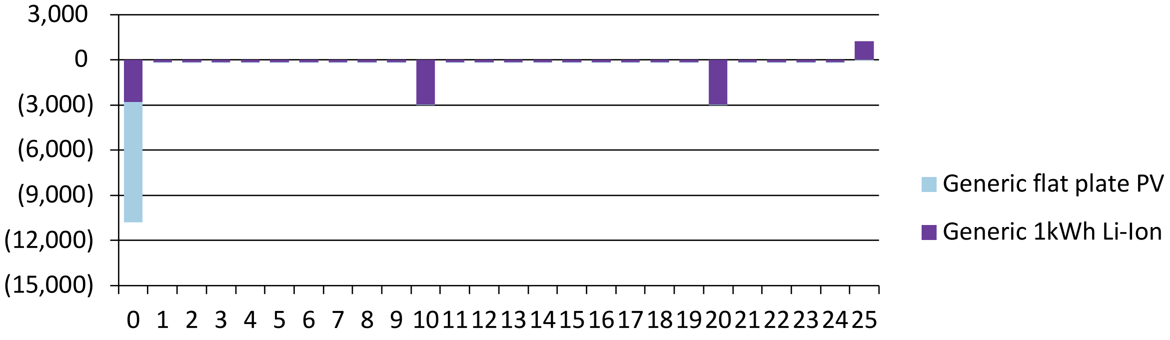
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$2,800	$1,922	$2,239	-$278.88	$0.00	$6,682
Generic flat plate PV	$7,993	$600.05	$0.00	$0.00	$0.00	$8,593
System	$10,793	$2,522	$2,239	-$278.88	$0.00	$15,274

Annualized Costs

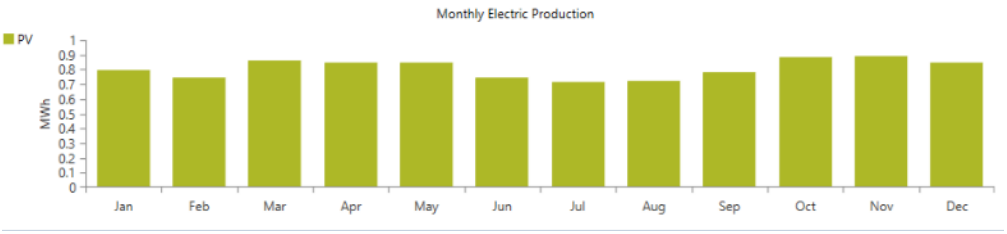
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$233.10	$160.00	$186.37	-$23.22	$0.00	$556.25
Generic flat plate PV	$665.38	$49.95	$0.00	$0.00	$0.00	$715.34
System	$898.48	$209.95	$186.37	-$23.22	$0.00	$1,272

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	7,108	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.49	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	9,670	100
Total	9,670	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,508	100
Deferrable Load	0	0
Total	2,508	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

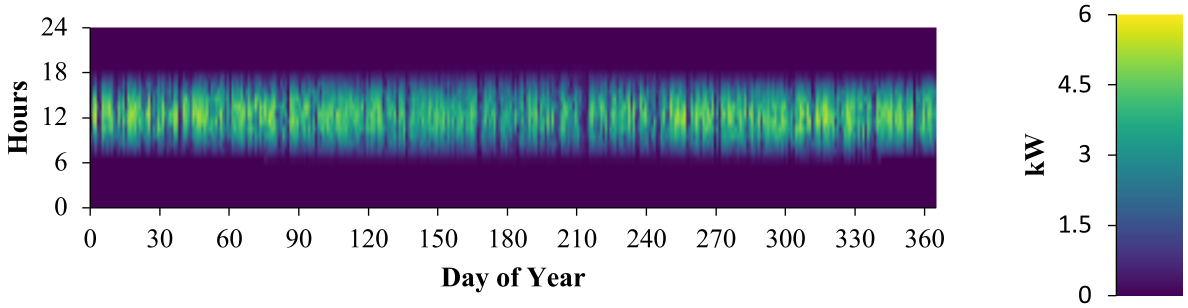
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	5.44	kW
PV Penetration	385	%
Hours of Operation	4,387	hrs/yr
Levelized Cost	0.0740	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	5.00	kW
Mean Output	1.10	kW
Mean Output	26.5	kWh/d
Capacity Factor	22.1	%
Total Production	9,670	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	8.00	qty.
String Size	2.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	12.0	V

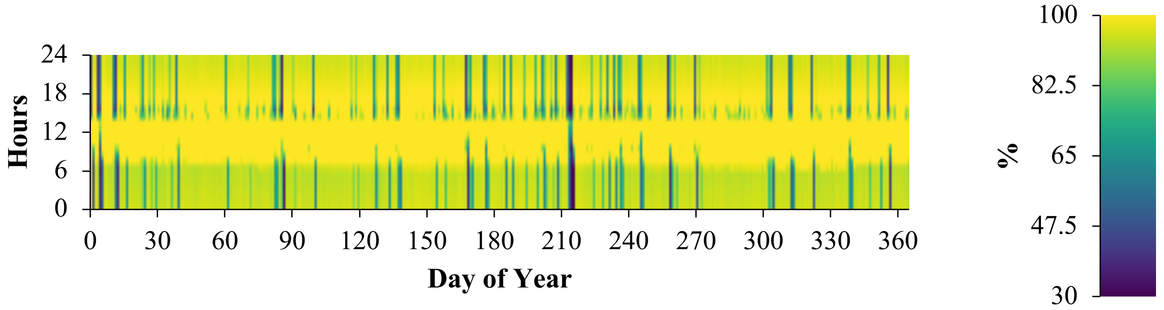
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	540	kWh/yr
Energy Out	486	kWh/yr
Storage Depletion	0.384	kWh/yr
Losses	54.0	kWh/yr
Annual Throughput	512	kWh/yr

Generic 1kWh Li-Ion Statistics

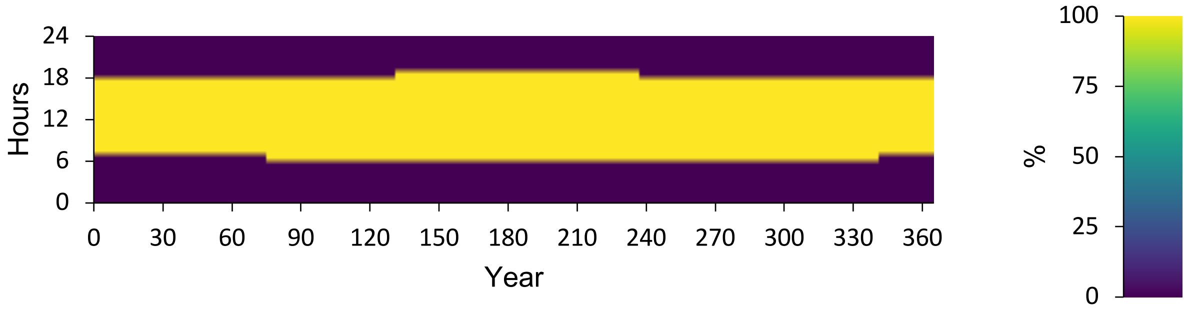
Quantity	Value	Units
Autonomy	19.6	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	8.00	kWh
Usable Nominal Capacity	5.60	kWh
Lifetime Throughput	5,125	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

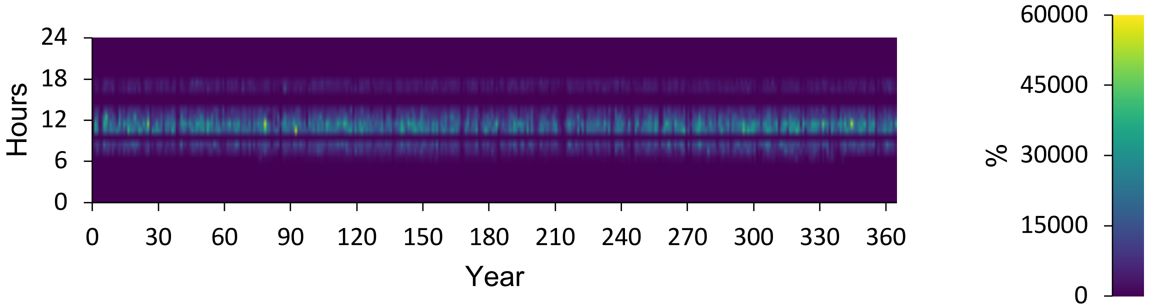


Renewable Summary

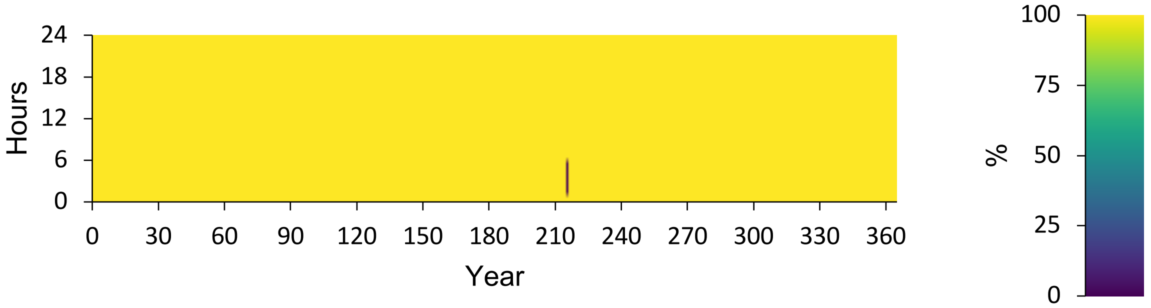
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$15,274
CAPEX	$10,793
OPEX	$373.11
LCOE (per kWh)	$0.507
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

Appendix B

Techno-economic Analysis of Standalone DC microgrid for Rural Health Center in Sub-Saharan Africa: A case of Ethiopia and Burkina Faso

System Simulation Report (Under Scenario 1)

Location: Zozi, Ethiopia (12°22.7'N, 38°8.5'E)

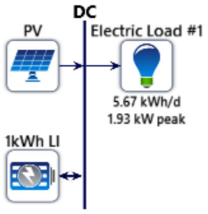
Total Net Present Cost: $11,052.60

Levelized Cost of Energy ($/kWh): $0.420

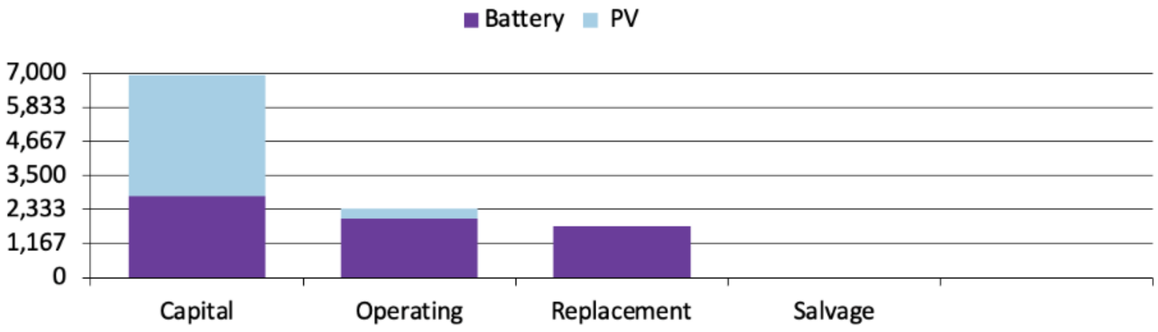
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.58	kW
Storage	Generic 1kWh Li-Ion	4	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



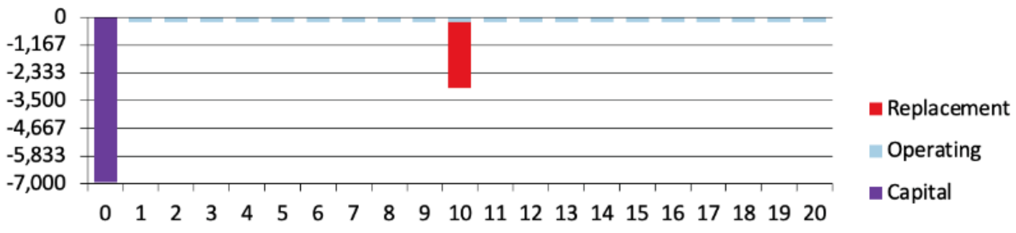
Net Present Costs

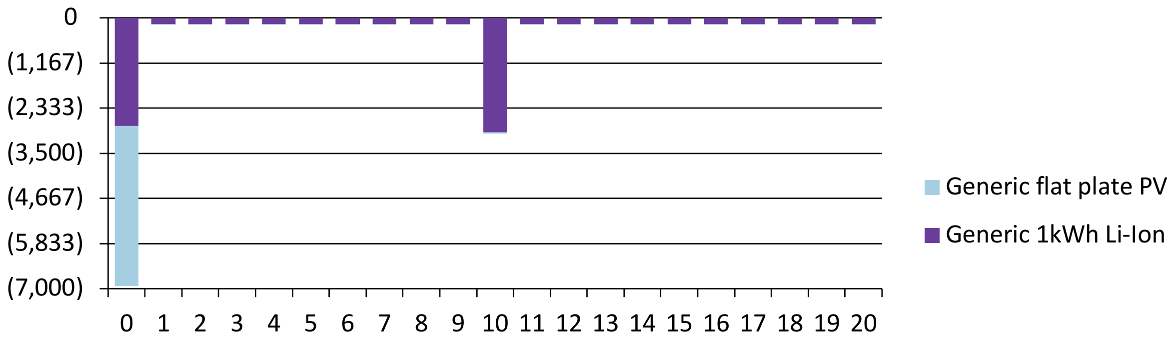
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$2,800	$2,035	$1,758	$0.00	$0.00	$6,593
Generic flat plate PV	$4,131	$328.35	$0.00	$0.00	$0.00	$4,459
System	$6,931	$2,363	$1,758	$0.00	$0.00	$11,053

Annualized Costs

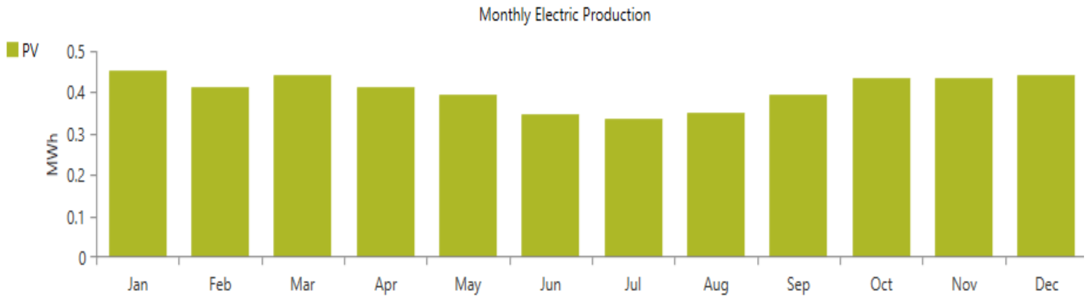
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$220.17	$160.00	$138.27	$0.00	$0.00	$518.43
Generic flat plate PV	$324.82	$25.82	$0.00	$0.00	$0.00	$350.64
System	$544.99	$185.82	$138.27	$0.00	$0.00	$869.07

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,754	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	1.99	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,852	100
Total	4,852	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

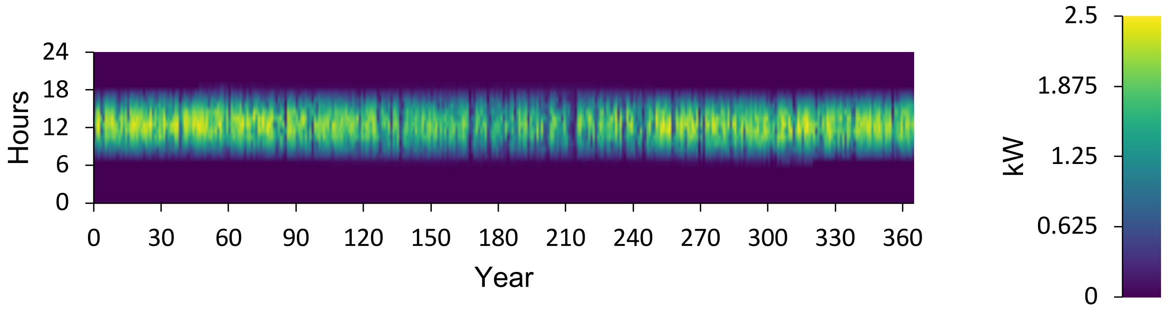
Quantity	Value	Units

Minimum Output	0	kW
Maximum Output	2.48	kW
PV Penetration	234	%
Hours of Operation	4,450	hrs/yr
Levelized Cost	0.0723	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.58	kW
Mean Output	0.554	kW
Mean Output	13.3	kWh/d
Capacity Factor	21.5	%
Total Production	4,852	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	8.00	qty.
String Size	2.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	12.0	V

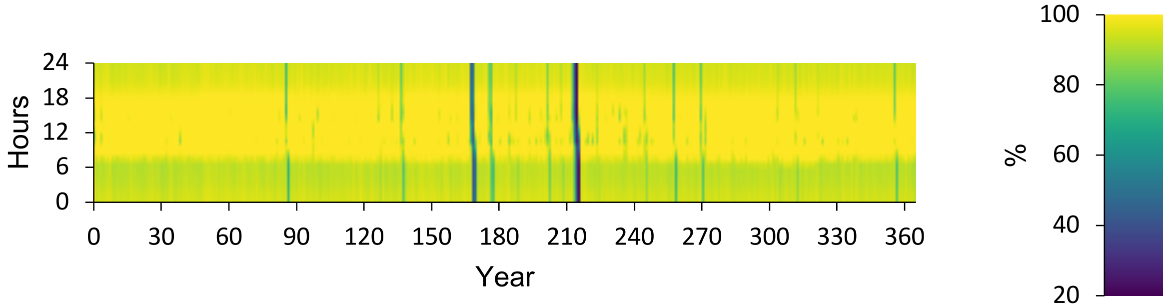
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	302	kWh/yr
Energy Out	272	kWh/yr
Storage Depletion	0.421	kWh/yr
Losses	30.2	kWh/yr
Annual Throughput	287	kWh/yr

Generic 1kWh Li-Ion Statistics

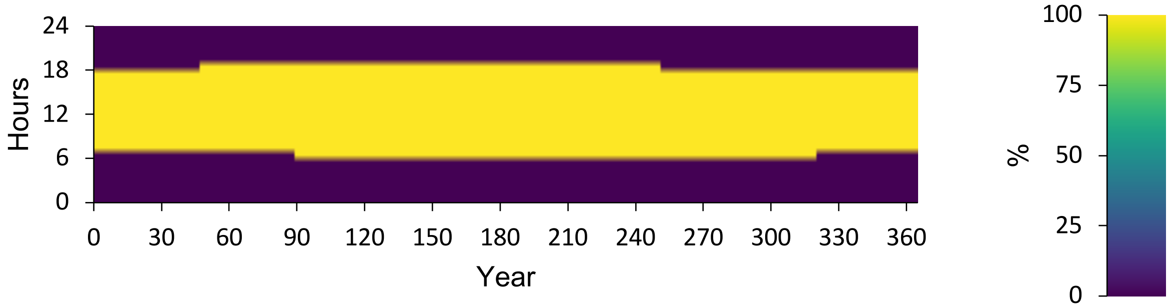
Quantity	Value	Units
Autonomy	27.1	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	8.00	kWh
Usable Nominal Capacity	6.40	kWh
Lifetime Throughput	2,865	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

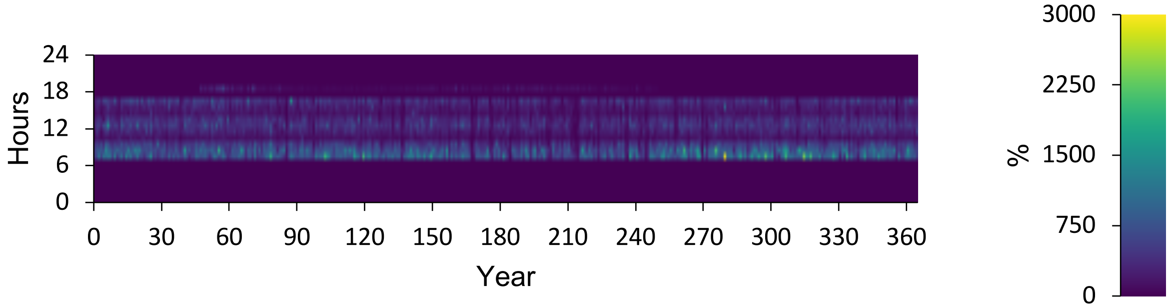


Renewable Summary

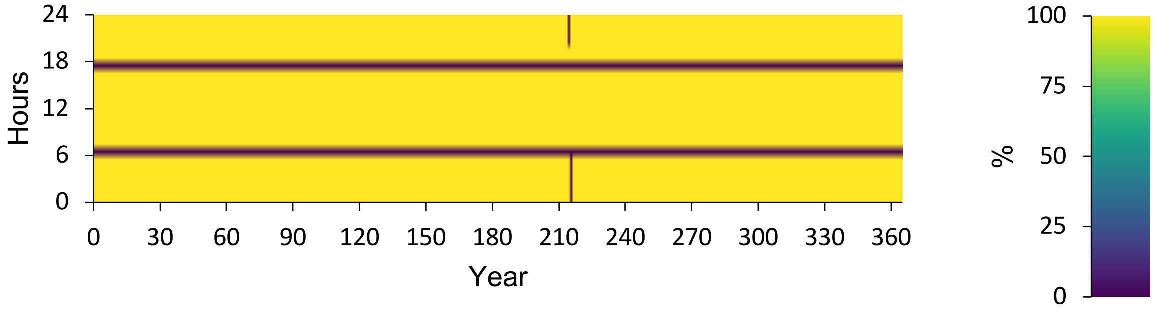
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$11,053
CAPEX	$6,931
OPEX	$324.08
LCOE (per kWh)	$0.420
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2) – Ethiopia

Location: Zozi, Ethiopia (12°22.7'N, 38°8.5'E)

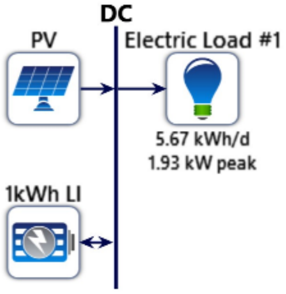
Total Net Present Cost: $18,789.57

Levelized Cost of Energy ($/kWh): $0.455

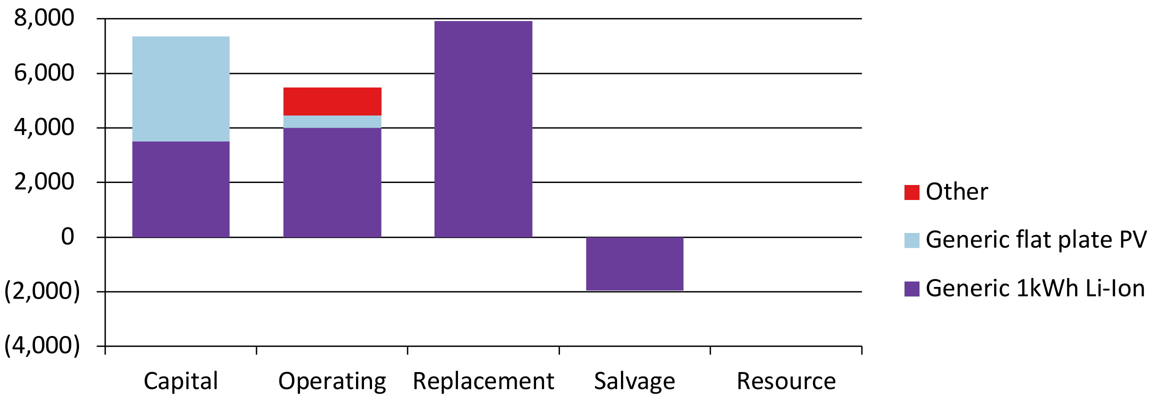
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.41	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



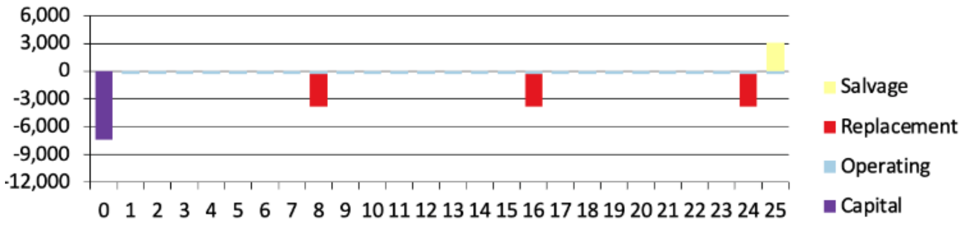
Net Present Costs

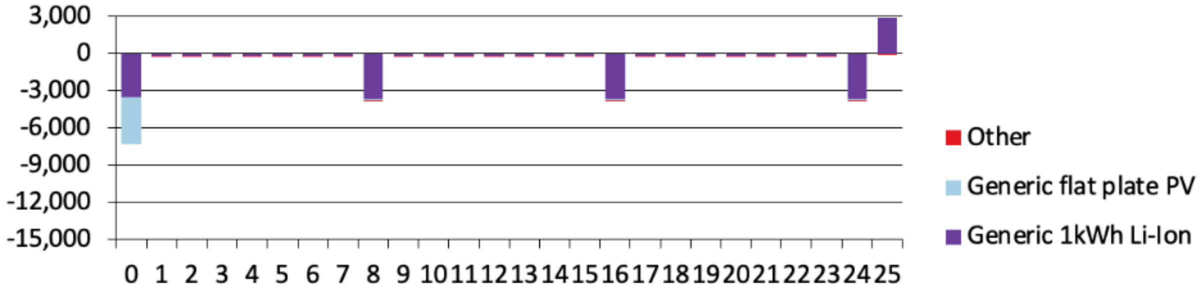
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$3,989	$7,925	-$1,952	$0.00	$13,462
Generic flat plate PV	$3,850	$479.97	$0.00	$0.00	$0.00	$4,330
Other	$0.00	$997.33	$0.00	$0.00	$0.00	$997.33
System	$7,350	$5,467	$7,925	-$1,952	$0.00	$18,790

Annualized Costs

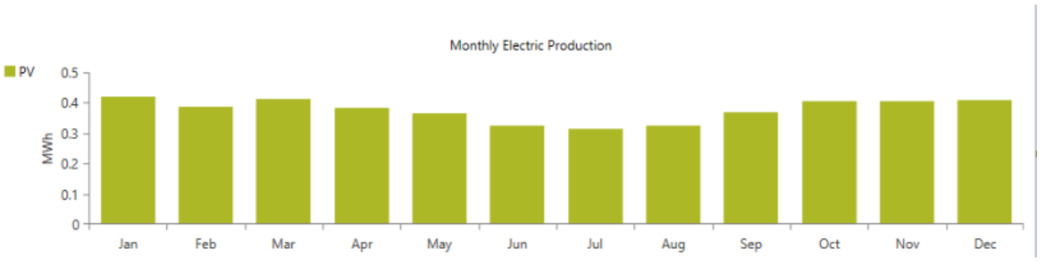
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$175.47	$200.00	$397.30	-$97.85	$0.00	$674.91
Generic flat plate PV	$193.01	$24.06	$0.00	$0.00	$0.00	$217.08
Other	$0.00	$50.00	$0.00	$0.00	$0.00	$50.00
System	$368.48	$274.06	$397.30	-$97.85	$0.00	$941.99

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,421	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	1.90	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,522	100
Total	4,522	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

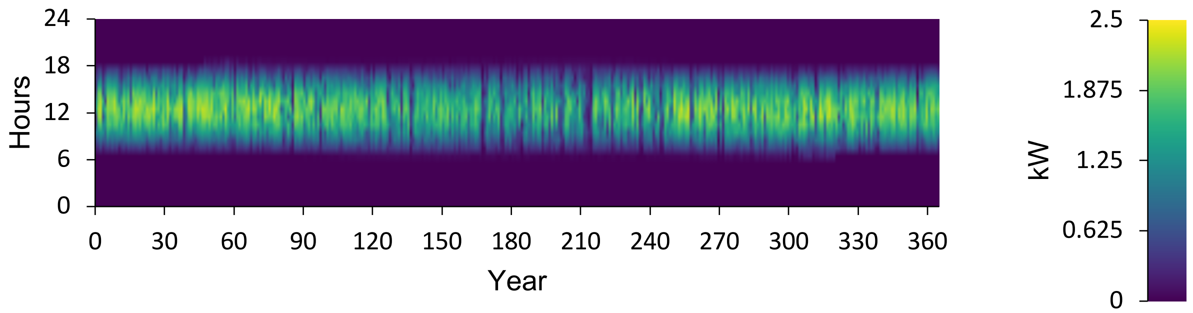
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	2.31	kW
PV Penetration	218	%
Hours of Operation	4,450	hrs/yr
Levelized Cost	0.0480	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.41	kW
Mean Output	0.516	kW
Mean Output	12.4	kWh/d
Capacity Factor	21.5	%
Total Production	4,522	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

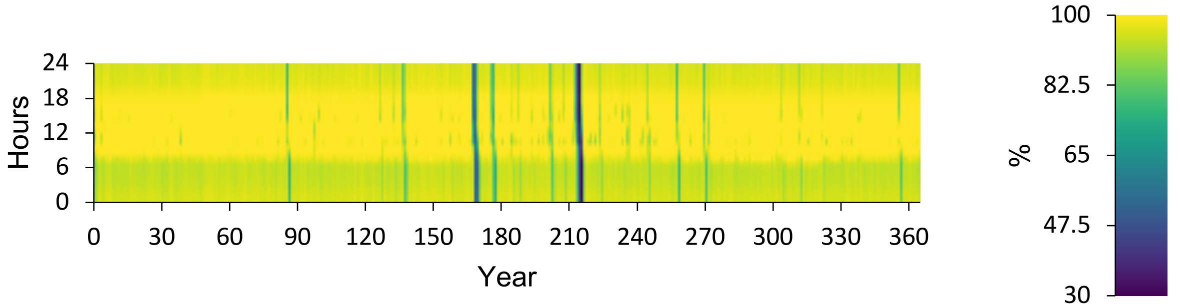
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	316	kWh/yr
Energy Out	283	kWh/yr
Storage Depletion	-0.579	kWh/yr
Losses	31.5	kWh/yr
Annual Throughput	299	kWh/yr

Generic 1kWh Li-Ion Statistics

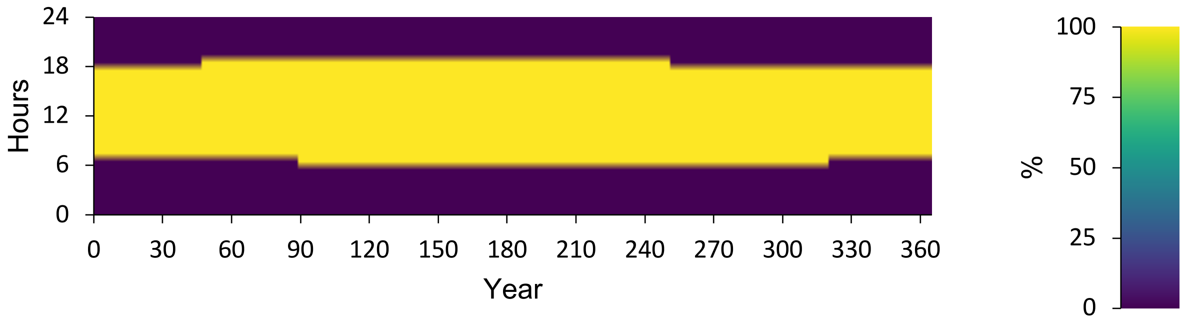
Quantity	Value	Units
Autonomy	29.6	hr
Storage Wear Cost	0.123	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	7.00	kWh
Lifetime Throughput	2,390	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

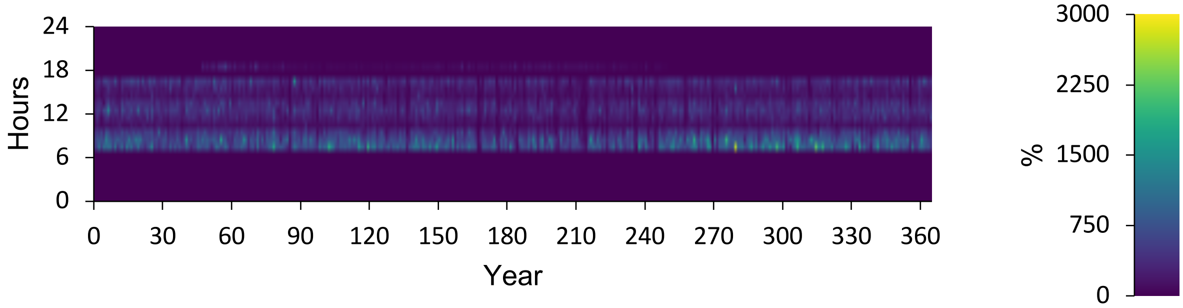


Renewable Summary

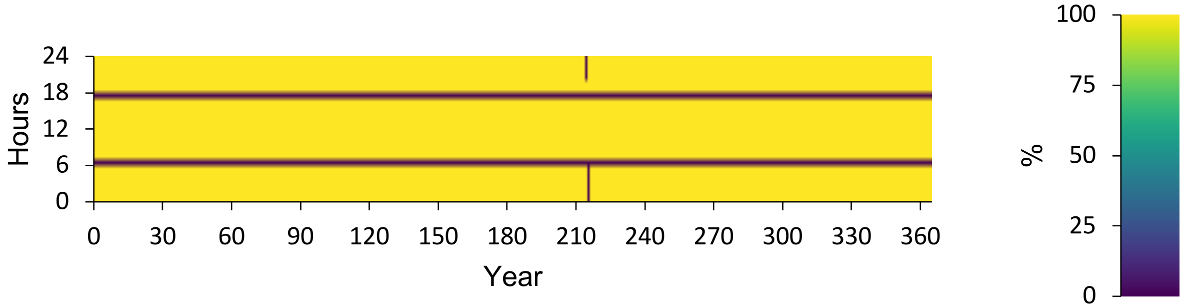
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$18,790
CAPEX	$7,350
OPEX	$573.51
LCOE (per kWh)	$0.455
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 3) – Ethiopia

Location: Zozi, Ethiopia (12°22.7'N, 38°8.5'E)

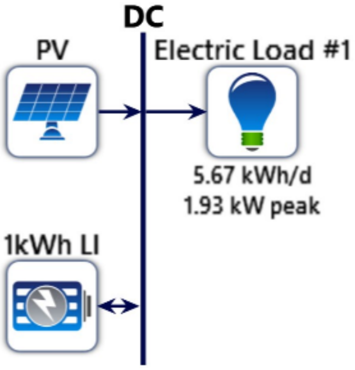
Total Net Present Cost: $19,406.25

Levelized Cost of Energy ($/kWh): $0.375

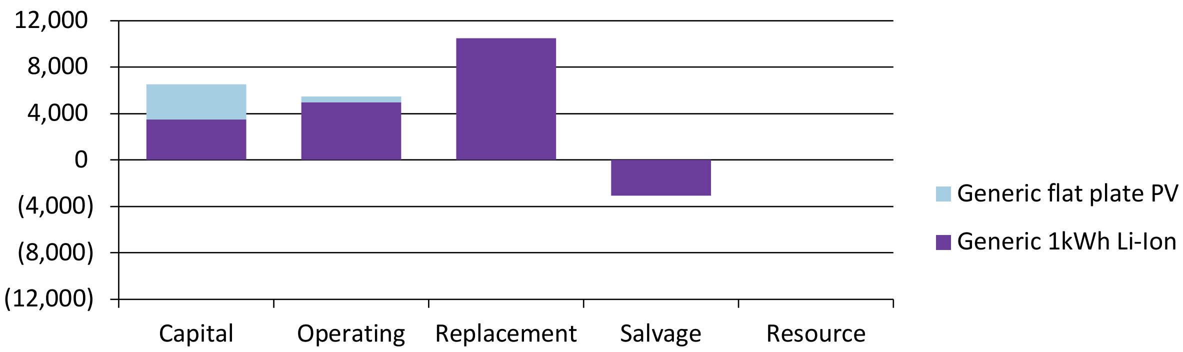
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1.88	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



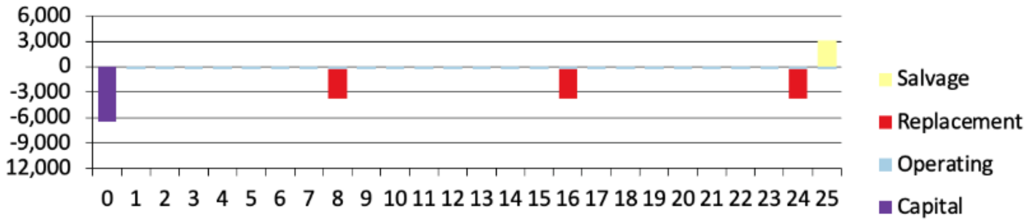
Net Present Costs

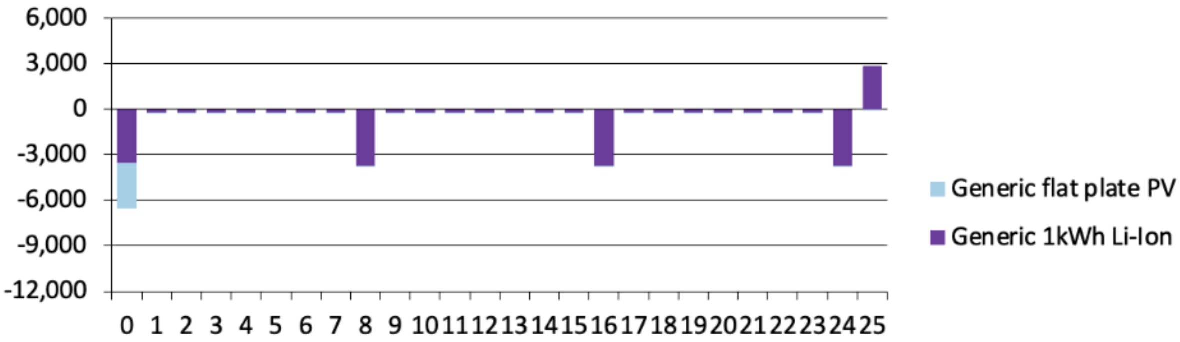
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$5,000	$10,500	-$3,063	$0.00	$15,938
Generic flat plate PV	$3,000	$468.75	$0.00	$0.00	$0.00	$3,469
System	$6,500	$5,469	$10,500	-$3,063	$0.00	$19,406

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$140.00	$200.00	$420.00	-$122.50	$0.00	$637.50
Generic flat plate PV	$120.00	$18.75	$0.00	$0.00	$0.00	$138.75
System	$260.00	$218.75	$420.00	-$122.50	$0.00	$776.25

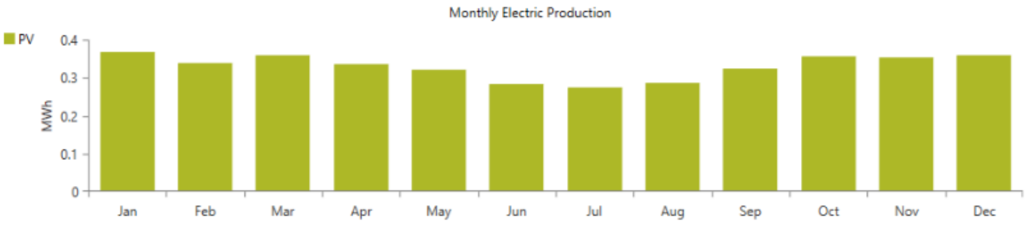
Cash Flow





HOMER Pro

Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,861	kWh/yr
Unmet Electric Load	1.40	kWh/yr
Capacity Shortage	2.02	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	3,964	100
Total	3,964	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

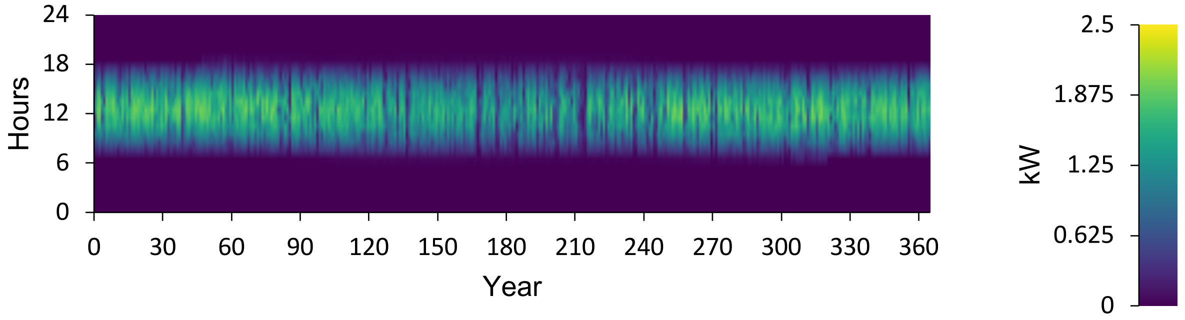
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	2.03	kW
PV Penetration	192	%
Hours of Operation	4,450	hrs/yr
Levelized Cost	0.0350	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1.88	kW
Mean Output	0.453	kW
Mean Output	10.9	kWh/d
Capacity Factor	24.1	%
Total Production	3,964	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

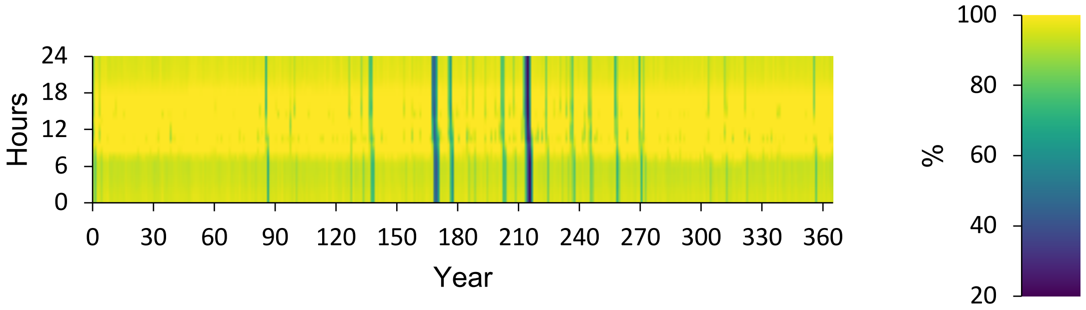
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	347	kWh/yr
Energy Out	312	kWh/yr
Storage Depletion	-0.579	kWh/yr
Losses	34.7	kWh/yr
Annual Throughput	329	kWh/yr

Generic 1kWh Li-Ion Statistics

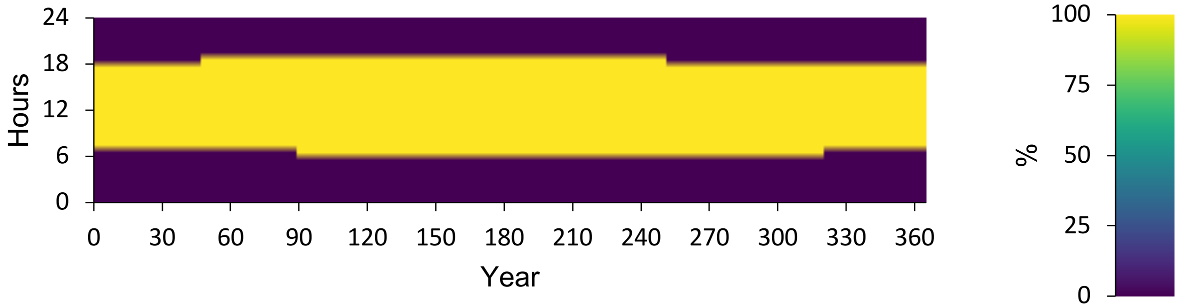
Quantity	Value	Units
Autonomy	33.9	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	8.00	kWh
Lifetime Throughput	2,632	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

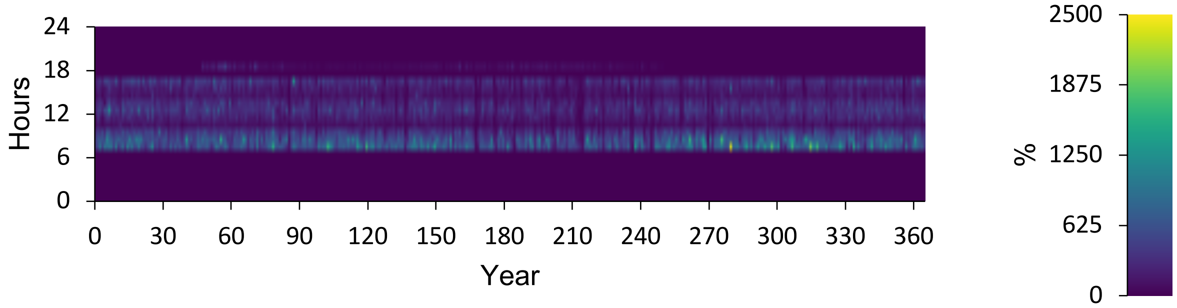


Renewable Summary

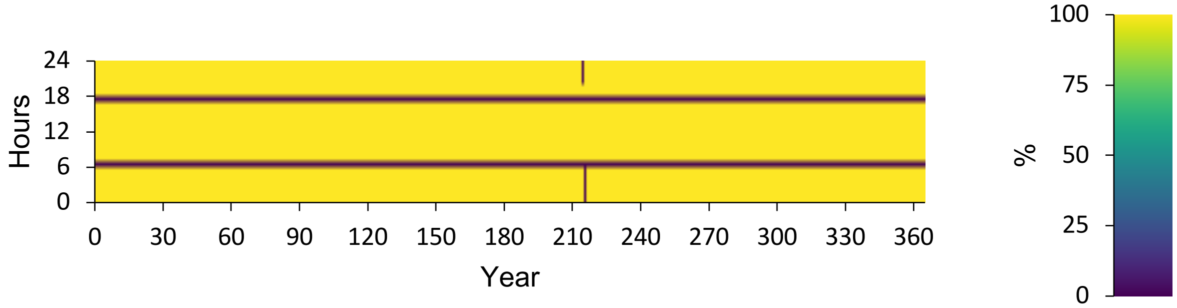
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$19,406
CAPEX	$6,500
OPEX	$516.25
LCOE (per kWh)	$0.375
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4) - Ethiopia

Location: Zozi, Ethiopia (12°22.7'N, 38°8.5'E)

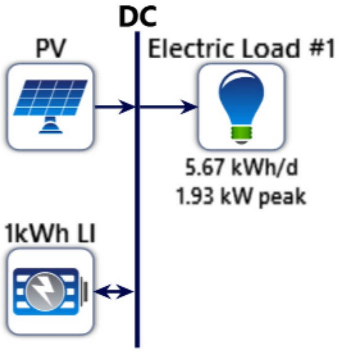
Total Net Present Cost: $11,035.76

Levelized Cost of Energy ($/kWh): $0.444

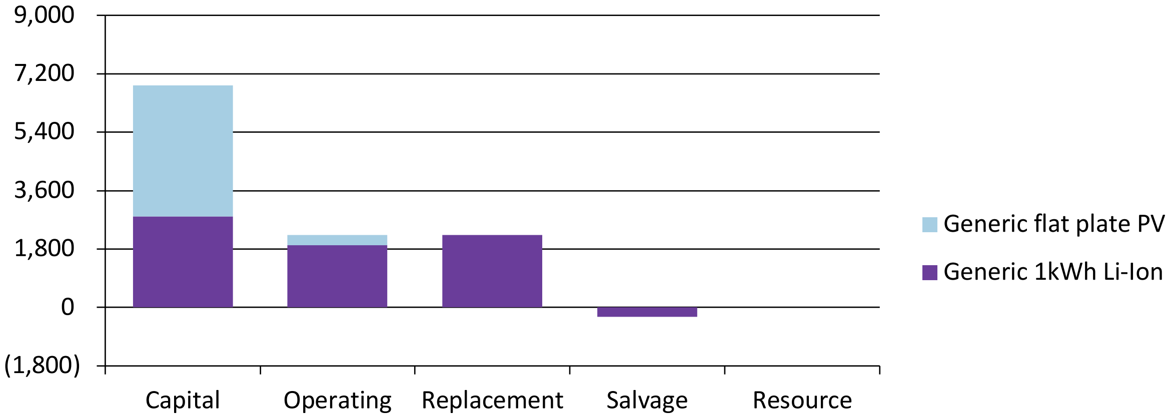
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.53	kW
Storage	Generic 1kWh Li-Ion	4	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



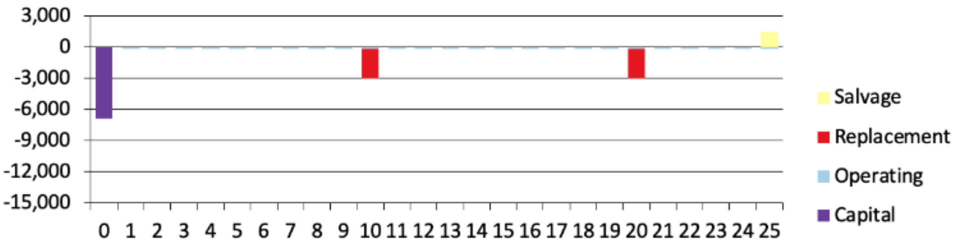
Net Present Costs

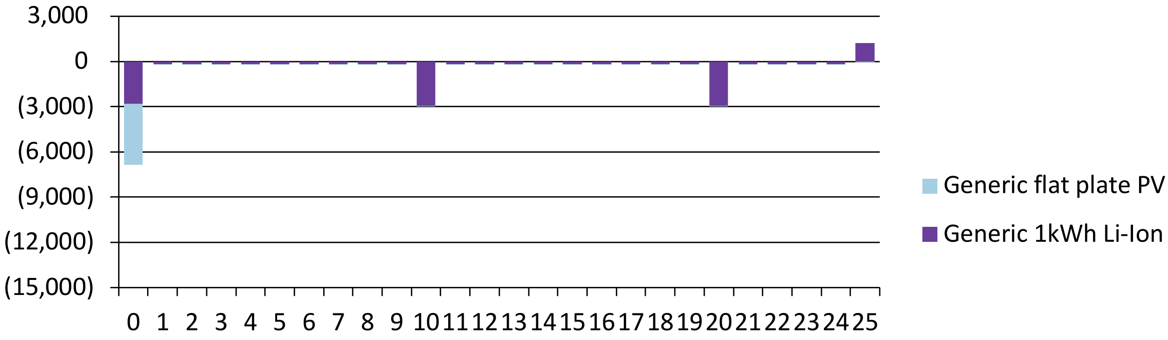
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$2,800	$1,922	$2,239	-$278.88	$0.00	$6,682
Generic flat plate PV	$4,050	$304.06	$0.00	$0.00	$0.00	$4,354
System	$6,850	$2,226	$2,239	-$278.88	$0.00	$11,036

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$233.10	$160.00	$186.37	-$23.22	$0.00	$556.25
Generic flat plate PV	$337.16	$25.31	$0.00	$0.00	$0.00	$362.47
System	$570.26	$185.31	$186.37	-$23.22	$0.00	$918.72

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	3,255	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	1.92	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	5,351	100
Total	5,351	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

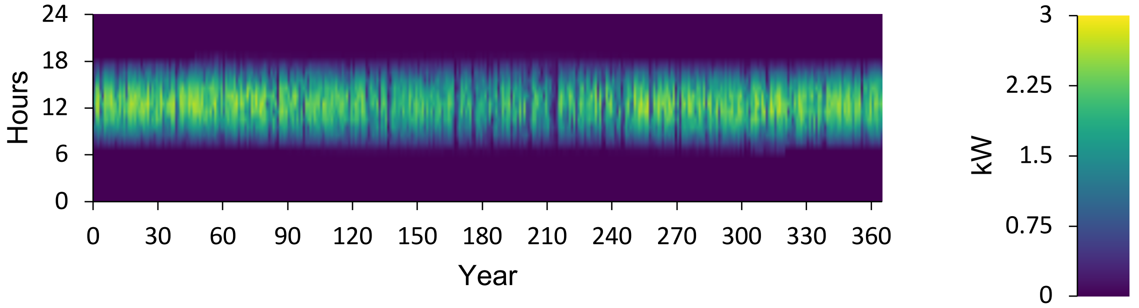
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	2.73	kW
PV Penetration	259	%
Hours of Operation	4,450	hrs/yr
Levelized Cost	0.0677	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.53	kW
Mean Output	0.611	kW
Mean Output	14.7	kWh/d
Capacity Factor	24.1	%
Total Production	5,351	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	8.00	qty.
String Size	2.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

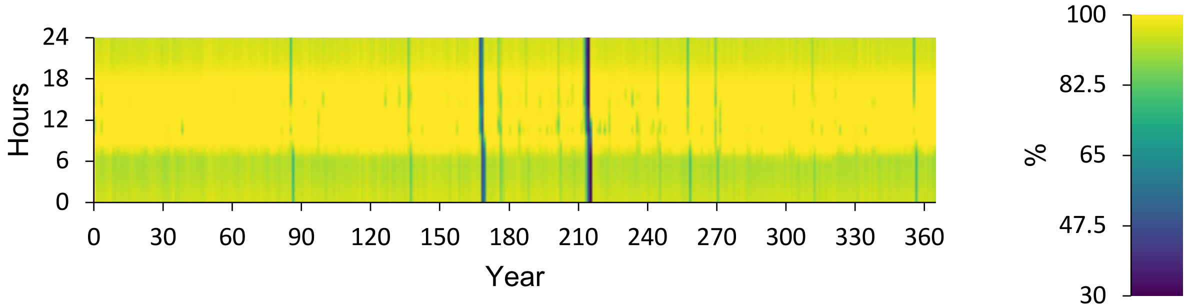
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	287	kWh/yr

Energy Out	259	kWh/yr
Storage Depletion	0.421	kWh/yr
Losses	28.7	kWh/yr
Annual Throughput	273	kWh/yr

Generic 1kWh Li-Ion Statistics

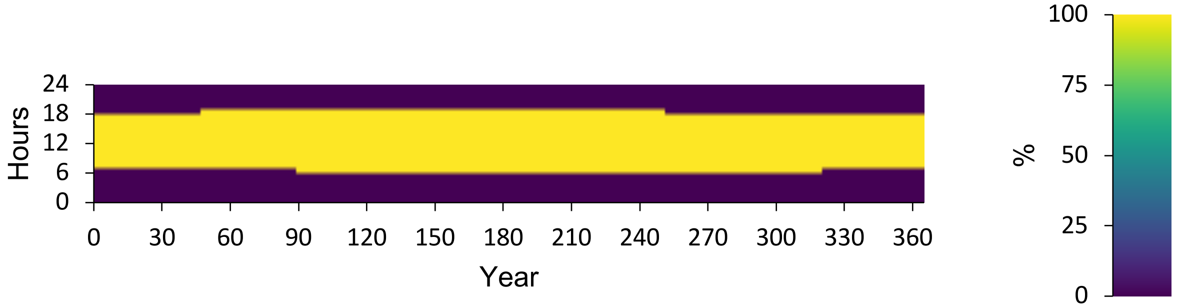
Quantity	Value	Units
Autonomy	23.7	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	8.00	kWh
Usable Nominal Capacity	5.60	kWh
Lifetime Throughput	2,727	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

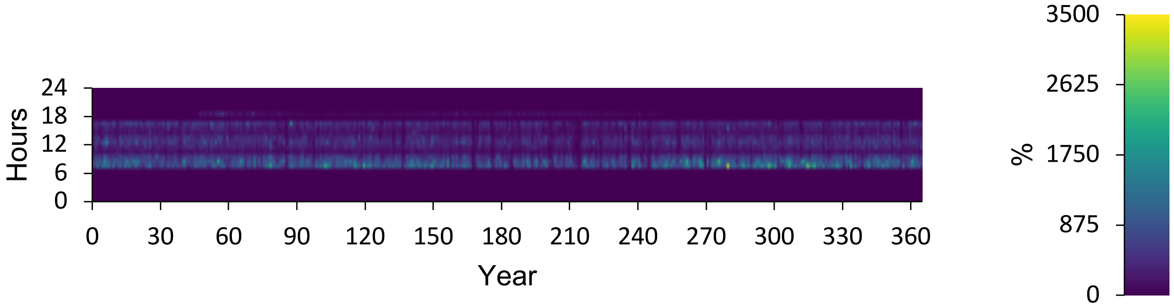


Renewable Summary

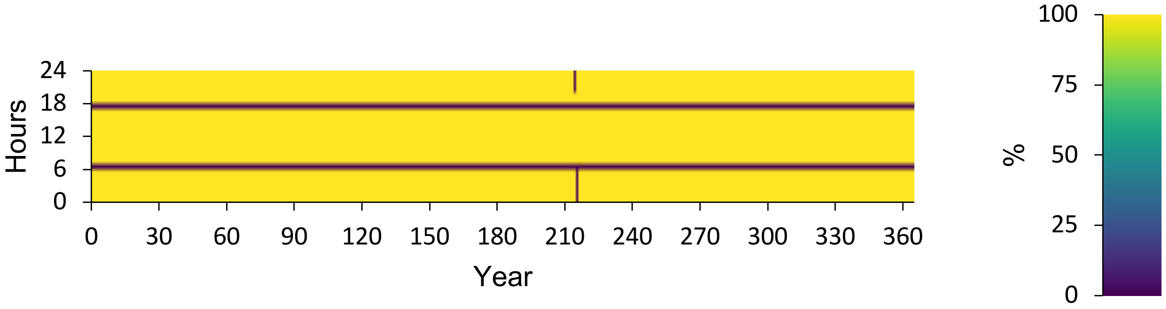
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$11,036
CAPEX	$6,850
OPEX	$348.46
LCOE (per kWh)	$0.444
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 1) – Burkina Faso

Location: D 35, Bèna, Burkina Faso (12°4.5'N, 4°11.4'W)

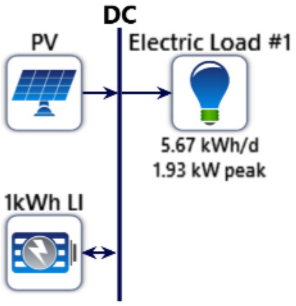
Total Net Present Cost: $11,990.68

Levelized Cost of Energy ($/kWh): $0.456

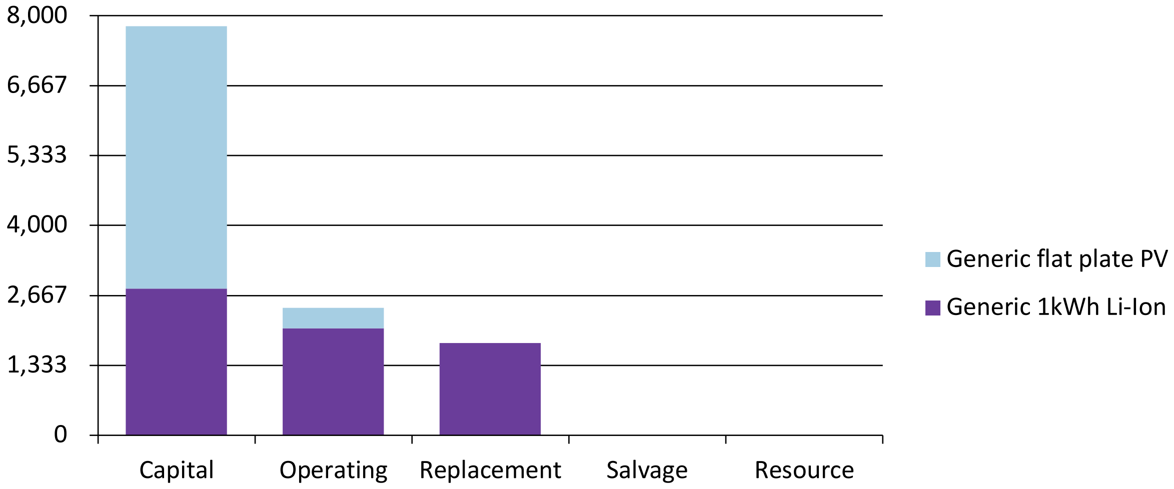
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	3.13	kW
Storage	Generic 1kWh Li-Ion	4	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



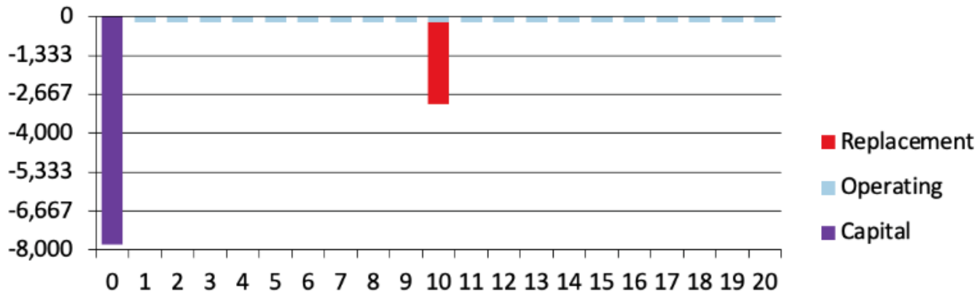
Net Present Costs

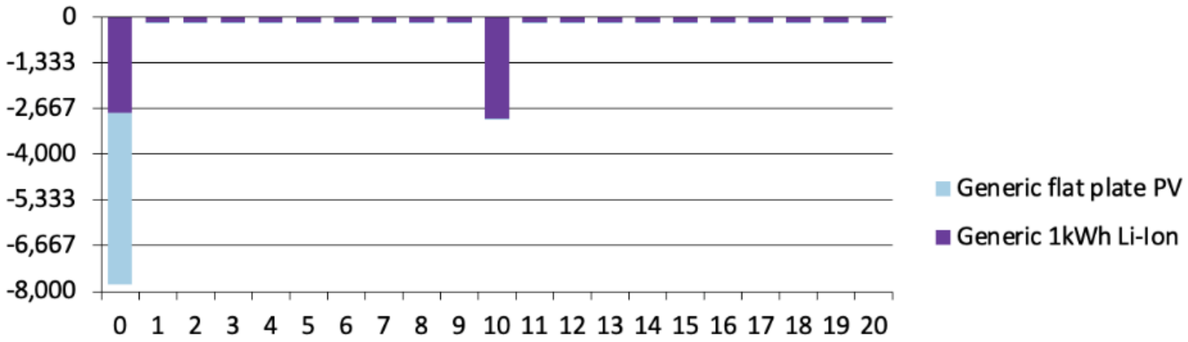
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$2,800	$2,035	$1,758	$0.00	$0.00	$6,593
Generic flat plate PV	$5,000	$397.43	$0.00	$0.00	$0.00	$5,397
System	$7,800	$2,432	$1,758	$0.00	$0.00	$11,991

Annualized Costs

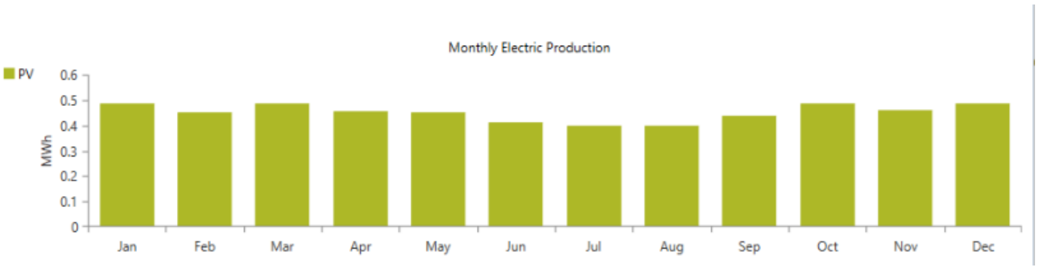
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	$220.17	$160.00	$138.27	$0.00	$0.00	$518.43
Generic flat plate PV	$393.15	$31.25	$0.00	$0.00	$0.00	$424.40
System	$613.32	$191.25	$138.27	$0.00	$0.00	$942.84

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	3,311	kWh/yr
Unmet Electric Load	1.20	kWh/yr
Capacity Shortage	1.92	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	5,411	100
Total	5,411	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

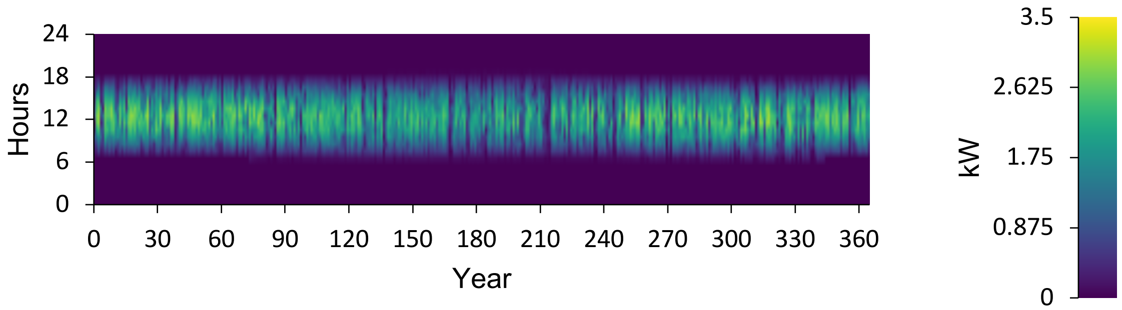
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	3.04	kW
PV Penetration	261	%
Hours of Operation	4,382	hrs/yr
Levelized Cost	0.0784	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	3.13	kW
Mean Output	0.618	kW
Mean Output	14.8	kWh/d
Capacity Factor	19.8	%
Total Production	5,411	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	8.00	qty.
String Size	2.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	12.0	V

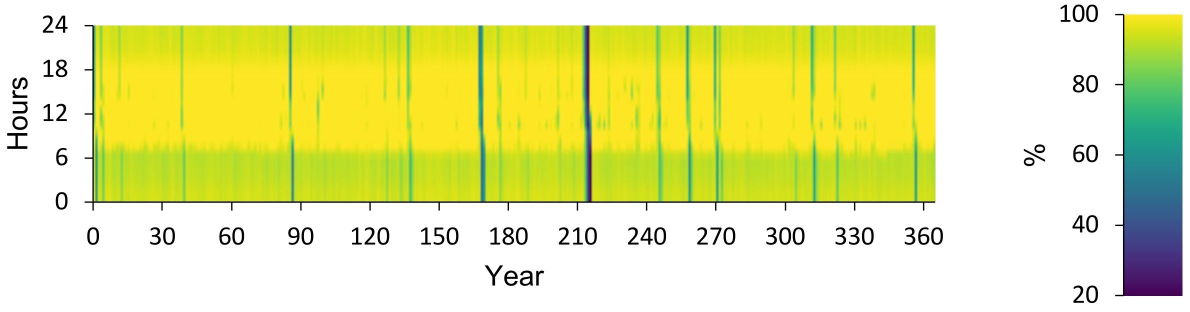
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	320	kWh/yr
Energy Out	289	kWh/yr
Storage Depletion	0.421	kWh/yr
Losses	32.1	kWh/yr
Annual Throughput	304	kWh/yr

Generic 1kWh Li-Ion Statistics

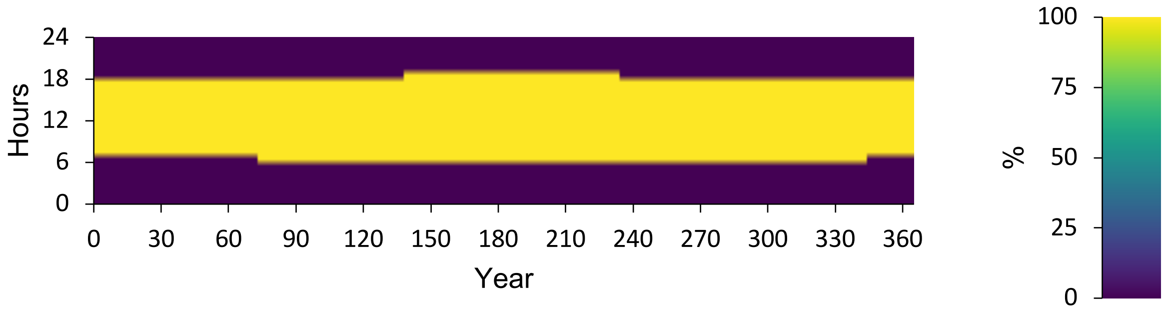
Quantity	Value	Units
Autonomy	27.1	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	8.00	kWh
Usable Nominal Capacity	6.40	kWh
Lifetime Throughput	3,044	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

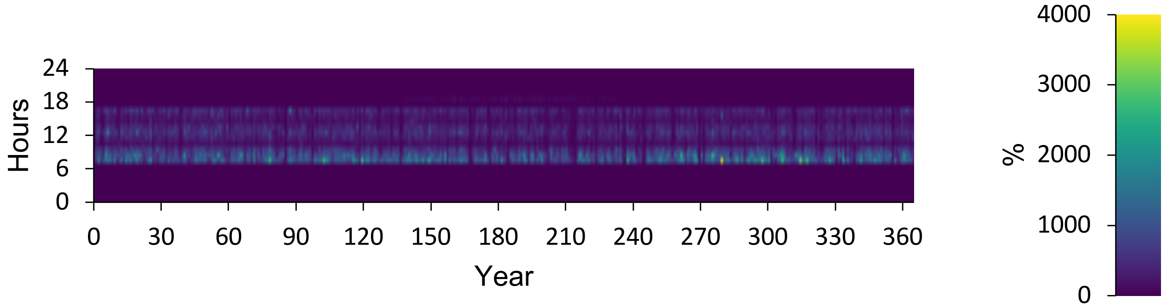


Renewable Summary

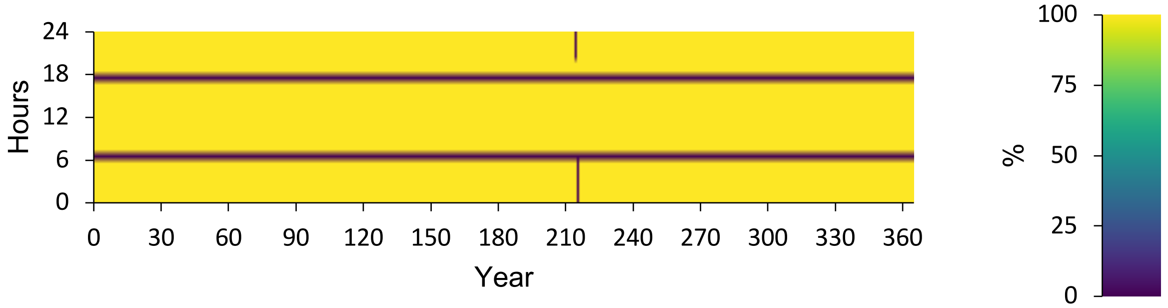
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$11,991
CAPEX	$7,800
OPEX	$329.52
LCOE (per kWh)	$0.456
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2) – Burkina Faso

Location: D 35, Bèna, Burkina Faso (12°4.5'N, 4°11.4'W)

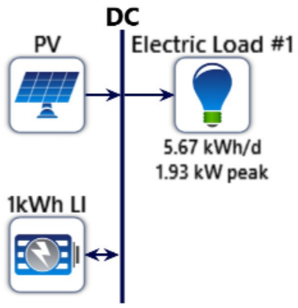
Total Net Present Cost: $19,633.07

Levelized Cost of Energy ($/kWh): $0.476

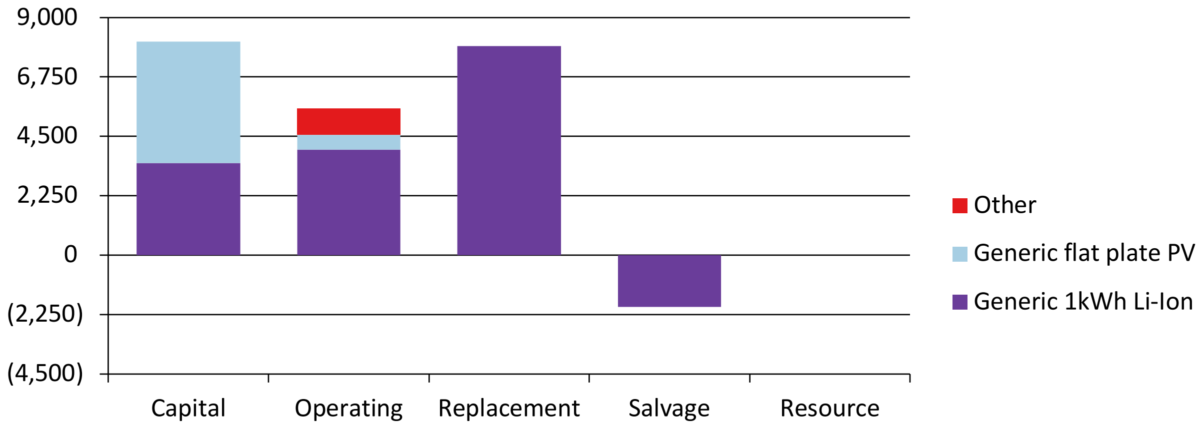
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.88	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



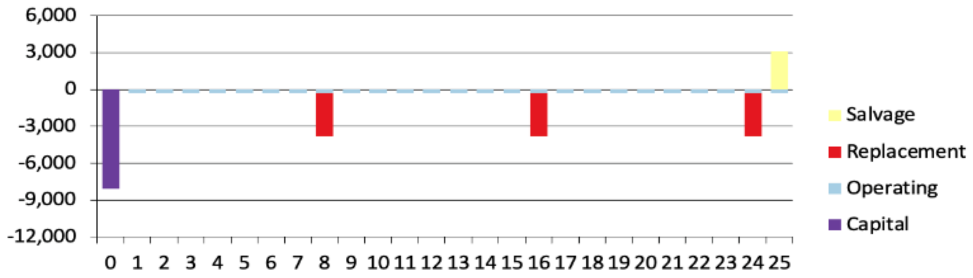
Net Present Costs

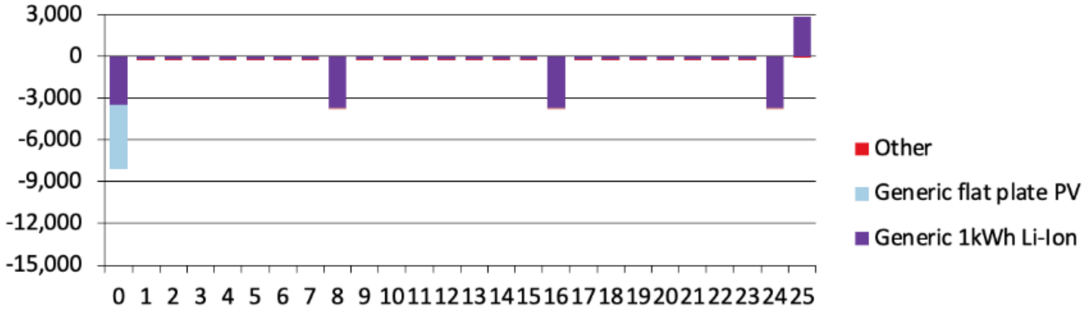
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$3,989	$7,925	-$1,952	$0.00	$13,462
Generic flat plate PV	$4,600	$573.47	$0.00	$0.00	$0.00	$5,173
Other	$0.00	$997.33	$0.00	$0.00	$0.00	$997.33
System	$8,100	$5,560	$7,925	-$1,952	$0.00	$19,633

Annualized Costs

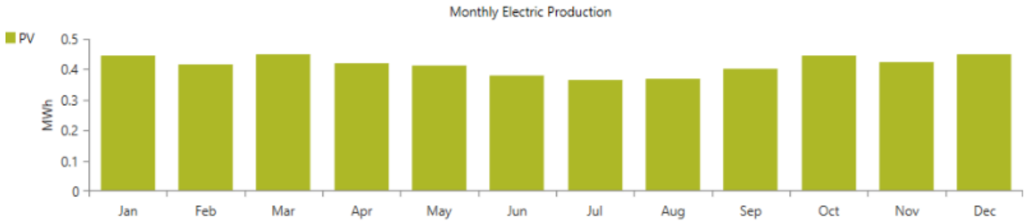
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$175.47	$200.00	$397.30	-$97.85	$0.00	$674.91
Generic flat plate PV	$230.61	$28.75	$0.00	$0.00	$0.00	$259.36
Other	$0.00	$50.00	$0.00	$0.00	$0.00	$50.00
System	$406.08	$278.75	$397.30	-$97.85	$0.00	$984.28

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,876	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.03	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,978	100
Total	4,978	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

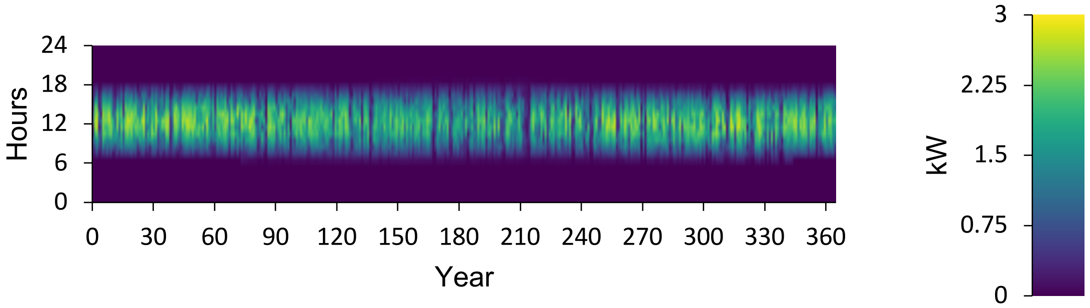
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	2.80	kW
PV Penetration	241	%
Hours of Operation	4,382	hrs/yr
Levelized Cost	0.0521	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.88	kW
Mean Output	0.568	kW
Mean Output	13.6	kWh/d
Capacity Factor	19.8	%
Total Production	4,978	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

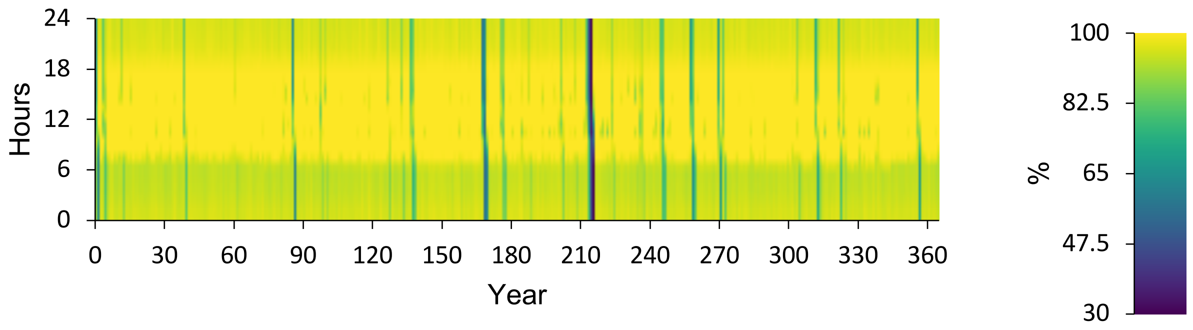
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	335	kWh/yr
Energy Out	301	kWh/yr
Storage Depletion	-0.579	kWh/yr
Losses	33.5	kWh/yr
Annual Throughput	318	kWh/yr

Generic 1kWh Li-Ion Statistics

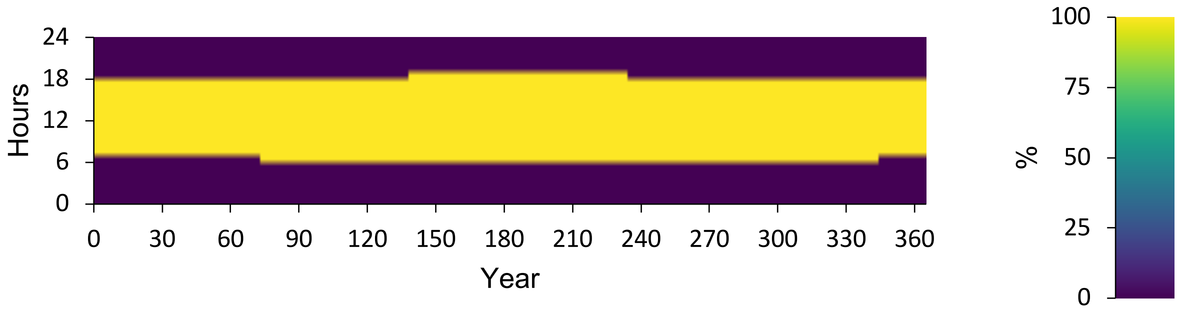
Quantity	Value	Units
Autonomy	29.6	hr
Storage Wear Cost	0.123	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	7.00	kWh
Lifetime Throughput	2,540	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

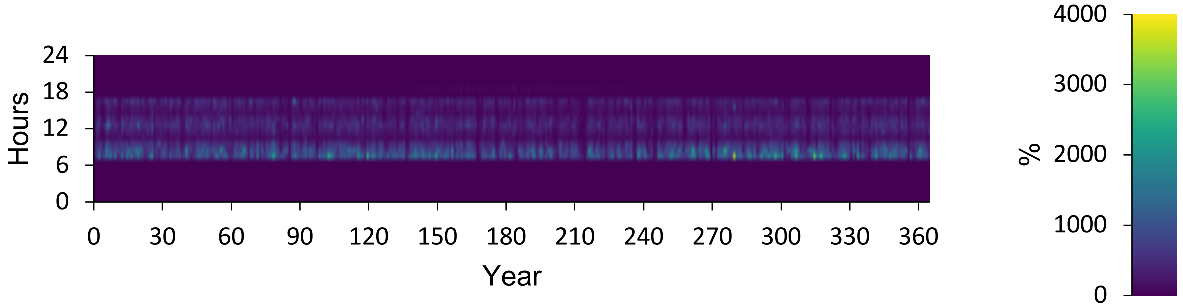


Renewable Summary

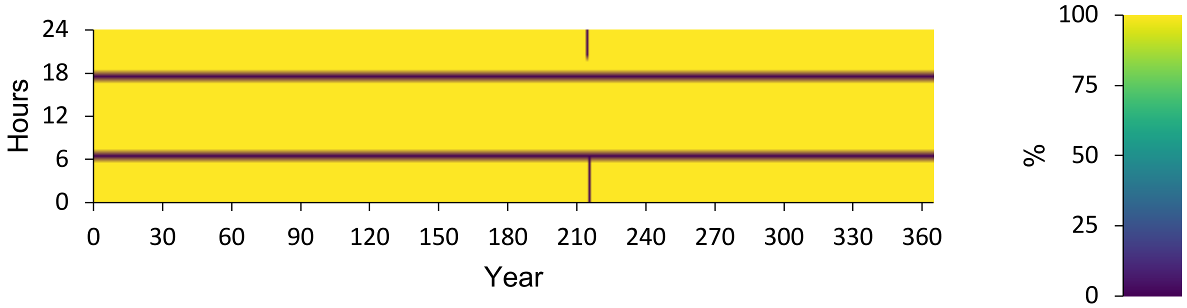
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$19,633
CAPEX	$8,100
OPEX	$578.20
LCOE (per kWh)	$0.476
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 3) – Burkina Faso

Location: D 35, Bèna, Burkina Faso (12°4.5'N, 4°11.4'W)

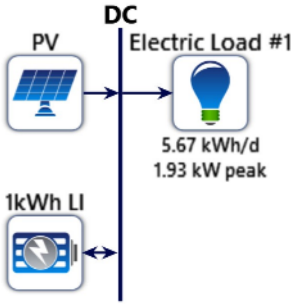
Total Net Present Cost: $20,100.00

Levelized Cost of Energy ($/kWh): $0.389

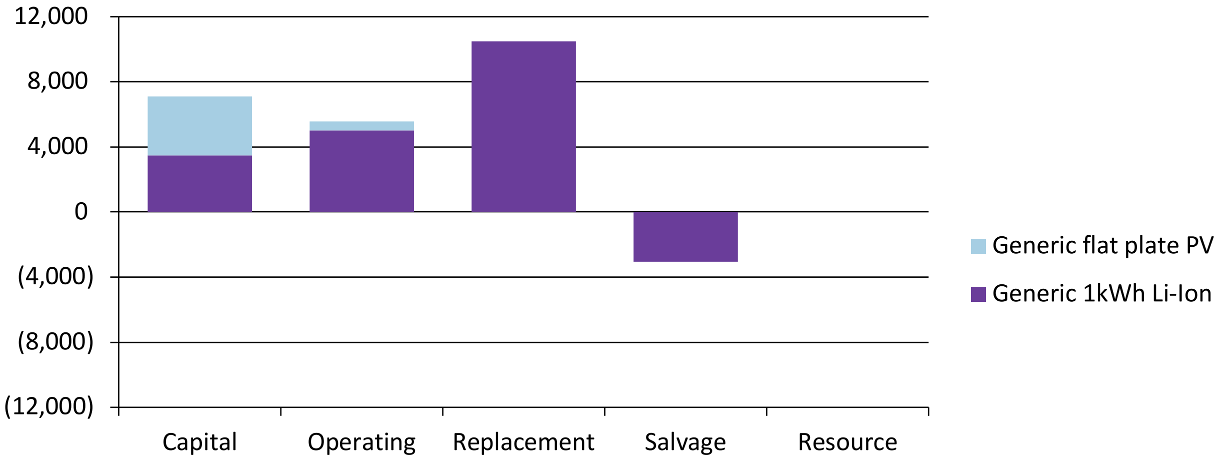
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	2.25	kW
Storage	Generic 1kWh Li-Ion	5	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



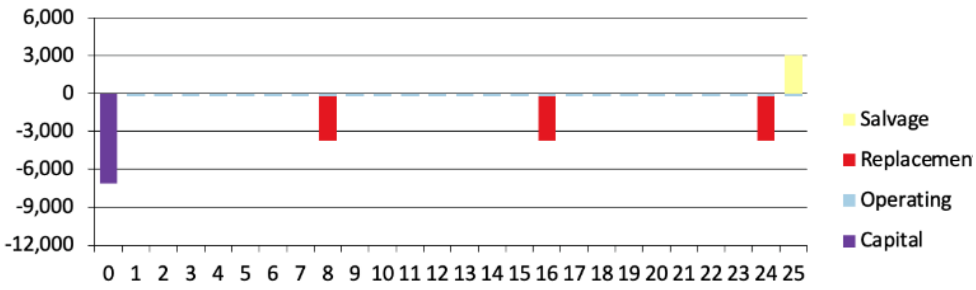
Net Present Costs

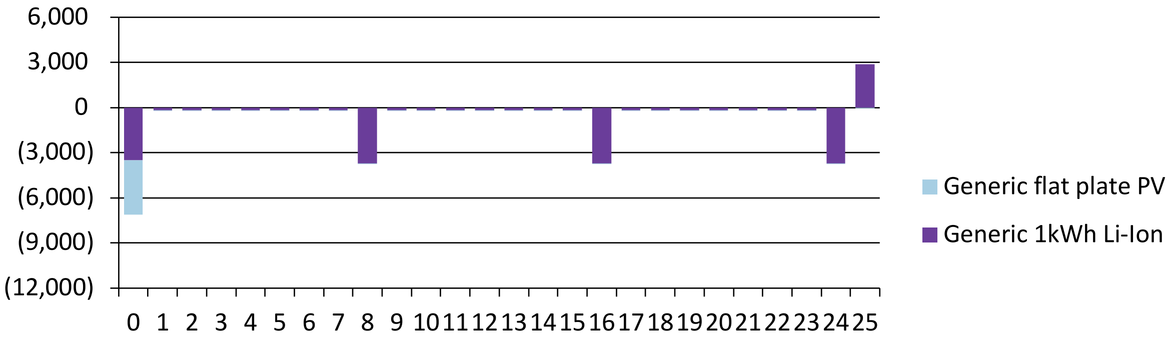
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$3,500	$5,000	$10,500	-$3,063	$0.00	$15,938
Generic flat plate PV	$3,600	$562.50	$0.00	$0.00	$0.00	$4,163
System	$7,100	$5,563	$10,500	-$3,063	$0.00	$20,100

Annualized Costs

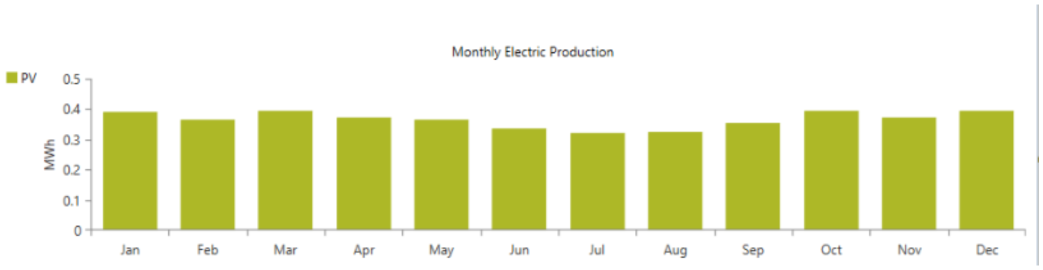
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$140.00	$200.00	$420.00	-$122.50	$0.00	$637.50
Generic flat plate PV	$144.00	$22.50	$0.00	$0.00	$0.00	$166.50
System	$284.00	$222.50	$420.00	-$122.50	$0.00	$804.00

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,278	kWh/yr
Unmet Electric Load	1.42	kWh/yr
Capacity Shortage	1.90	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	4,383	100
Total	4,383	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

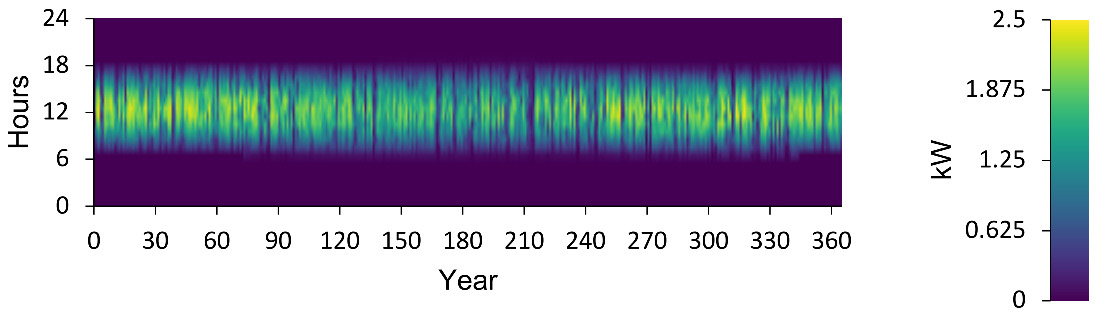
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	2.46	kW
PV Penetration	212	%
Hours of Operation	4,382	hrs/yr
Levelized Cost	0.0380	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	2.25	kW
Mean Output	0.500	kW
Mean Output	12.0	kWh/d
Capacity Factor	22.2	%
Total Production	4,383	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	10.0	qty.
String Size	2.00	batteries
Strings in Parallel	5.00	strings
Bus Voltage	12.0	V

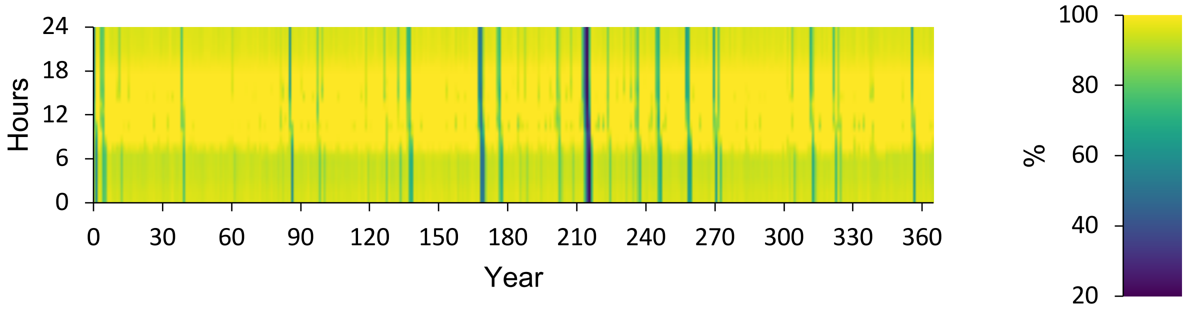
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	361	kWh/yr
Energy Out	325	kWh/yr
Storage Depletion	-0.579	kWh/yr
Losses	36.1	kWh/yr
Annual Throughput	342	kWh/yr

Generic 1kWh Li-Ion Statistics

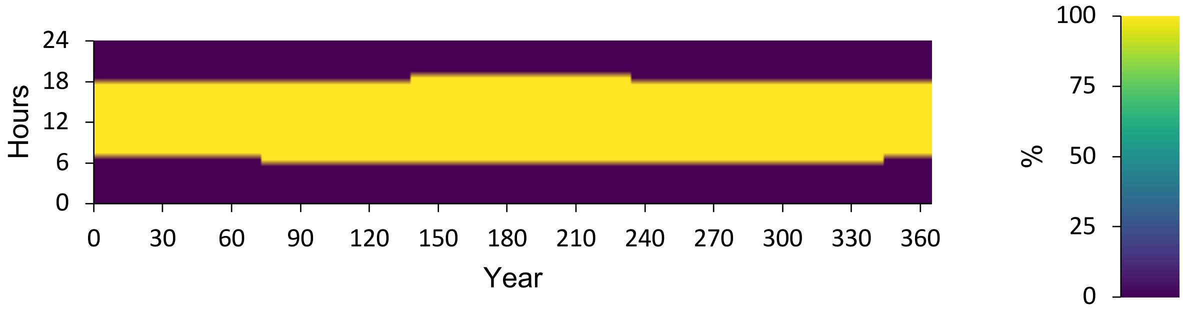
Quantity	Value	Units
Autonomy	33.9	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	10.0	kWh
Usable Nominal Capacity	8.00	kWh
Lifetime Throughput	2,738	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

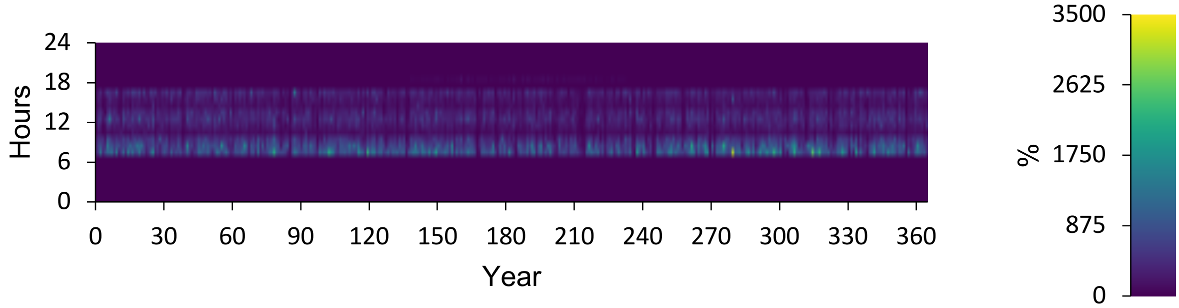


Renewable Summary

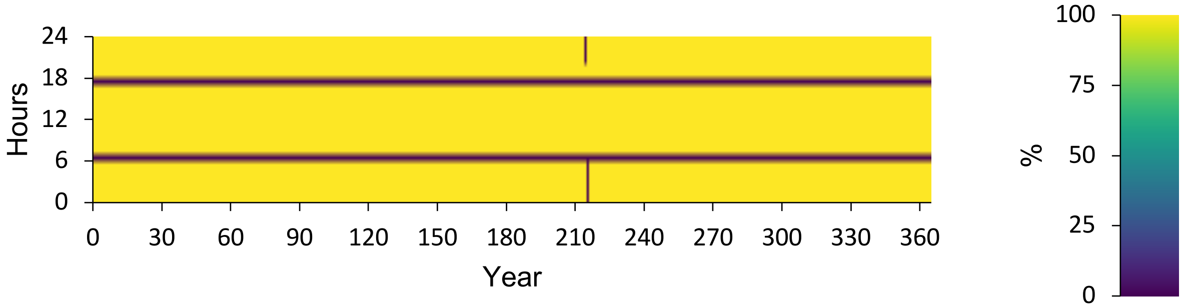
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$20,100
CAPEX	$7,100
OPEX	$520.00
LCOE (per kWh)	$0.389
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4) – Burkina Faso

Location: D 35, Bèna, Burkina Faso (12°4.5'N, 4°11.4'W)

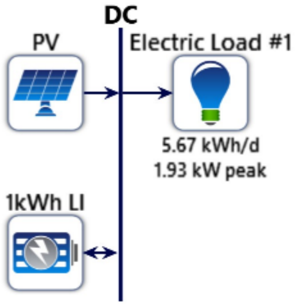
Total Net Present Cost: $11,895.82

Levelized Cost of Energy ($/kWh): $0.479

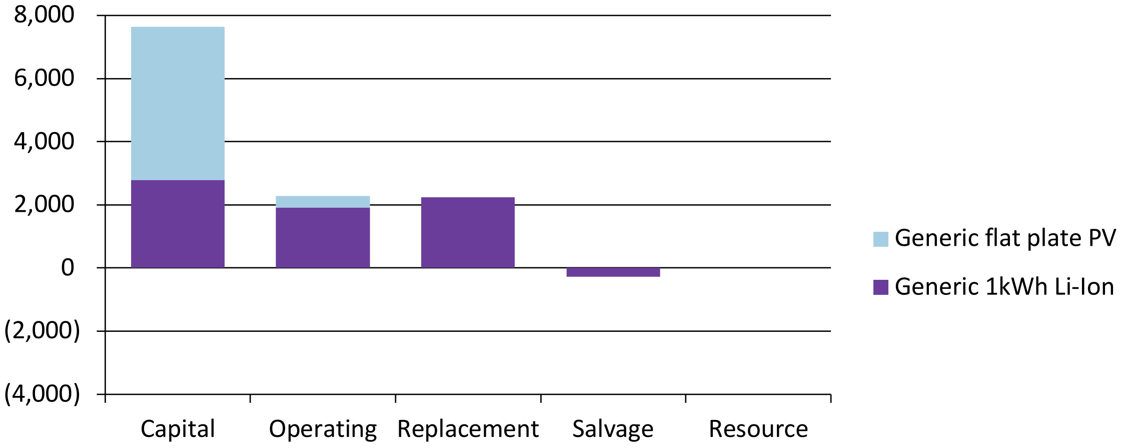
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	3.03	kW
Storage	Generic 1kWh Li-Ion	4	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



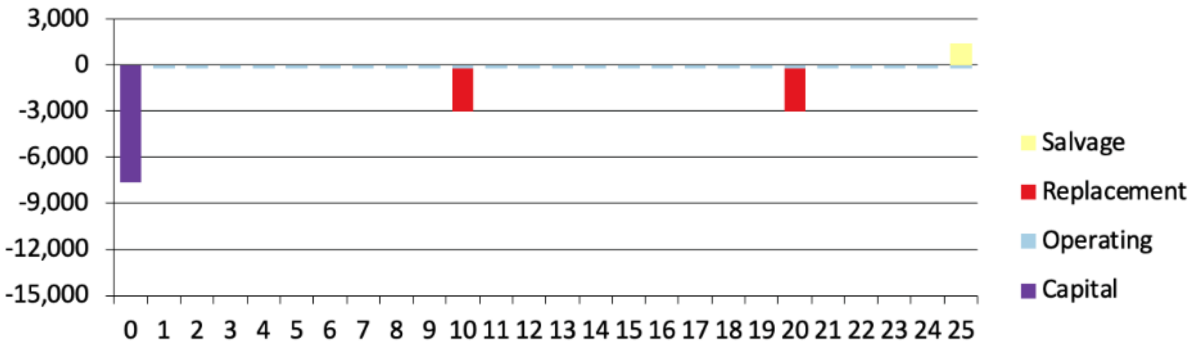
Net Present Costs

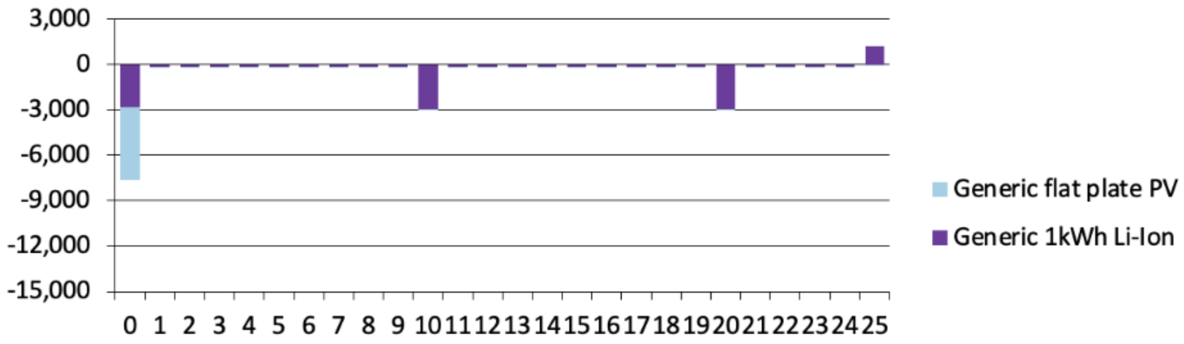
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$2,800	$1,922	$2,239	-$278.88	$0.00	$6,682
Generic flat plate PV	$4,850	$364.12	$0.00	$0.00	$0.00	$5,214
System	$7,650	$2,286	$2,239	-$278.88	$0.00	$11,896

Annualized Costs

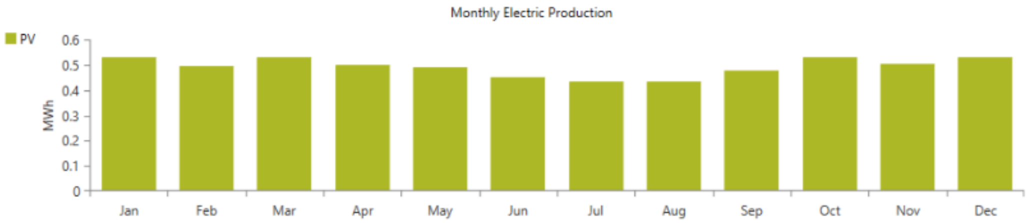
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$233.10	$160.00	$186.37	-$23.22	$0.00	$556.25
Generic flat plate PV	$403.76	$30.31	$0.00	$0.00	$0.00	$434.07
System	$636.86	$190.31	$186.37	-$23.22	$0.00	$990.32

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	3,806	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	2.03	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	5,905	100
Total	5,905	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	2,068	100
Deferrable Load	0	0
Total	2,068	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

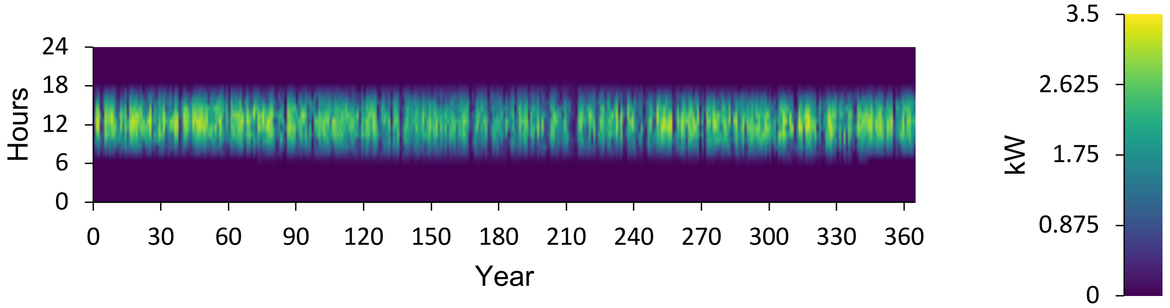
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	3.32	kW
PV Penetration	285	%
Hours of Operation	4,382	hrs/yr
Levelized Cost	0.0735	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	3.03	kW
Mean Output	0.674	kW
Mean Output	16.2	kWh/d
Capacity Factor	22.2	%
Total Production	5,905	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	8.00	qty.
String Size	2.00	batteries
Strings in Parallel	4.00	strings
Bus Voltage	12.0	V

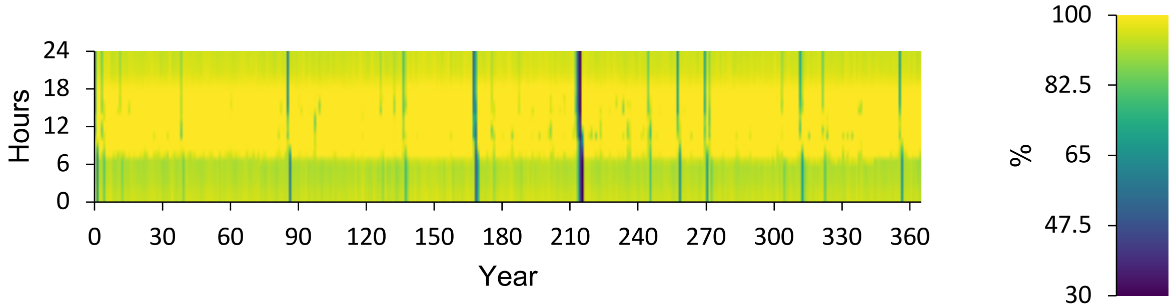
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	308	kWh/yr
Energy Out	278	kWh/yr
Storage Depletion	0.421	kWh/yr
Losses	30.9	kWh/yr
Annual Throughput	293	kWh/yr

Generic 1kWh Li-Ion Statistics

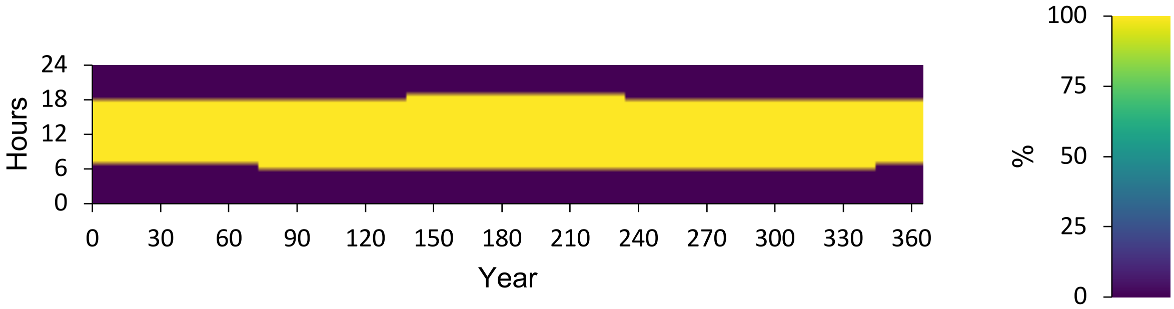
Quantity	Value	Units
Autonomy	23.7	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	8.00	kWh
Usable Nominal Capacity	5.60	kWh
Lifetime Throughput	2,929	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

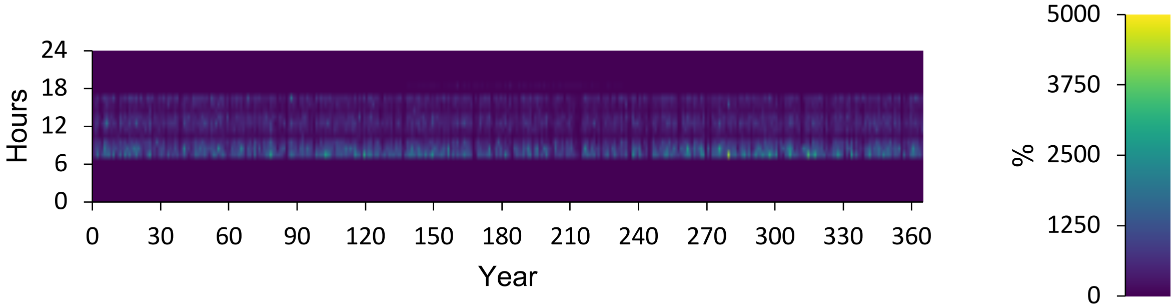


Renewable Summary

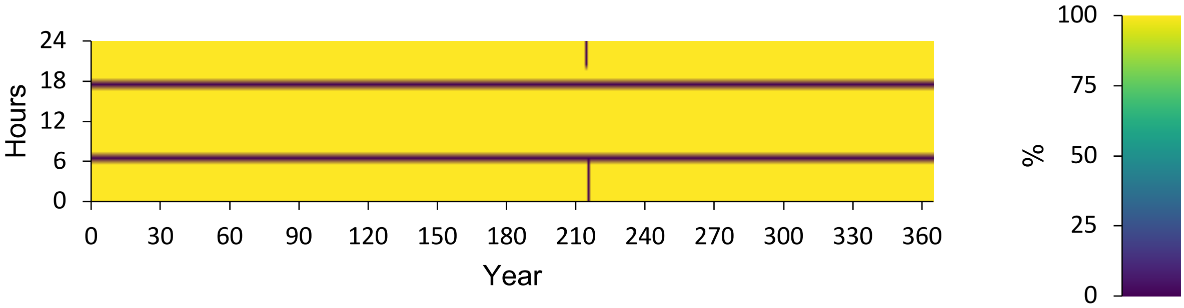
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$11,896
CAPEX	$7,650
OPEX	$353.46
LCOE (per kWh)	$0.479
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

HOMER Pro

Appendix C

Techno-economic Analysis of Standalone DC microgrid for Rural Village in Sub-Saharan Africa: A case of Ethiopia

System Simulation Report (Under Scenario 1)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

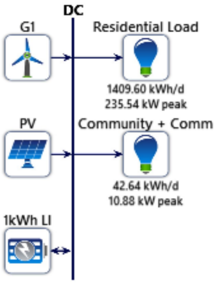
Total Net Present Cost: $2,821,702.00

Levelized Cost of Energy ($/kWh): $0.419

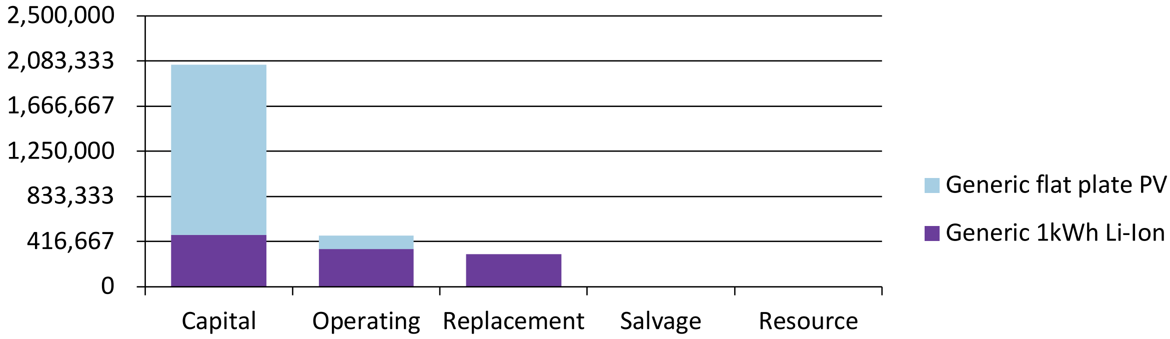
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	984	kW
Storage	Generic 1kWh Li-Ion	681	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



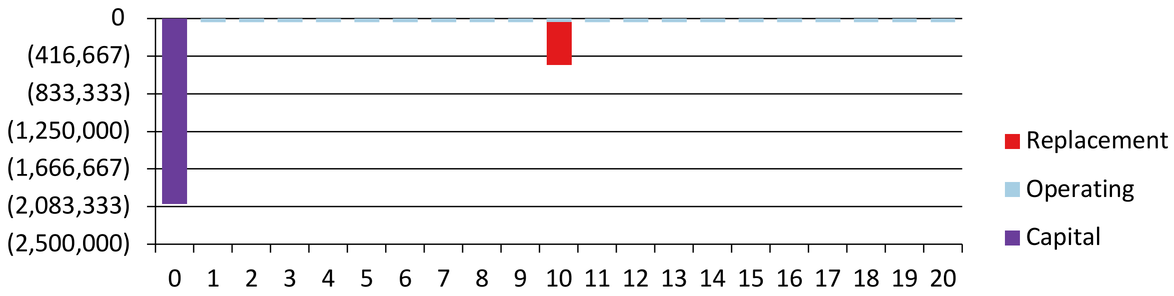
Net Present Costs

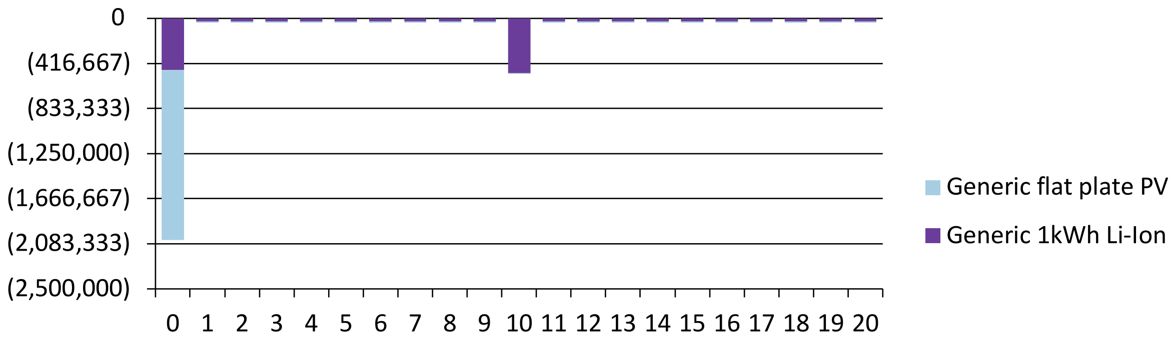
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$476,700	$346,430	$299,372	$0.00	$0.00	$1.12M
Generic flat plate PV	$1.57M	$125,117	$0.00	$0.00	$0.00	$1.70M
System	$2.05M	$471,547	$299,372	$0.00	$0.00	$2.82M

Annualized Costs

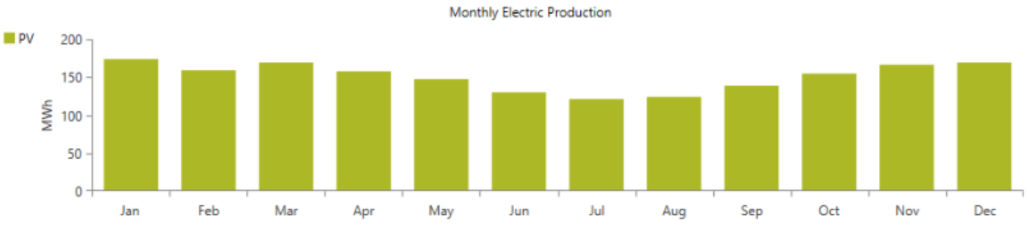
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$37,483	$27,240	$23,540	$0.00	$0.00	$88,263
Generic flat plate PV	$123,771	$9,838	$0.00	$0.00	$0.00	$133,609
System	$161,254	$37,078	$23,540	$0.00	$0.00	$221,872

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,272,773	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	510	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	1,812,038	100
Total	1,812,038	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	529,736	100
Deferrable Load	0	0
Total	529,736	100

PV: Generic flat plate PV

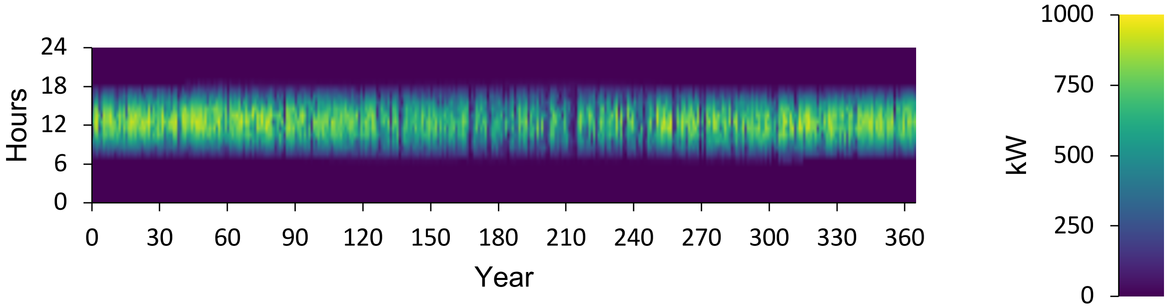
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	944	kW
PV Penetration	342	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0737	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	984	kW
Mean Output	207	kW
Mean Output	4,964	kWh/d
Capacity Factor	21.0	%
Total Production	1,812,038	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	1,362	qty.
String Size	2.00	batteries
Strings in Parallel	681	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

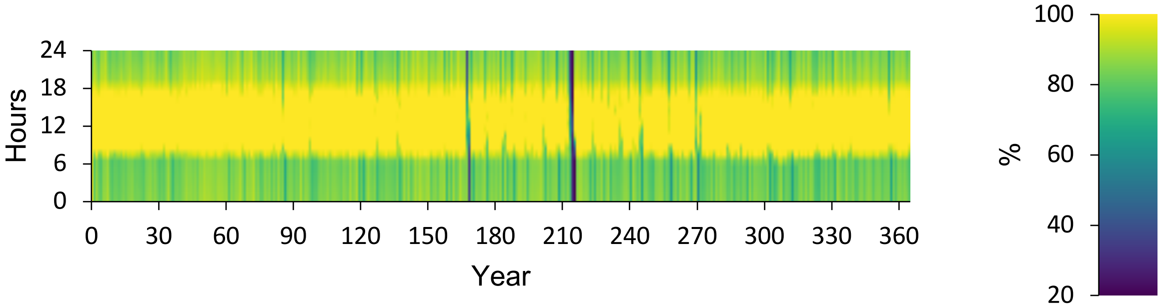
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	97,365	kWh/yr
Energy Out	87,837	kWh/yr
Storage Depletion	219	kWh/yr
Losses	9,748	kWh/yr
Annual Throughput	92,588	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	18.0	hr

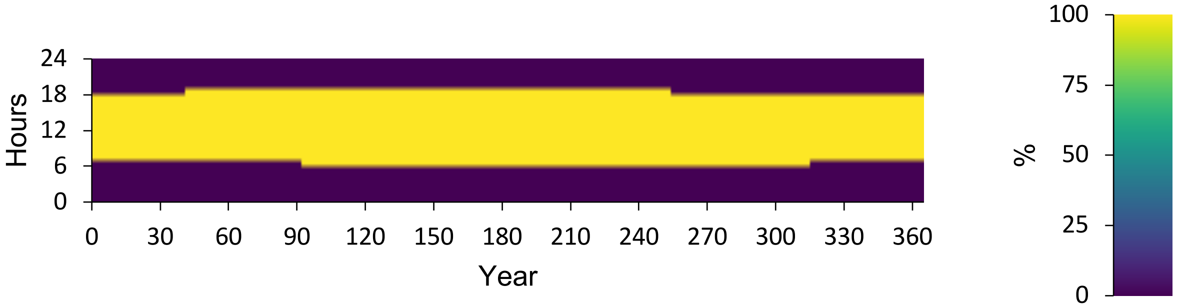
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	1,362	kWh
Usable Nominal Capacity	1,090	kWh
Lifetime Throughput	925,879	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

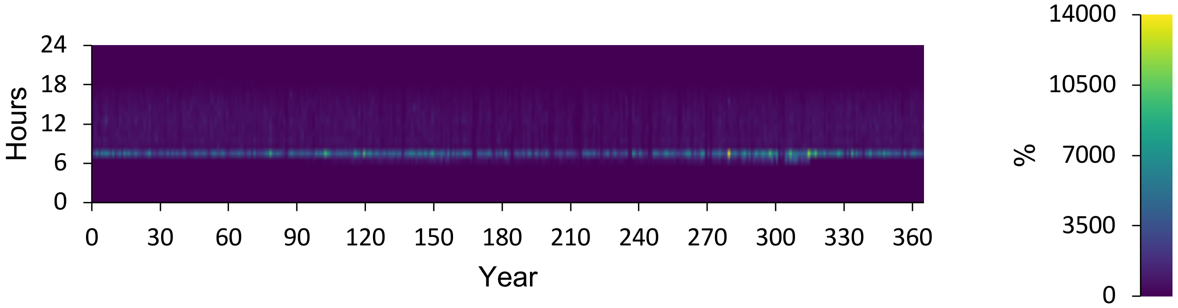


Renewable Summary

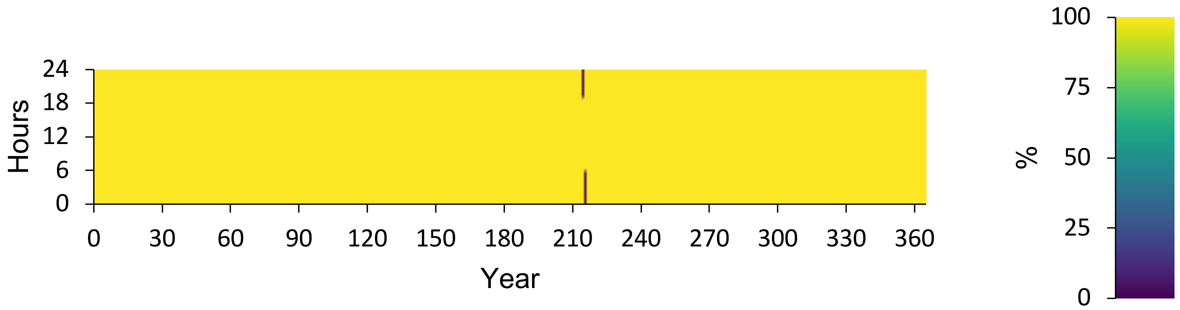
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$2.82M
CAPEX	$2.05M
OPEX	$60,618
LCOE (per kWh)	$0.419
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

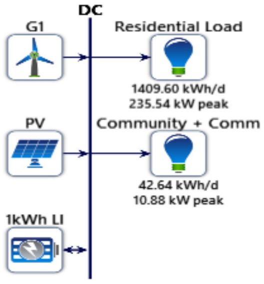
Total Net Present Cost: $3,292,716.00

Levelized Cost of Energy ($/kWh): $0.312

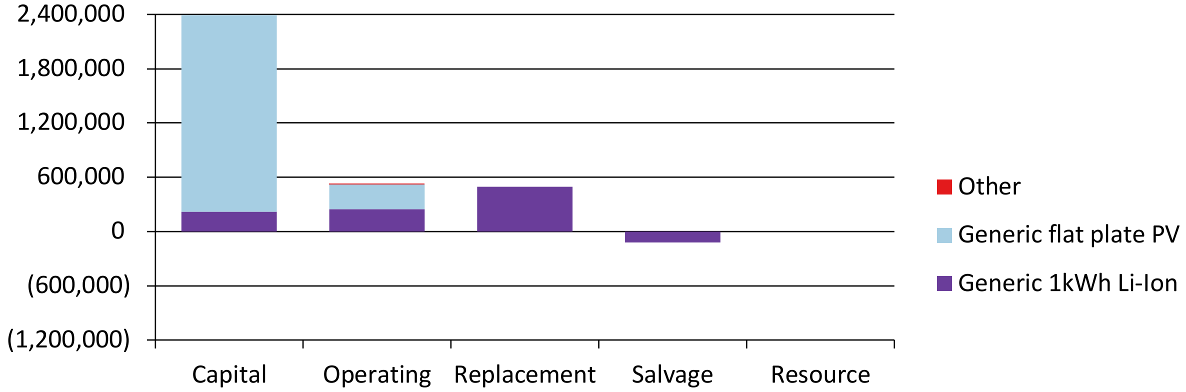
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,357	kW
Storage	Generic 1kWh Li-Ion	312	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



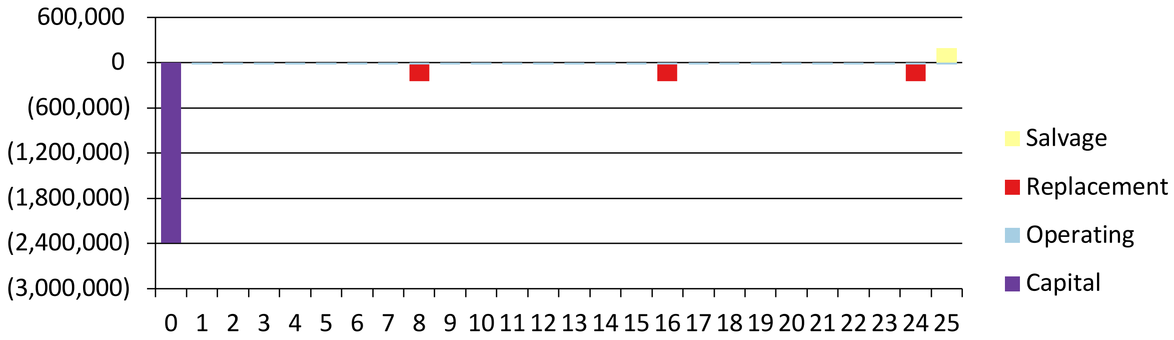
Net Present Costs

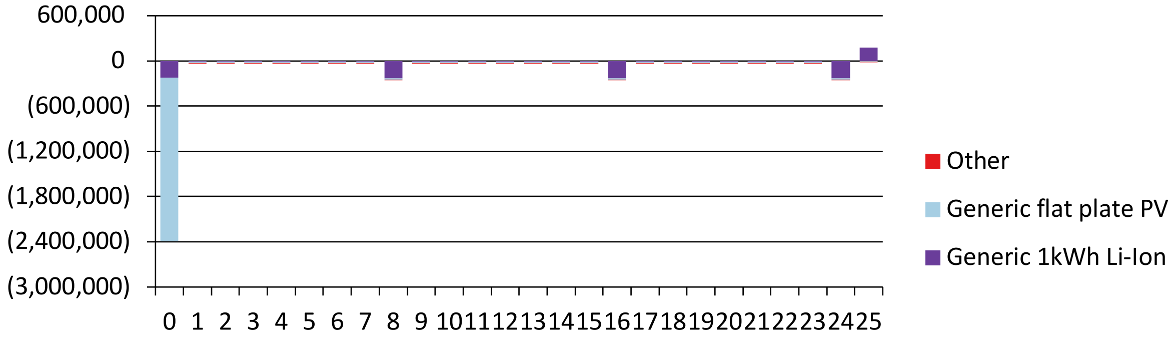
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$218,400	$248,934	$494,506	-$121,794	$0.00	$840,046
Generic flat plate PV	$2.17M	$270,767	$0.00	$0.00	$0.00	$2.44M
Other	$0.00	$9,973	$0.00	$0.00	$0.00	$9,973
System	$2.39M	$529,675	$494,506	-$121,794	$0.00	$3.29M

Annualized Costs

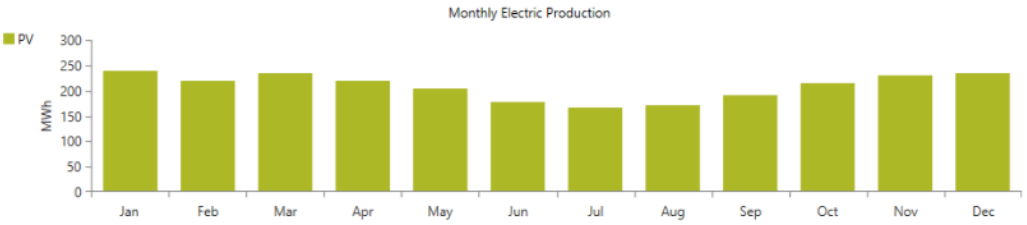
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$10,949	$12,480	$24,791	-$6,106	$0.00	$42,115
Generic flat plate PV	$108,887	$13,575	$0.00	$0.00	$0.00	$122,461
Other	$0.00	$500.00	$0.00	$0.00	$0.00	$500.00
System	$119,836	$26,555	$24,791	-$6,106	$0.00	$165,076

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,961,668	kWh/yr
Unmet Electric Load	278	kWh/yr
Capacity Shortage	522	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	2,500,260	100
Total	2,500,260	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	529,790	100
Deferrable Load	0	0
Total	529,790	100

PV: Generic flat plate PV

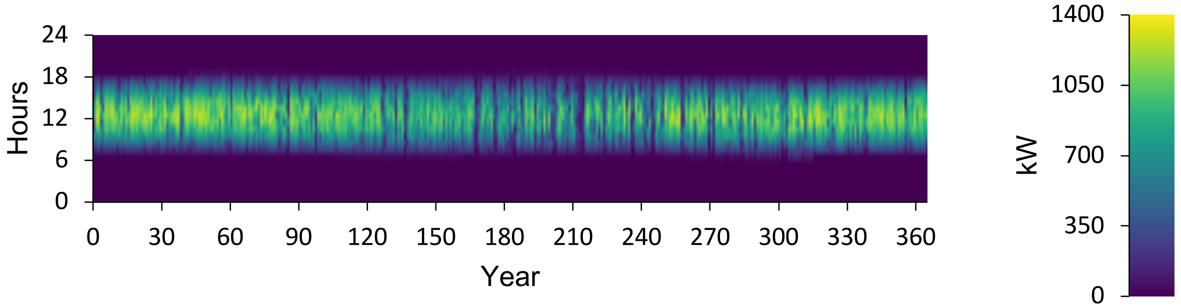
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,303	kW
PV Penetration	472	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0490	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,357	kW
Mean Output	285	kW
Mean Output	6,850	kWh/d
Capacity Factor	21.0	%
Total Production	2,500,260	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	624	qty.
String Size	2.00	batteries
Strings in Parallel	312	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

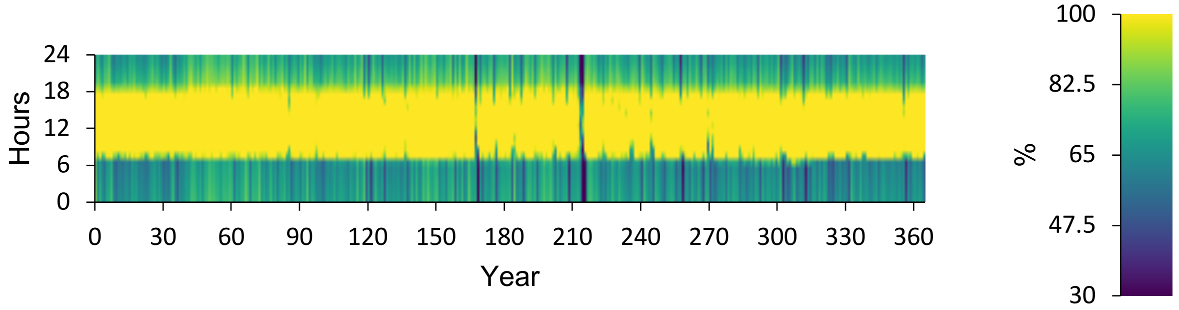
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	89,465	kWh/yr
Energy Out	80,663	kWh/yr
Storage Depletion	152	kWh/yr
Losses	8,954	kWh/yr
Annual Throughput	85,026	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	7.22	hr
Storage Wear Cost	0.184	$/kWh

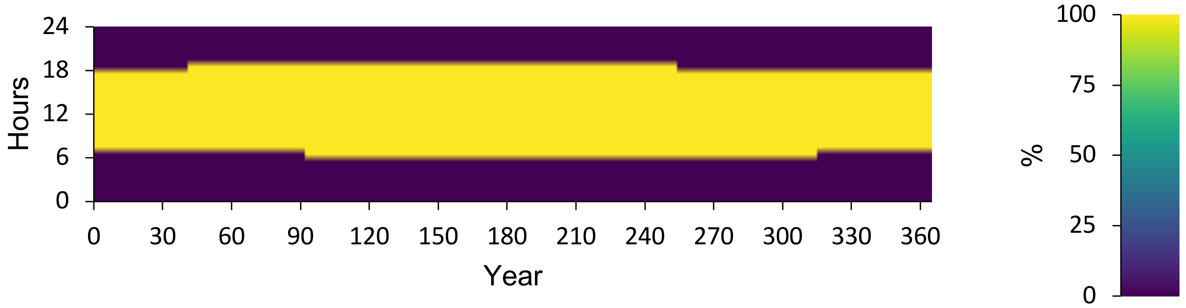
Nominal Capacity	624	kWh
Usable Nominal Capacity	437	kWh
Lifetime Throughput	680,209	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

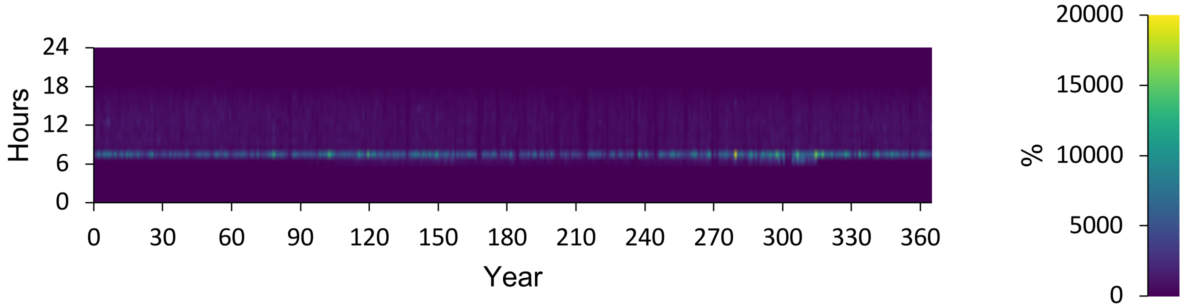


Renewable Summary

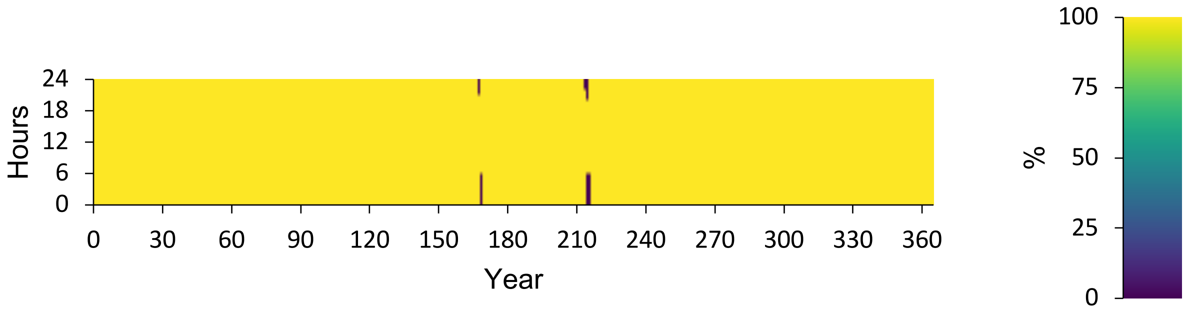
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$3.29M
CAPEX	$2.39M
OPEX	$45,240
LCOE (per kWh)	$0.312
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

HOMER Pro

System Simulation Report (Under Scenario 3)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

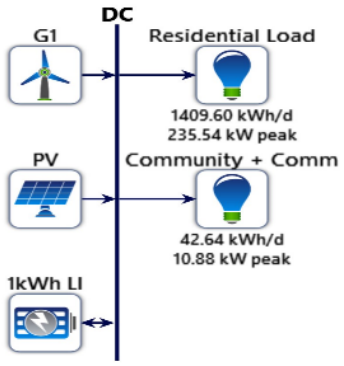
Total Net Present Cost: $2,865,402.00

Levelized Cost of Energy ($/kWh): $0.270

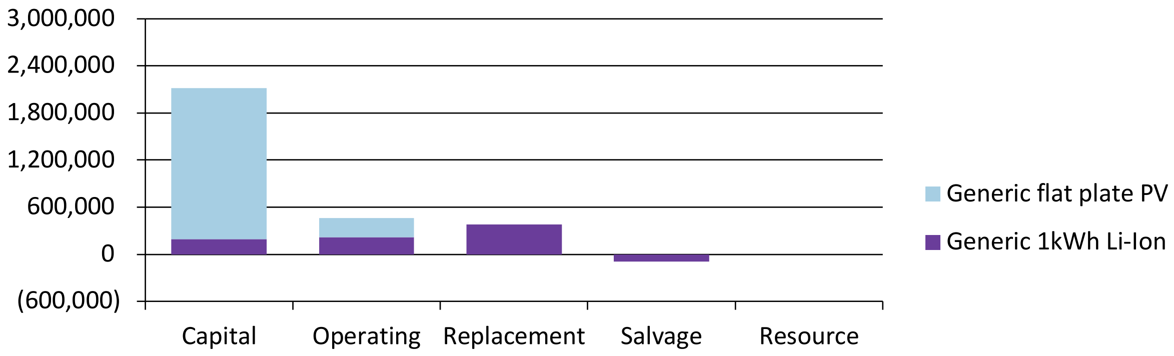
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,207	kW
Storage	Generic 1kWh Li-Ion	272	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



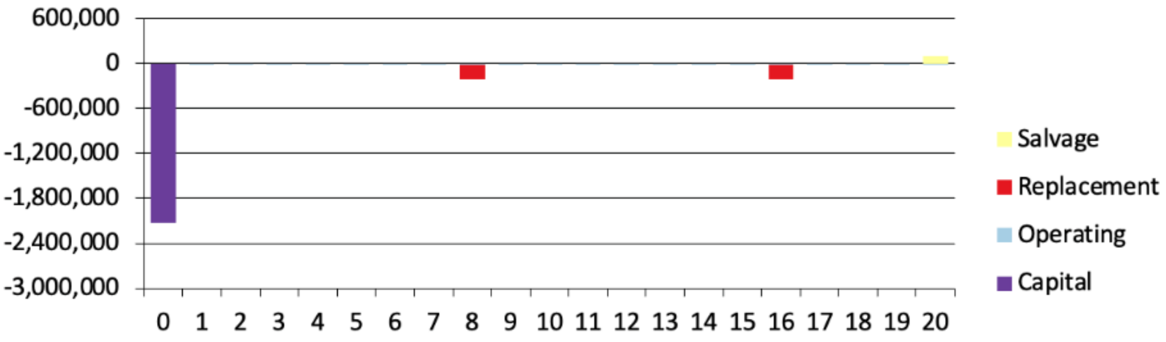
Net Present Costs

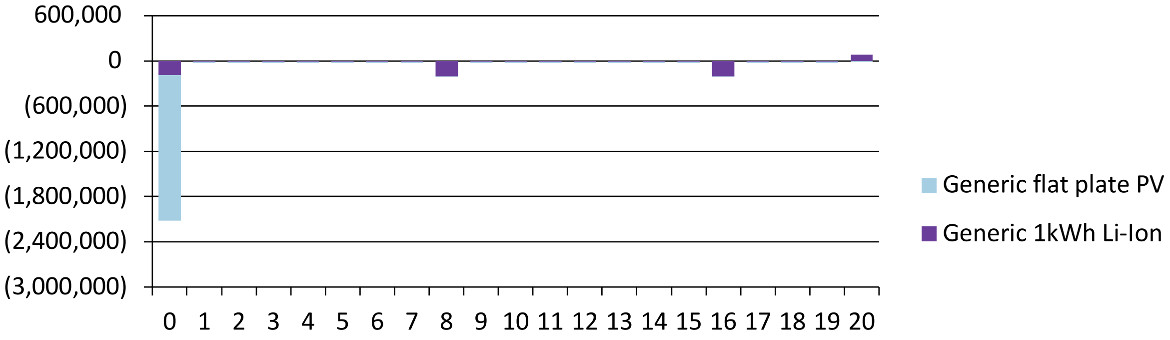
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	$190,400	$217,600	$380,800	-$95,200	$0.00	$693,600
Generic flat plate PV	$1.93M	$241,311	$0.00	$0.00	$0.00	$2.17M
System	$2.12M	$458,911	$380,800	-$95,200	$0.00	$2.87M

Annualized Costs

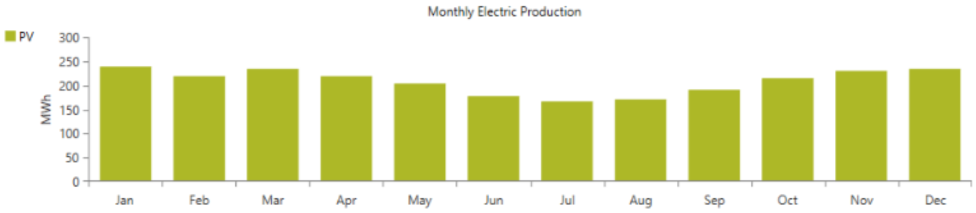
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Generic 1kWh Li-Ion	$9,520	$10,880	$19,040	-$4,760	$0.00	$34,680
Generic flat plate PV	$96,525	$12,066	$0.00	$0.00	$0.00	$108,590
System	$106,045	$22,946	$19,040	-$4,760	$0.00	$143,270

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,961,534	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	530	kWh/yr

Production Summary

Component	**Production (kWh/yr)**	**Percent**
Generic flat plate PV	2,500,114	100
Total	2,500,114	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	529,786	100
Deferrable Load	0	0
Total	529,786	100

PV: Generic flat plate PV

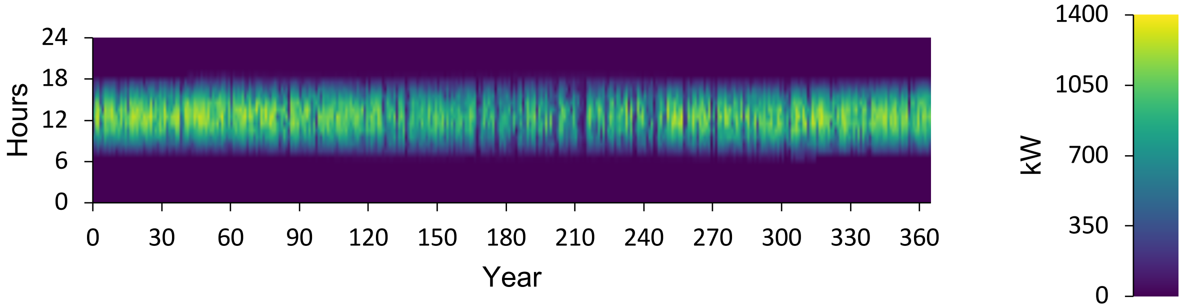
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,303	kW
PV Penetration	472	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0434	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,207	kW
Mean Output	285	kW
Mean Output	6,850	kWh/d
Capacity Factor	23.7	%
Total Production	2,500,114	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	544	qty.
String Size	2.00	batteries
Strings in Parallel	272	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

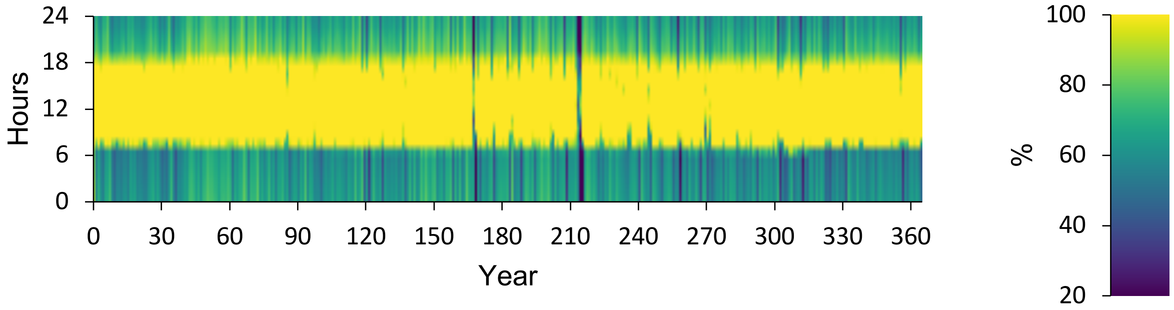
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	89,453	kWh/yr
Energy Out	80,660	kWh/yr
Storage Depletion	160	kWh/yr
Losses	8,954	kWh/yr
Annual Throughput	85,023	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	7.19	hr
Storage Wear Cost	0.184	$/kWh

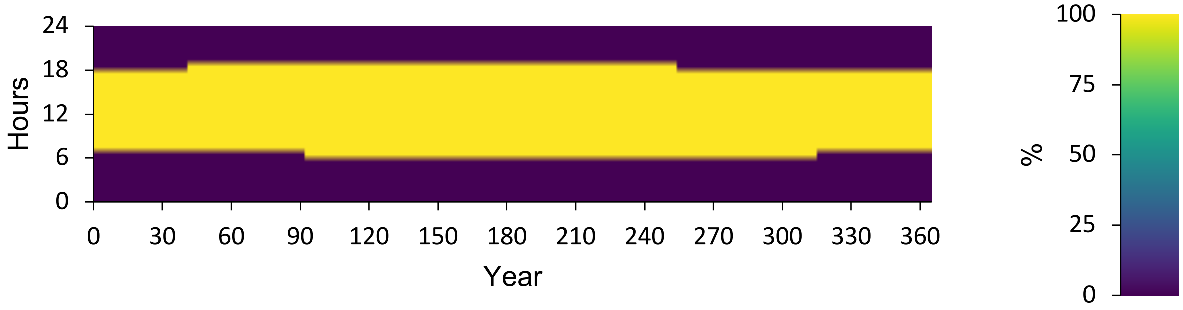
Nominal Capacity	544	kWh
Usable Nominal Capacity	435	kWh
Lifetime Throughput	680,184	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)

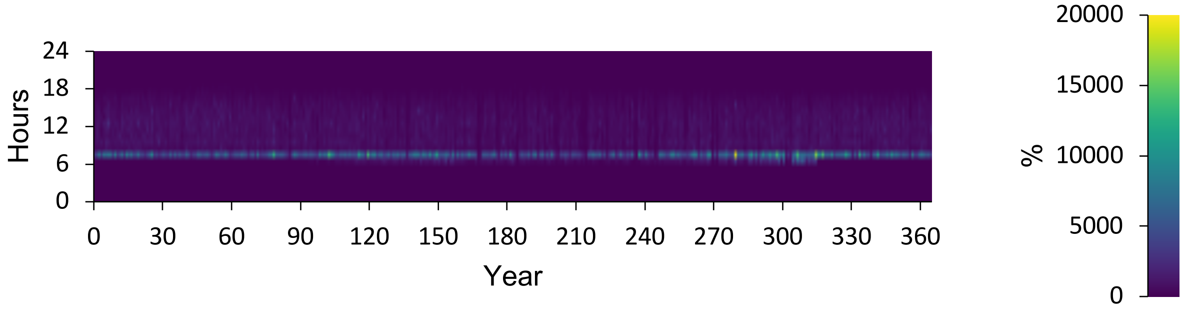


Renewable Summary

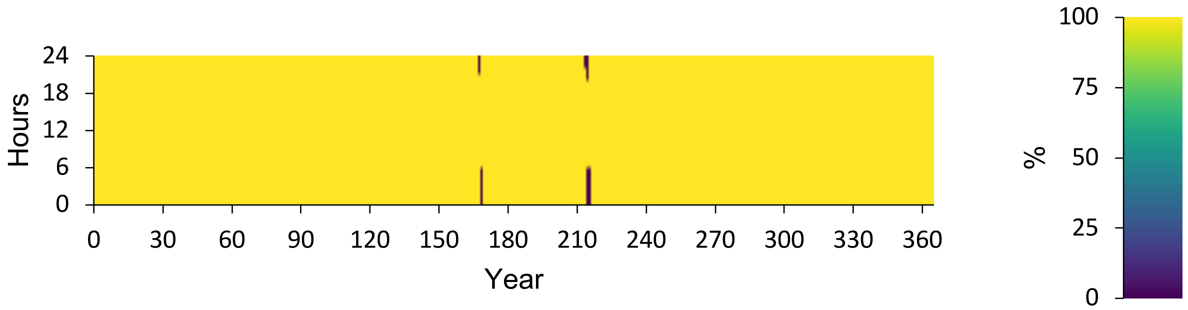
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$2.87M
CAPEX	$2.12M
OPEX	$37,226
LCOE (per kWh)	$0.270
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

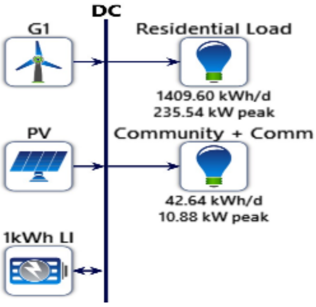
Total Net Present Cost: $2,754,769.00

Levelized Cost of Energy ($/kWh): $0.433

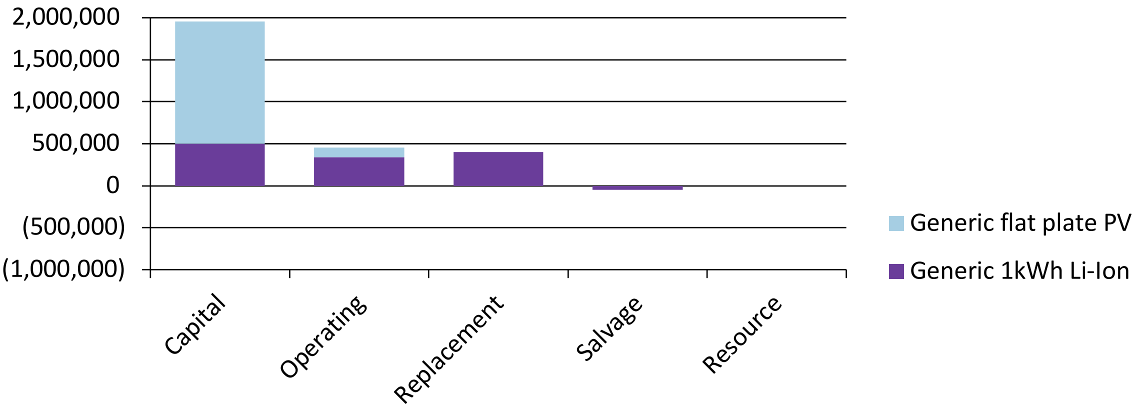
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	908	kW
Storage	Generic 1kWh Li-Ion	714	strings
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



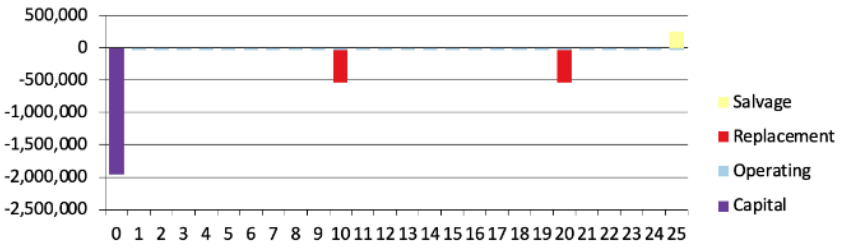
Net Present Costs

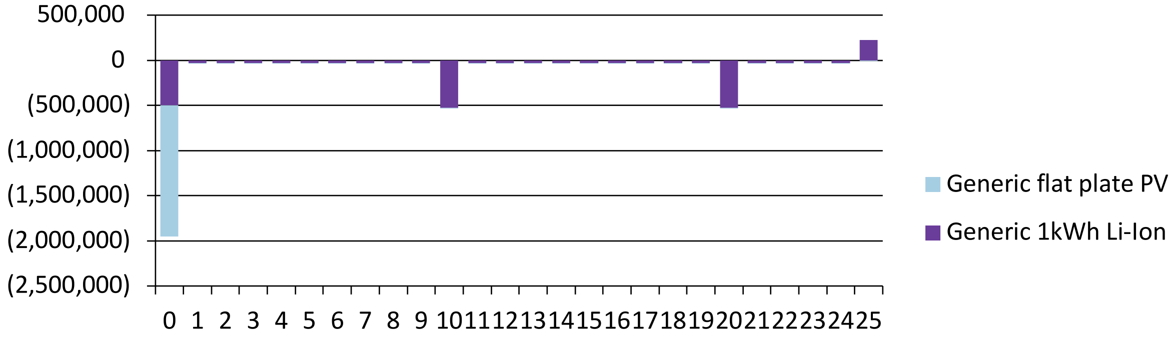
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$499,800	$343,064	$399,600	-$49,779	$0.00	$1.19M
Generic flat plate PV	$1.45M	$109,084	$0.00	$0.00	$0.00	$1.56M
System	$1.95M	$452,149	$399,600	-$49,779	$0.00	$2.75M

Annualized Costs

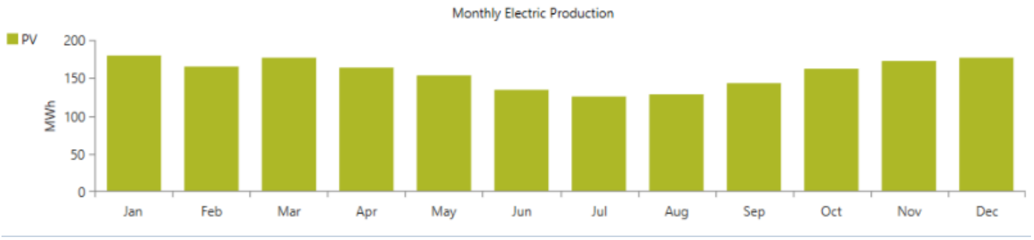
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$41,608	$28,560	$33,267	-$4,144	$0.00	$99,291
Generic flat plate PV	$120,962	$9,081	$0.00	$0.00	$0.00	$130,043
System	$162,570	$37,641	$33,267	-$4,144	$0.00	$229,334

Cash Flow





Electrical Summary



Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,342,569	kWh/yr
Unmet Electric Load	320	kWh/yr
Capacity Shortage	526	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	1,881,732	100
Total	1,881,732	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	0	0
DC Primary Load	529,748	100
Deferrable Load	0	0
Total	529,748	100

PV: Generic flat plate PV

Generic flat plate PV Electrical Summary

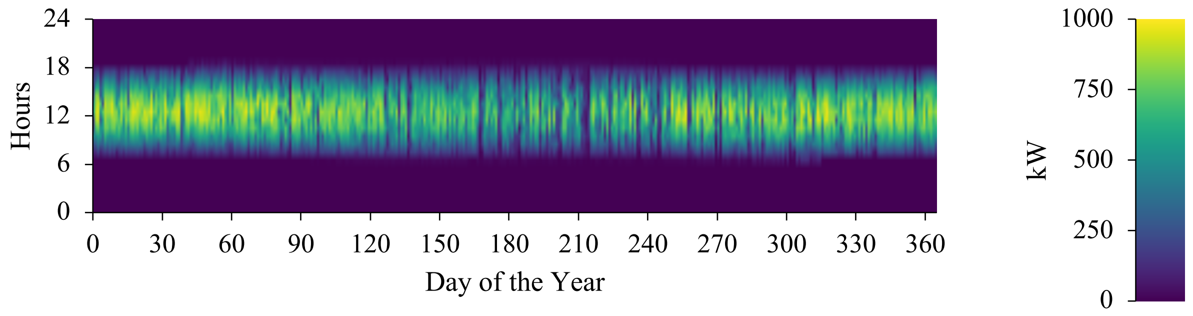
Quantity	Value	Units
Minimum Output	0	kW

Maximum Output	981	kW
PV Penetration	355	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0691	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	908	kW
Mean Output	215	kW
Mean Output	5,155	kWh/d
Capacity Factor	23.7	%
Total Production	1,881,732	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	1,428	qty.
String Size	2.00	batteries
Strings in Parallel	714	strings
Bus Voltage	12.0	V

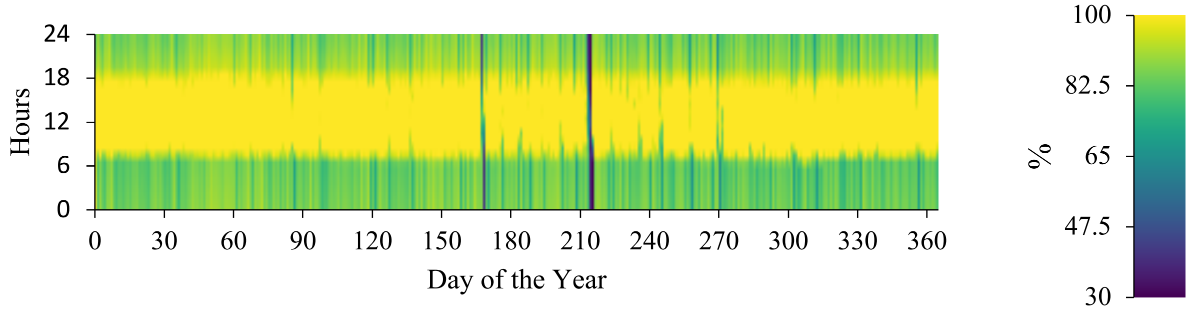
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	96,182	kWh/yr
Energy Out	86,768	kWh/yr
Storage Depletion	215	kWh/yr
Losses	9,629	kWh/yr
Annual Throughput	91,461	kWh/yr

Generic 1kWh Li-Ion Statistics

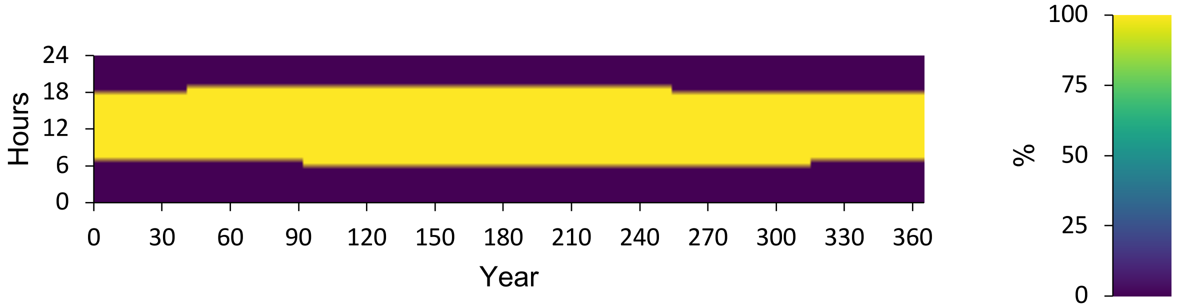
Quantity	Value	Units
Autonomy	16.5	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	1,428	kWh
Usable Nominal Capacity	1,000	kWh
Lifetime Throughput	914,613	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)

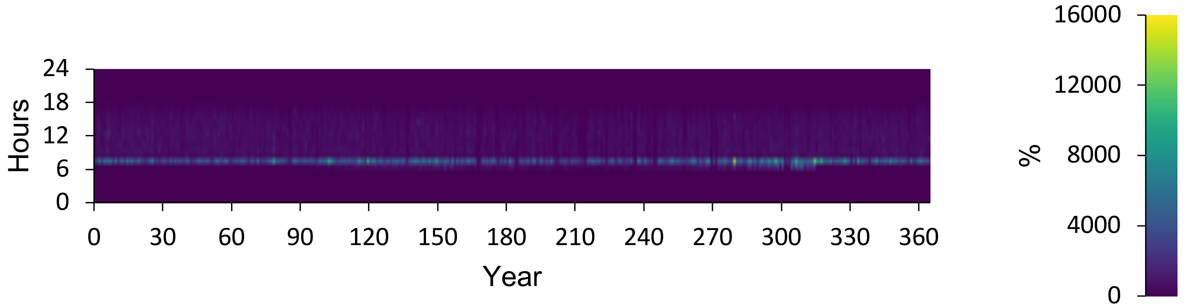


Renewable Summary

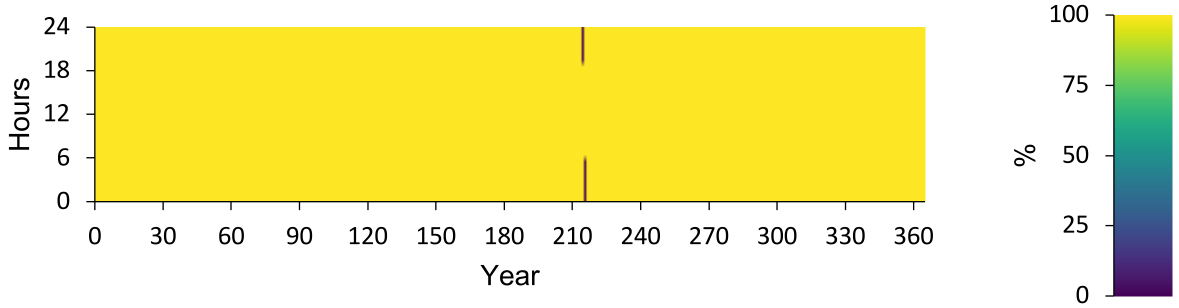
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$2.75M
CAPEX	$1.95M
OPEX	$66,764
LCOE (per kWh)	$0.433
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

HOMER Pro

Appendix D

Techno-economic Analysis of Standalone AC-DC microgrid for Rural Village in Sub-Saharan Africa: A case of Ethiopia

System Simulation Report (Under Scenario 1)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

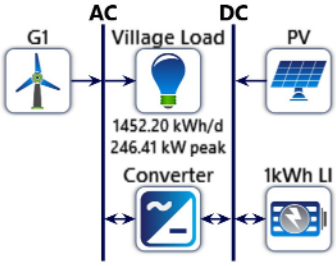
Total Net Present Cost: $3,677,156.00

Levelized Cost of Energy ($/kWh): $0.546

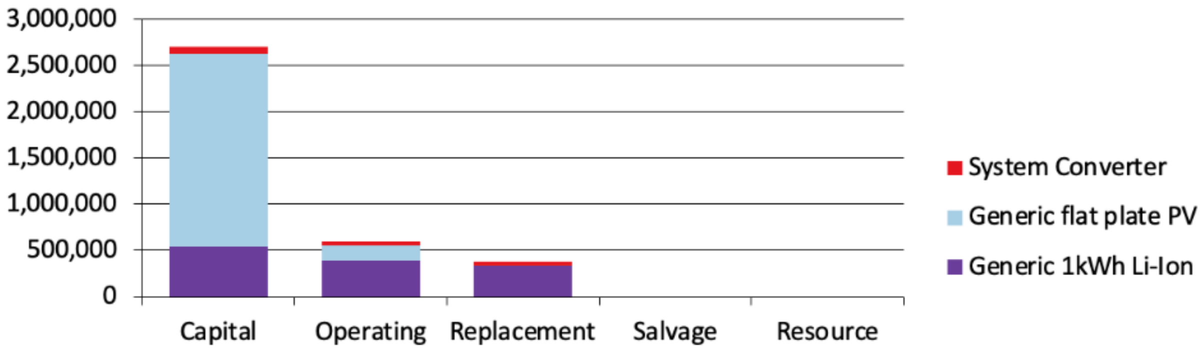
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,303	kW
Storage	Generic 1kWh Li-Ion	771	strings
System converter	System Converter	291	kW
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



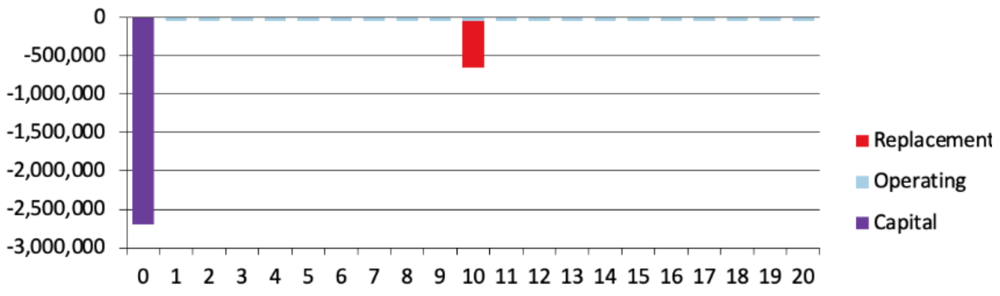
Net Present Costs

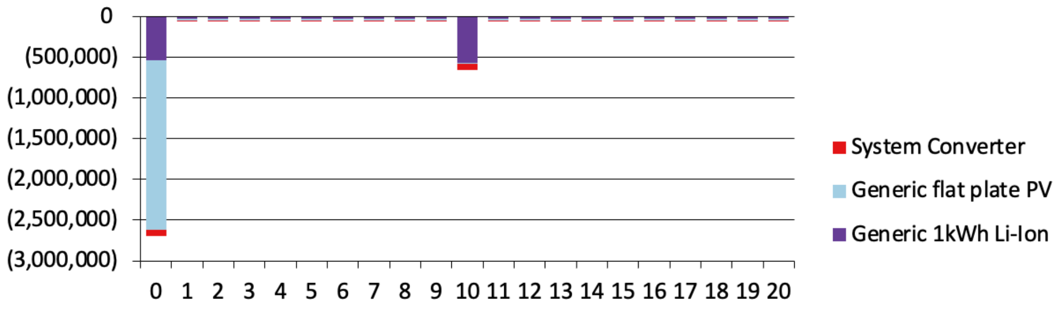
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$539,700	$392,214	$338,937	$0.00	$0.00	$1.27M
Generic flat plate PV	$2.09M	$165,733	$0.00	$0.00	$0.00	$2.25M
System Converter	$72,776	$37,022	$45,704	$0.00	$0.00	$155,502
System	$2.70M	$594,968	$384,641	$0.00	$0.00	$3.68M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$42,437	$30,840	$26,651	$0.00	$0.00	$99,928
Generic flat plate PV	$163,950	$13,032	$0.00	$0.00	$0.00	$176,982
System Converter	$5,722	$2,911	$3,594	$0.00	$0.00	$12,227
System	$212,110	$46,783	$30,245	$0.00	$0.00	$289,137

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,658,235	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	526	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	2,332,297	100
Total	2,332,297	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	529,737	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	529,737	100

PV: Generic flat plate PV

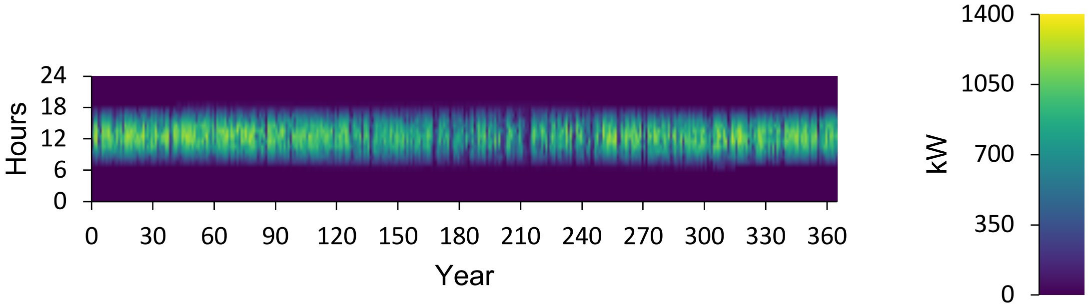
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,260	kW
PV Penetration	440	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0759	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,303	kW
Mean Output	266	kW
Mean Output	6,390	kWh/d
Capacity Factor	20.4	%
Total Production	2,332,297	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	1,542	qty.
String Size	2.00	batteries
Strings in Parallel	771	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

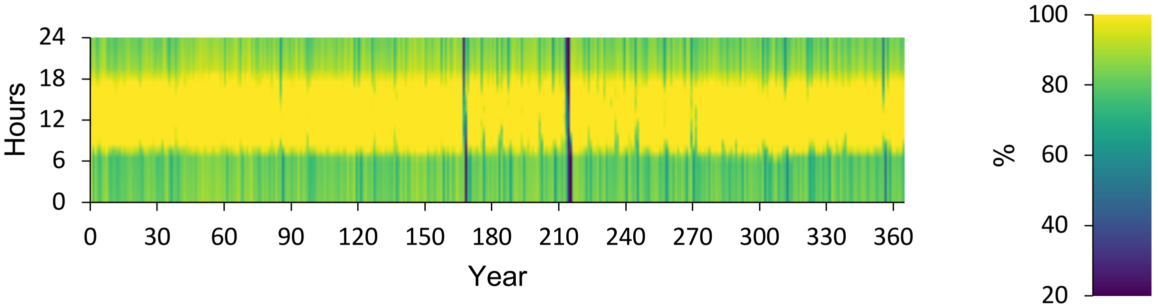
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	121,711	kWh/yr
Energy Out	109,820	kWh/yr

Storage Depletion	295	kWh/yr
Losses	12,186	kWh/yr
Annual Throughput	115,760	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	20.4	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	1,542	kWh
Usable Nominal Capacity	1,234	kWh
Lifetime Throughput	1,157,601	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

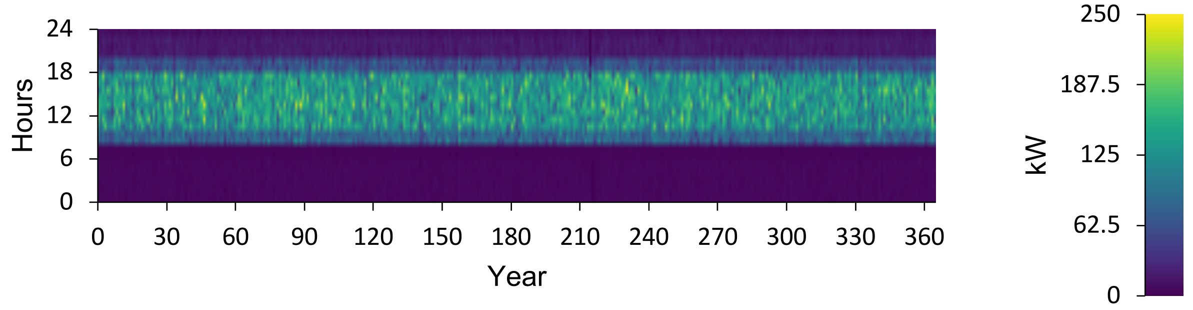
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	8,749	hrs/yr
Energy Out	529,737	kWh/yr
Energy In	662,171	kWh/yr
Losses	132,434	kWh/yr

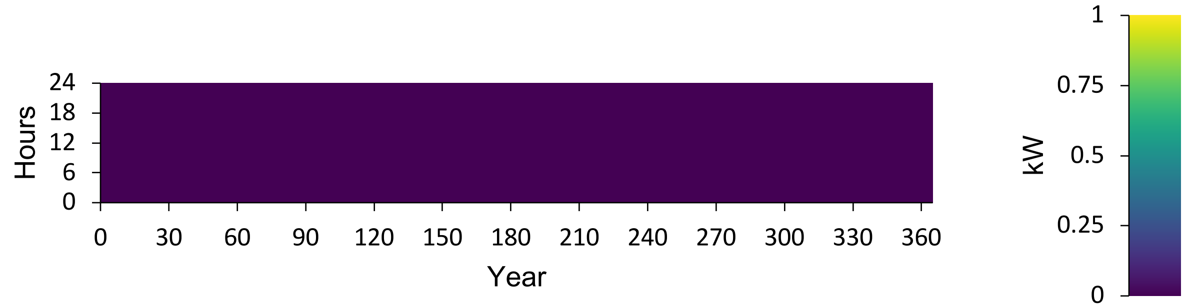
System Converter Statistics

Quantity	Value	Units
Capacity	291	kW
Mean Output	60.5	kW
Minimum Output	0	kW
Maximum Output	246	kW
Capacity Factor	20.8	%

System Converter Inverter Output (kW)

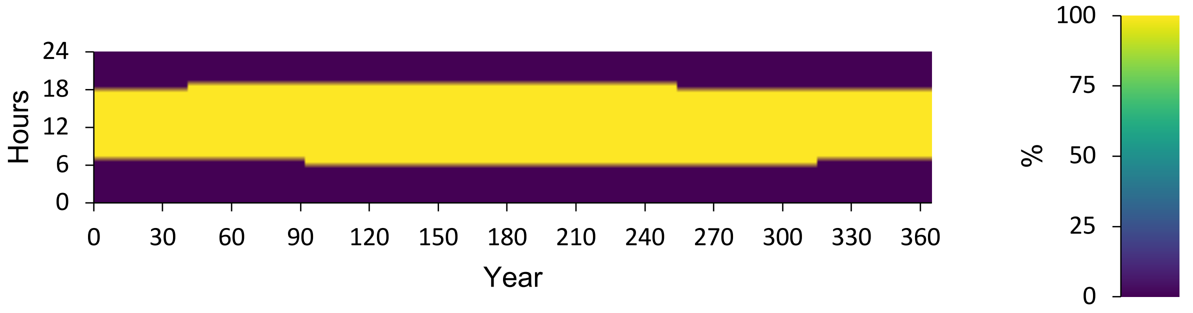


System Converter Rectifier Output (kW)

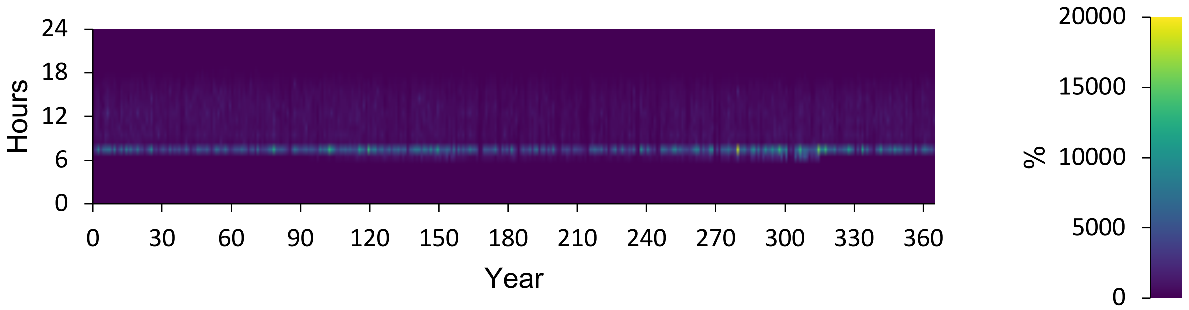


Renewable Summary

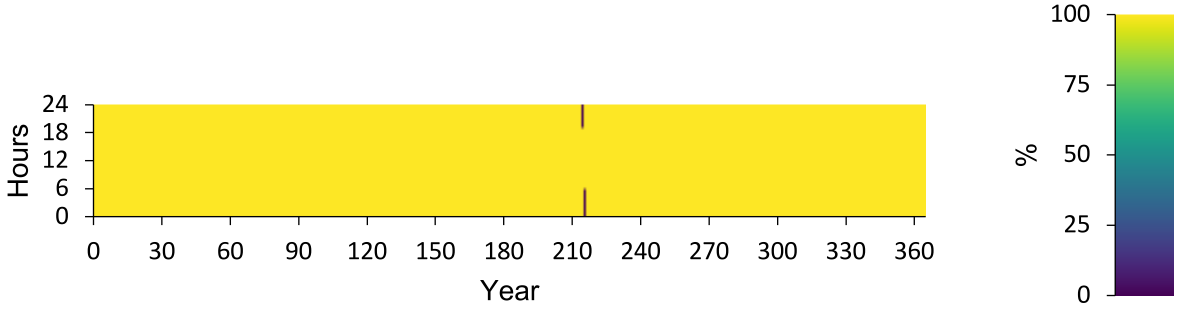
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$3.68M
CAPEX	$2.70M
OPEX	$77,027
LCOE (per kWh)	$0.546
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 2)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

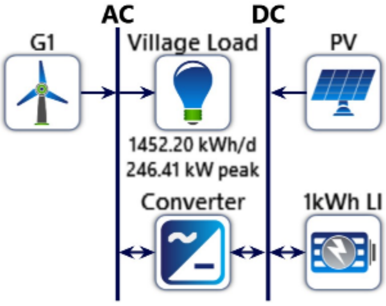
Total Net Present Cost: $4,016,151.00

Levelized Cost of Energy ($/kWh): $0.380

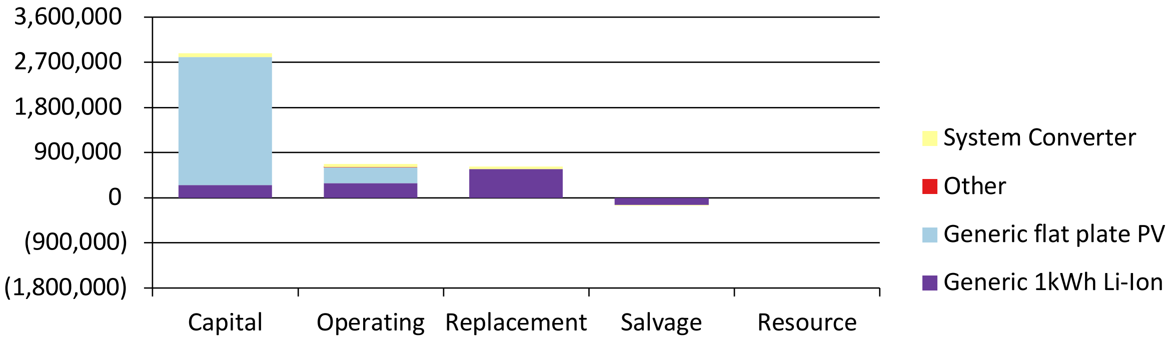
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,593	kW
Storage	Generic 1kWh Li-Ion	359	strings
System converter	System Converter	294	kW
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



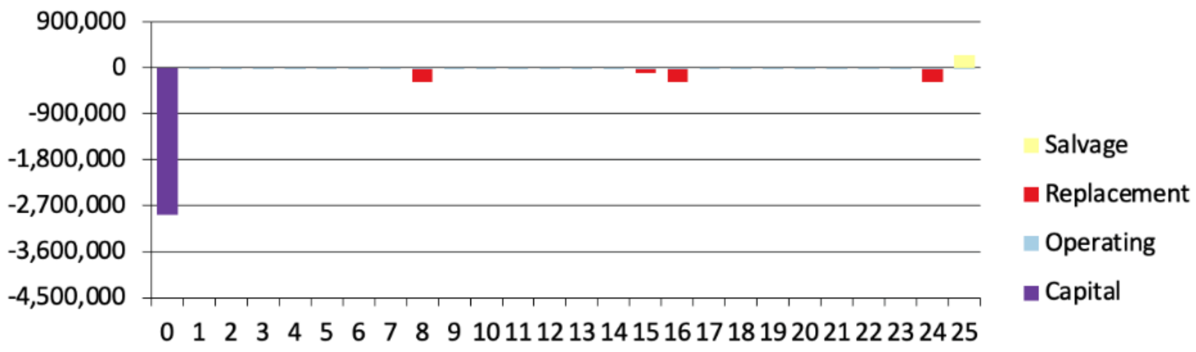
Net Present Costs

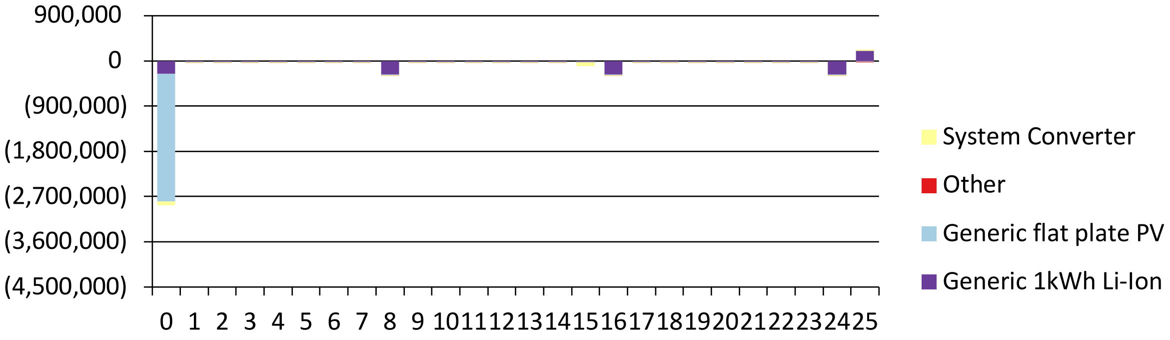
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$251,300	$286,434	$568,999	-$140,142	$0.00	$966,591
Generic flat plate PV	$2.55M	$317,783	$0.00	$0.00	$0.00	$2.87M
Other	$0.00	$9,973	$0.00	$0.00	$0.00	$9,973
System Converter	$73,552	$58,684	$56,132	-$15,626	$0.00	$172,743
System	$2.87M	$672,875	$625,131	-$155,767	$0.00	$4.02M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$12,599	$14,360	$28,526	-$7,026	$0.00	$48,459
Generic flat plate PV	$127,794	$15,932	$0.00	$0.00	$0.00	$143,725
Other	$0.00	$500.00	$0.00	$0.00	$0.00	$500.00
System Converter	$3,687	$2,942	$2,814	-$783.37	$0.00	$8,660
System	$144,080	$33,734	$31,340	-$7,809	$0.00	$201,344

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,252,896	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	529	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	2,851,302	100
Total	2,851,302	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	529,745	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	529,745	100

PV: Generic flat plate PV

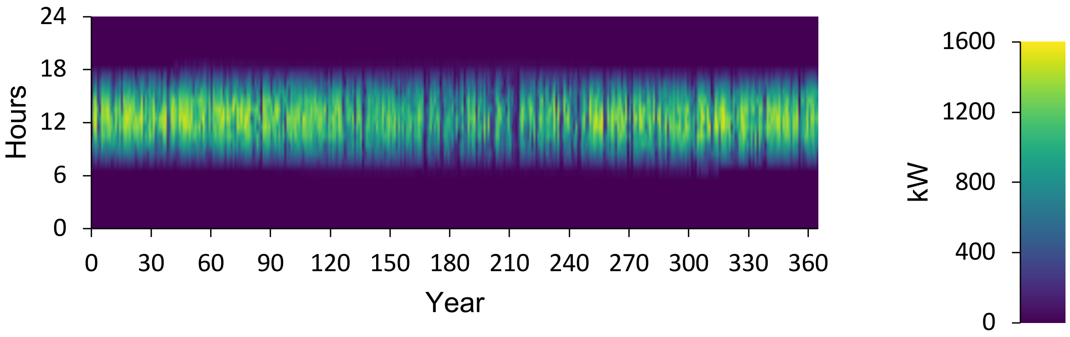
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,540	kW
PV Penetration	538	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0504	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,593	kW
Mean Output	325	kW
Mean Output	7,812	kWh/d
Capacity Factor	20.4	%
Total Production	2,851,302	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	718	qty.
String Size	2.00	batteries
Strings in Parallel	359	strings
Bus Voltage	12.0	V

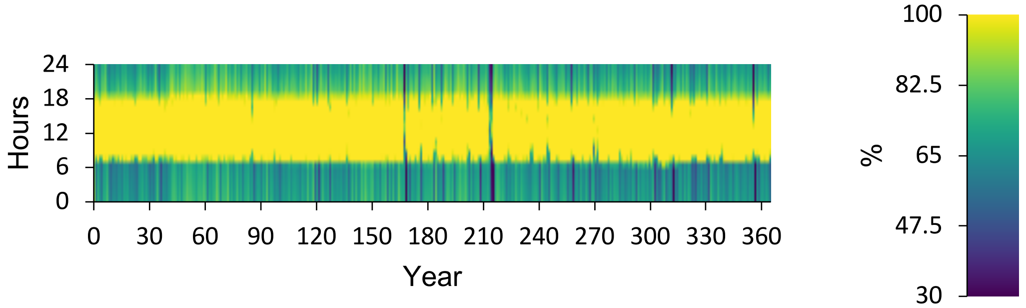
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	99,579	kWh/yr
Energy Out	89,779	kWh/yr
Storage Depletion	167	kWh/yr
Losses	9,966	kWh/yr
Annual Throughput	94,635	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	8.31	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	718	kWh
Usable Nominal Capacity	503	kWh
Lifetime Throughput	757,083	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

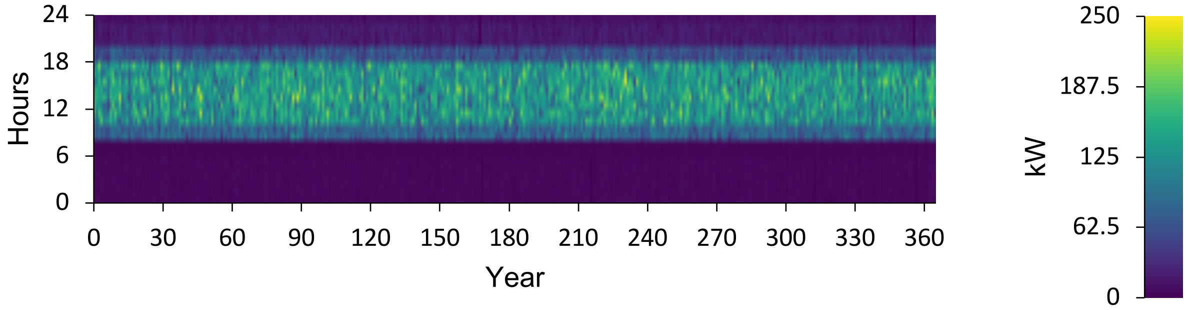
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	8,727	hrs/yr
Energy Out	529,745	kWh/yr
Energy In	588,605	kWh/yr
Losses	58,861	kWh/yr

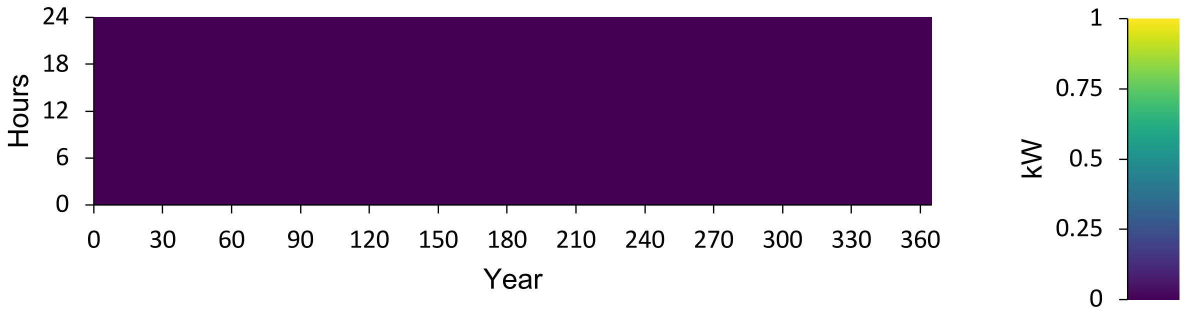
System Converter Statistics

Quantity	Value	Units
Capacity	294	kW
Mean Output	60.5	kW
Minimum Output	0	kW
Maximum Output	246	kW
Capacity Factor	20.6	%

System Converter Inverter Output (kW)

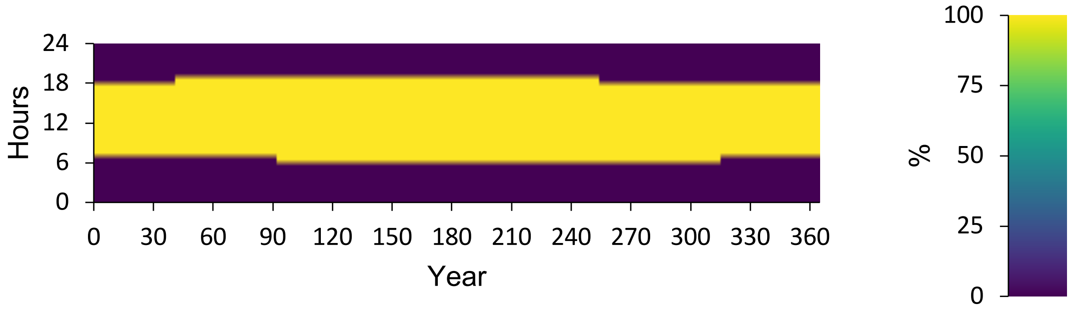


System Converter Rectifier Output (kW)

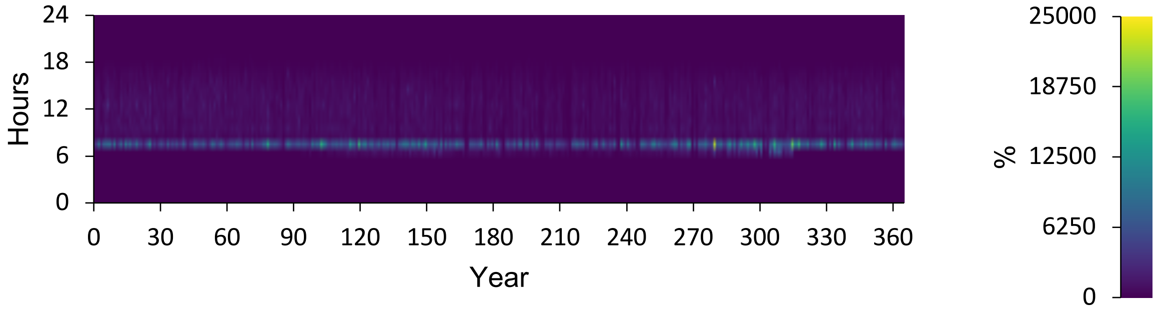


Renewable Summary

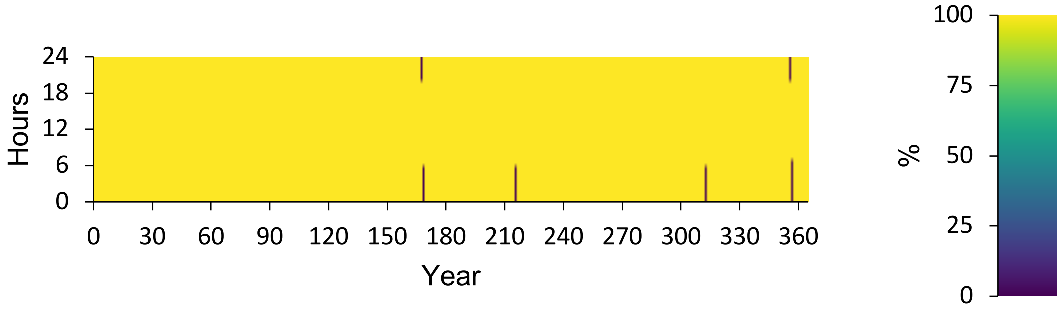
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$4.02M
CAPEX	$2.87M
OPEX	$57,265
LCOE (per kWh)	$0.380
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 3)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

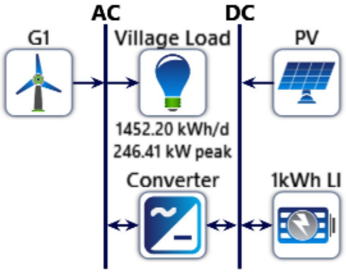
Total Net Present Cost: $3,537,012.00

Levelized Cost of Energy ($/kWh): $0.334

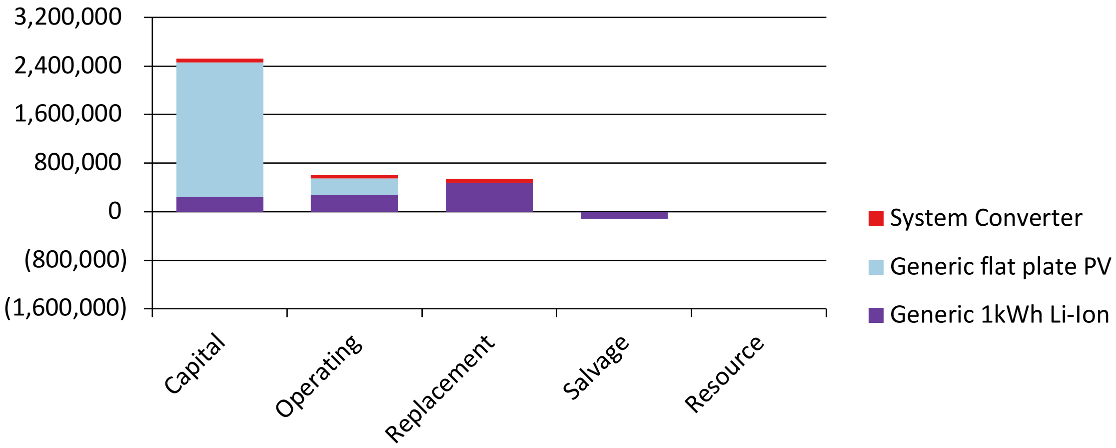
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,391	kW
Storage	Generic 1kWh Li-Ion	337	strings
System converter	System Converter	248	kW
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



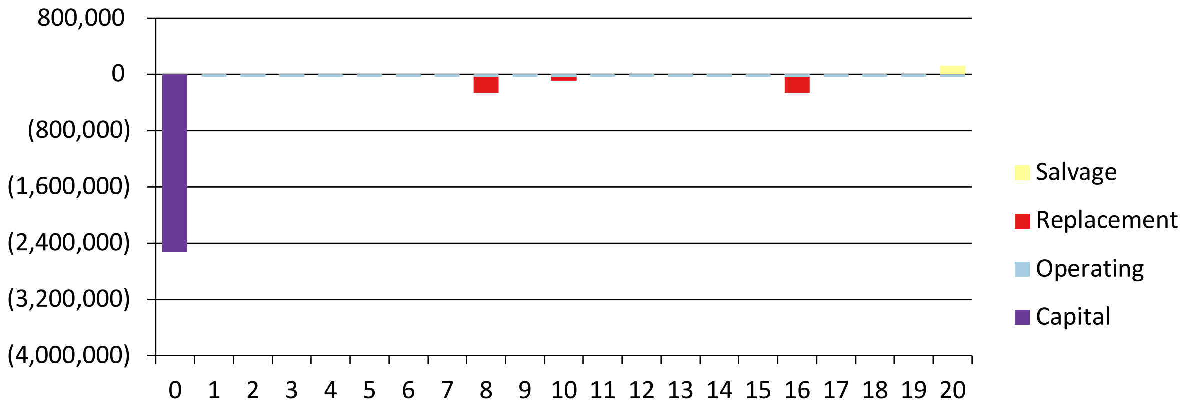
Net Present Costs

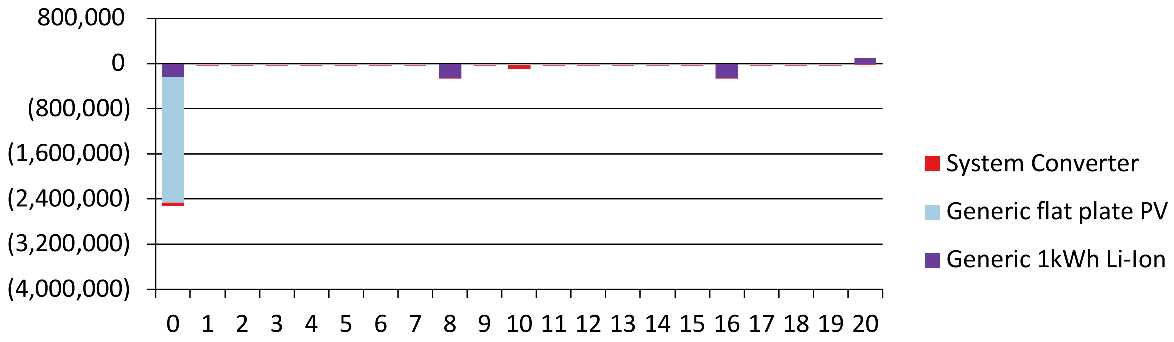
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$235,900	$269,600	$471,800	-$117,950	$0.00	$859,350
Generic flat plate PV	$2.23M	$278,199	$0.00	$0.00	$0.00	$2.50M
System Converter	$62,095	$49,676	$62,095	$0.00	$0.00	$173,867
System	$2.52M	$597,476	$533,895	-$117,950	$0.00	$3.54M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$11,795	$13,480	$23,590	-$5,898	$0.00	$42,968
Generic flat plate PV	$111,280	$13,910	$0.00	$0.00	$0.00	$125,190
System Converter	$3,105	$2,484	$3,105	$0.00	$0.00	$8,693
System	$126,180	$29,874	$26,695	-$5,898	$0.00	$176,851

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	2,202,171	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	525	kWh/yr

Production Summary

Component	**Production (kWh/yr)**	**Percent**
Generic flat plate PV	2,800,669	100
Total	2,800,669	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	529,791	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	529,791	100

PV: Generic flat plate PV

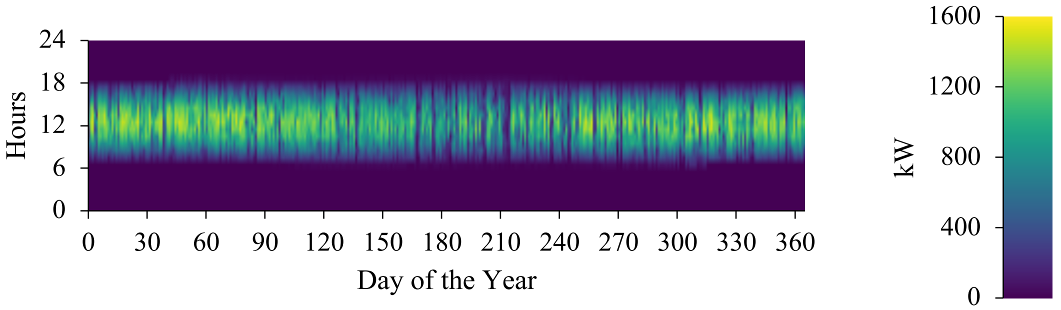
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,513	kW
PV Penetration	528	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0447	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,391	kW
Mean Output	320	kW
Mean Output	7,673	kWh/d
Capacity Factor	23.0	%
Total Production	2,800,669	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	674	qty.

String Size	2.00	batteries
Strings in Parallel	337	strings
Bus Voltage	12.0	V

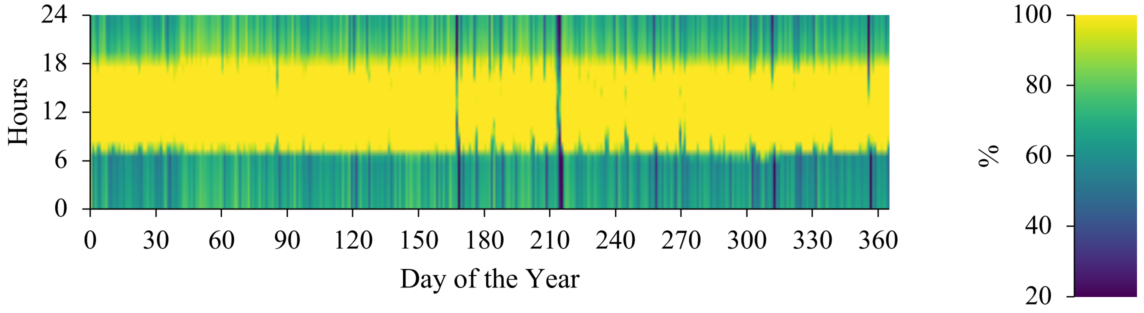
Generic 1kWh Li-Ion Result Data

Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	100,034	kWh/yr
Energy Out	90,193	kWh/yr
Storage Depletion	171	kWh/yr
Losses	10,012	kWh/yr
Annual Throughput	95,071	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	8.91	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	674	kWh
Usable Nominal Capacity	539	kWh
Lifetime Throughput	760,571	kWh
Expected Life	8.00	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

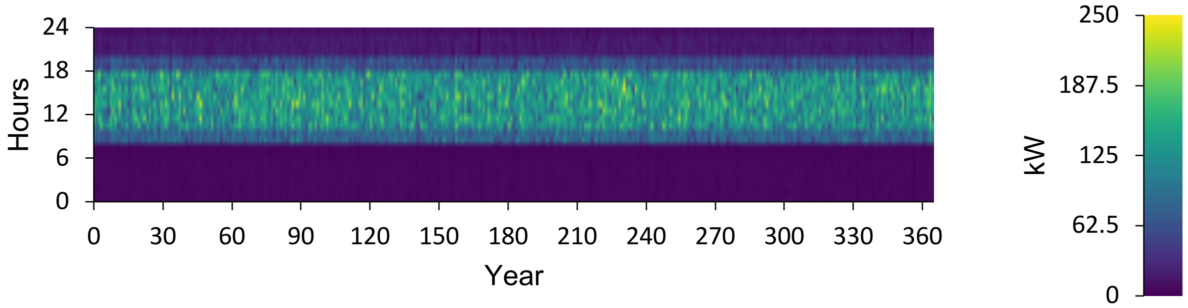
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	8,733	hrs/yr
Energy Out	529,791	kWh/yr
Energy In	588,657	kWh/yr
Losses	58,866	kWh/yr

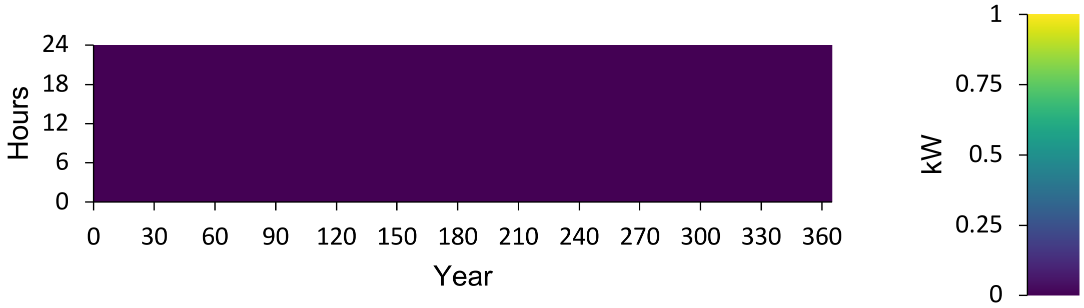
System Converter Statistics

Quantity	Value	Units
Capacity	248	kW
Mean Output	60.5	kW
Minimum Output	0	kW
Maximum Output	246	kW
Capacity Factor	24.3	%

System Converter Inverter Output (kW)

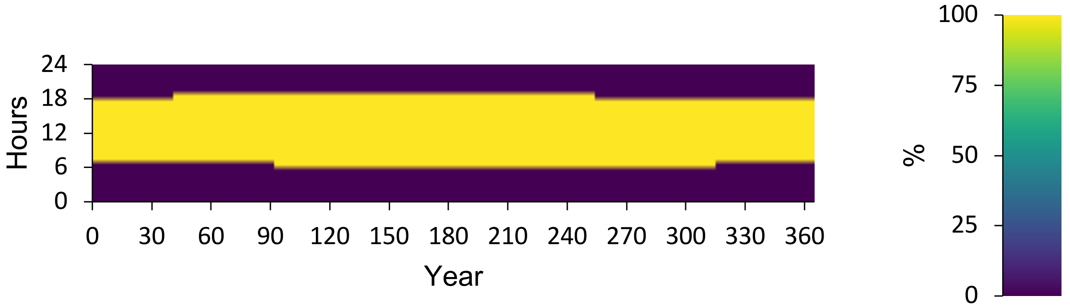


System Converter Rectifier Output (kW)

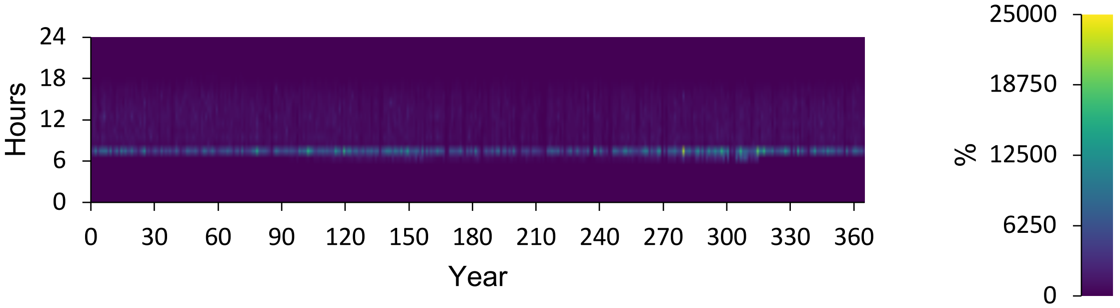


Renewable Summary

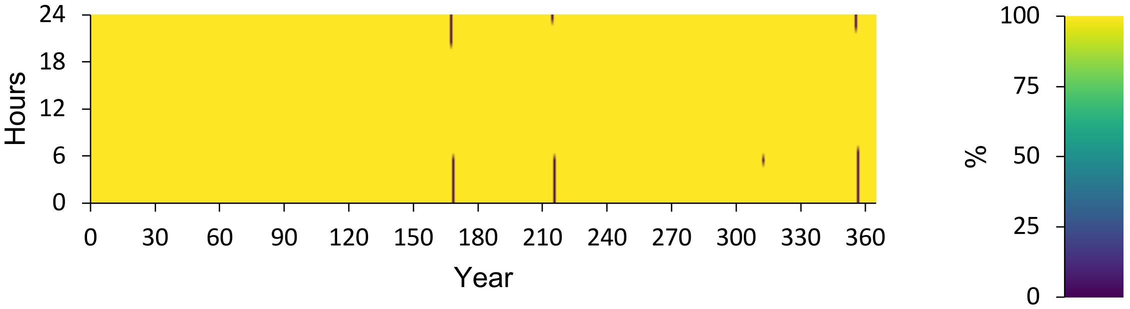
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

	System Cost
Net Present Cost	$3.54M
CAPEX	$2.52M
OPEX	$50,671
LCOE (per kWh)	$0.334
CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0

System Simulation Report (Under Scenario 4)

Location: Cushiranga Village, Ethiopia (12°22.6'N, 37°39.9'E)

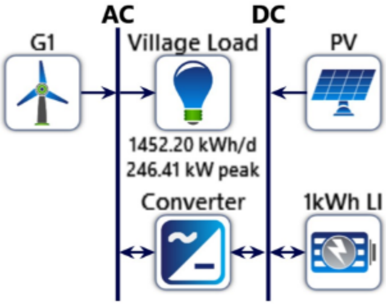
Total Net Present Cost: $3,581,485.00

Levelized Cost of Energy ($/kWh): $0.563

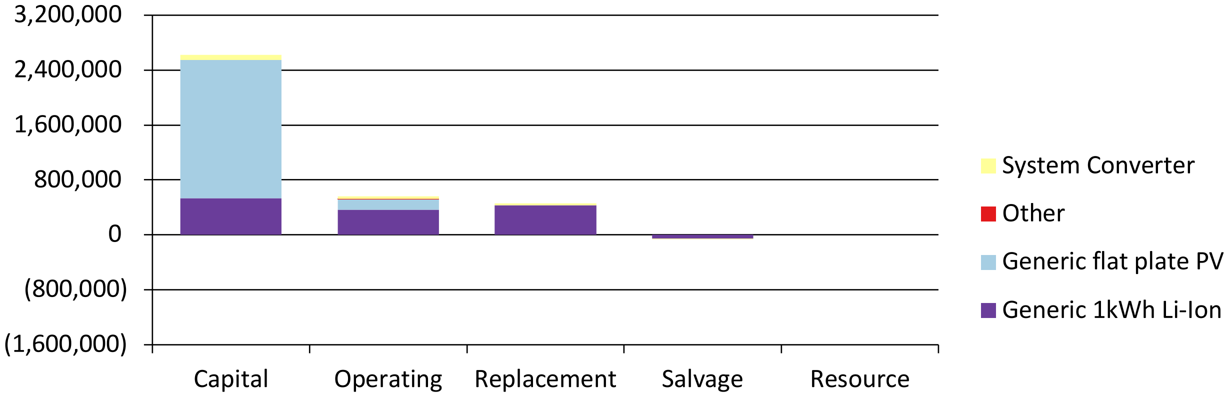
System Architecture

Component	Name	Size	Unit
PV	Generic flat plate PV	1,257	kW
Storage	Generic 1kWh Li-Ion	766	strings
System converter	System Converter	298	kW
Dispatch strategy	HOMER Load Following		

Schematic



Cost Summary



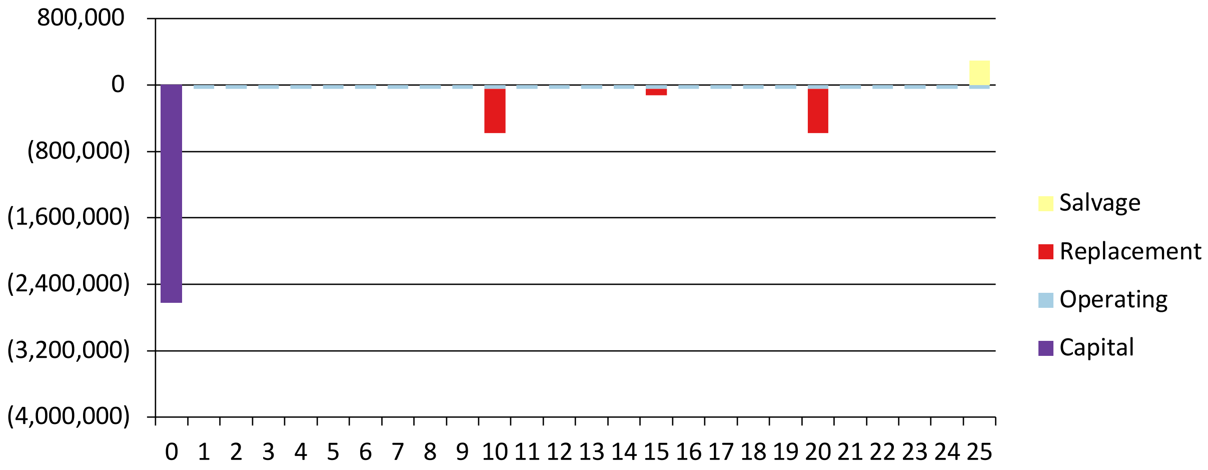
Net Present Costs

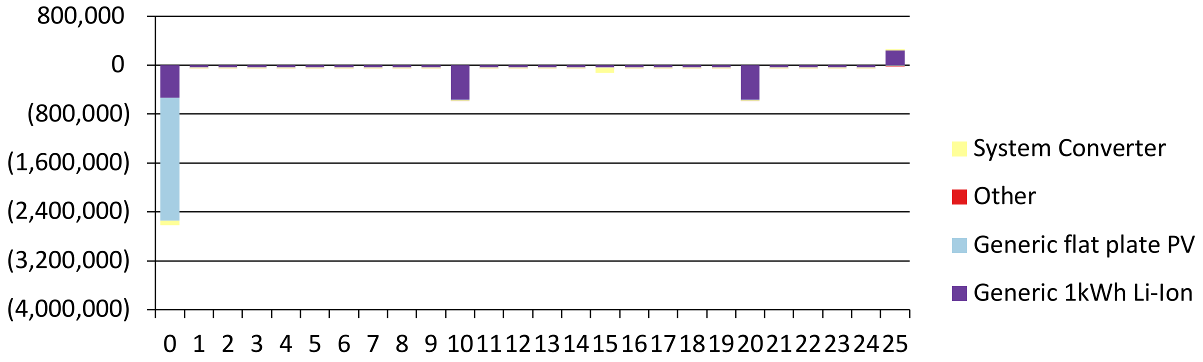
Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$536,200	$368,049	$428,702	-$53,405	$0.00	$1.28M
Generic flat plate PV	$2.01M	$150,989	$0.00	$0.00	$0.00	$2.16M
Other	$0.00	$6,006	$0.00	$0.00	$0.00	$6,006
System Converter	$74,574	$35,831	$28,324	-$4,952	$0.00	$133,777
System	$2.62M	$560,876	$457,026	-$58,356	$0.00	$3.58M

Annualized Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Li-Ion	$44,639	$30,640	$35,689	-$4,446	$0.00	$106,522
Generic flat plate PV	$167,429	$12,570	$0.00	$0.00	$0.00	$179,999
Other	$0.00	$500.00	$0.00	$0.00	$0.00	$500.00
System Converter	$6,208	$2,983	$2,358	-$412.22	$0.00	$11,137
System	$218,276	$46,693	$38,047	-$4,858	$0.00	$298,158

Cash Flow





Electrical Summary

Excess and Unmet

Quantity	Value	Units
Excess Electricity	1,856,994	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	523	kWh/yr

Production Summary

Component	Production (kWh/yr)	Percent
Generic flat plate PV	2,530,833	100
Total	2,530,833	100

Consumption Summary

Component	Consumption (kWh/yr)	Percent
AC Primary Load	529,789	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	529,789	100

PV: Generic flat plate PV

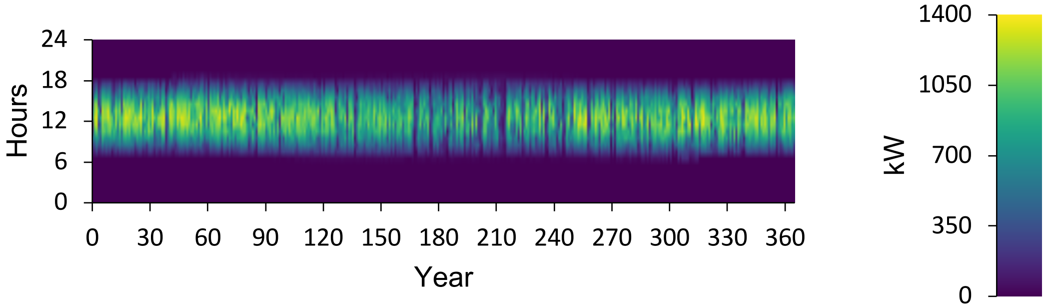
Generic flat plate PV Electrical Summary

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	1,367	kW
PV Penetration	477	%
Hours of Operation	4,451	hrs/yr
Levelized Cost	0.0711	$/kWh

Generic flat plate PV Statistics

Quantity	Value	Units
Rated Capacity	1,257	kW
Mean Output	289	kW
Mean Output	6,934	kWh/d
Capacity Factor	23.0	%
Total Production	2,530,833	kWh/yr

Generic flat plate PV Output (kW)



Storage: Li-Ion

Generic 1kWh Li-Ion Properties

Quantity	Value	Units
Batteries	1,532	qty.
String Size	2.00	batteries
Strings in Parallel	766	strings
Bus Voltage	12.0	V

Generic 1kWh Li-Ion Result Data

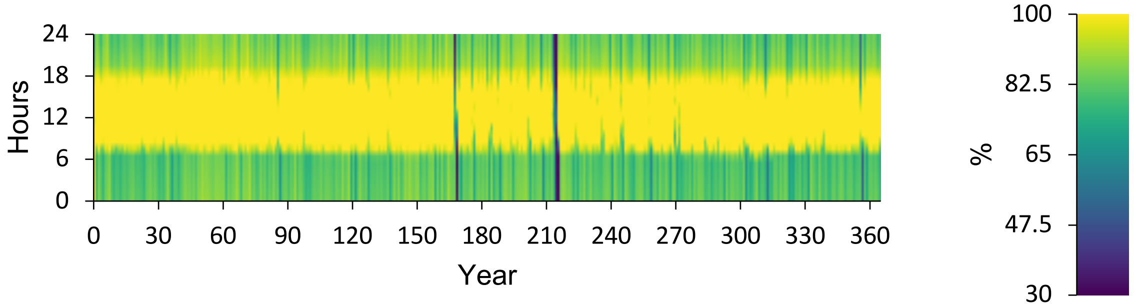
Quantity	Value	Units
Average Energy Cost	0	$/kWh
Energy In	118,736	kWh/yr
Energy Out	107,133	kWh/yr
Storage Depletion	285	kWh/yr
Losses	11,888	kWh/yr
Annual Throughput	112,928	kWh/yr

Generic 1kWh Li-Ion Statistics

Quantity	Value	Units
Autonomy	17.7	hr
Storage Wear Cost	0.184	$/kWh
Nominal Capacity	1,532	kWh

Usable Nominal Capacity	1,072	kWh
Lifetime Throughput	1,129,279	kWh
Expected Life	10.0	yr

Generic 1kWh Li-Ion State of Charge (%)



Converter: System Converter

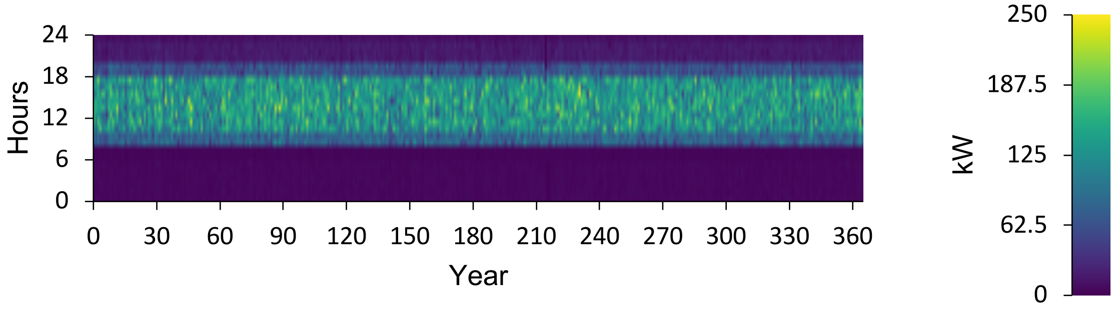
System Converter Electrical Summary

Quantity	Value	Units
Hours of Operation	8,749	hrs/yr
Energy Out	529,789	kWh/yr
Energy In	662,236	kWh/yr
Losses	132,447	kWh/yr

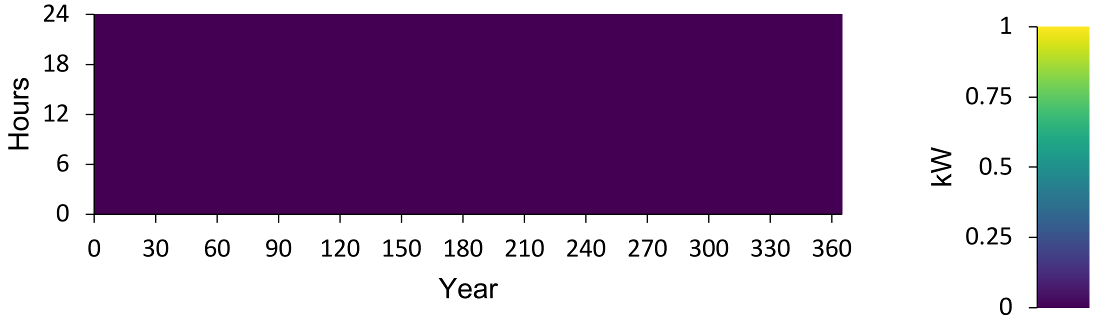
System Converter Statistics

Quantity	Value	Units
Capacity	298	kW
Mean Output	60.5	kW
Minimum Output	0	kW
Maximum Output	246	kW
Capacity Factor	20.3	%

System Converter Inverter Output (kW)

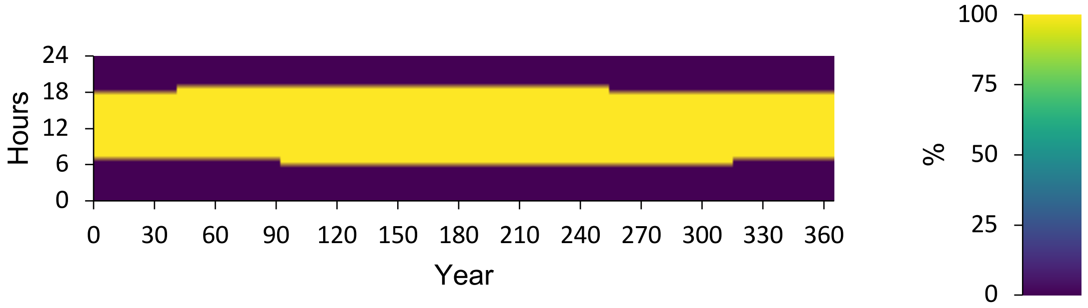


System Converter Rectifier Output (kW)

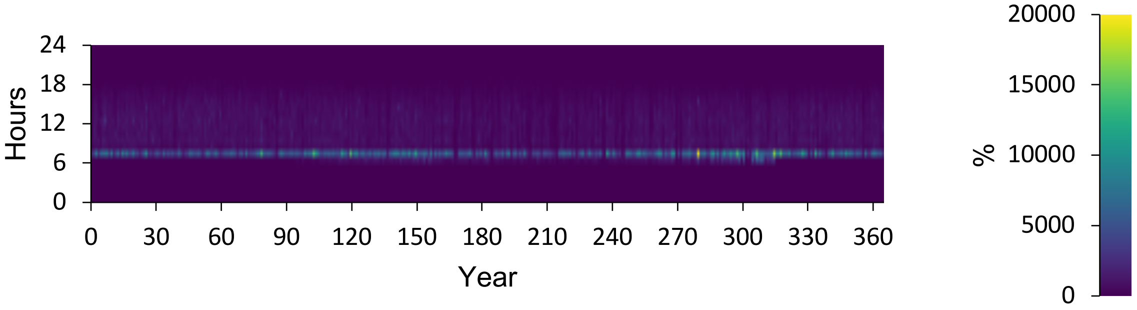


Renewable Summary

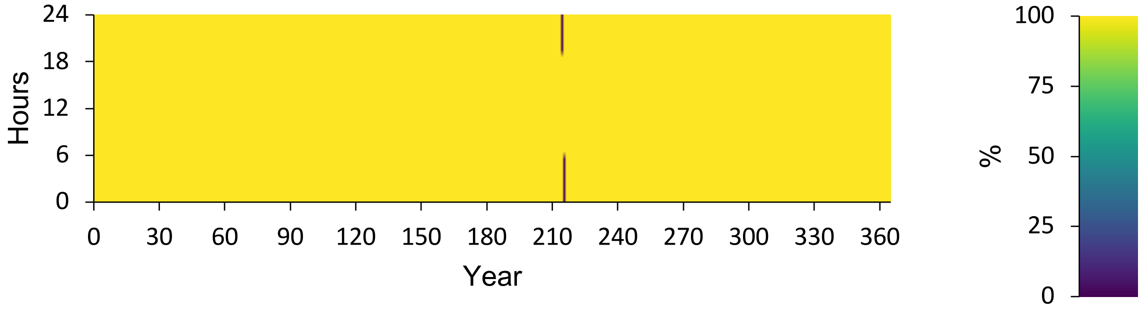
Instantaneous Renewable Output Percentage of Total Generation



Instantaneous Renewable Output Percentage of Total Load



100% Minus Instantaneous Nonrenewable Output as Percentage of Total Load



Compare Economics

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CO2 Emitted (kg/yr)	0
Fuel Consumption (L/yr)	0