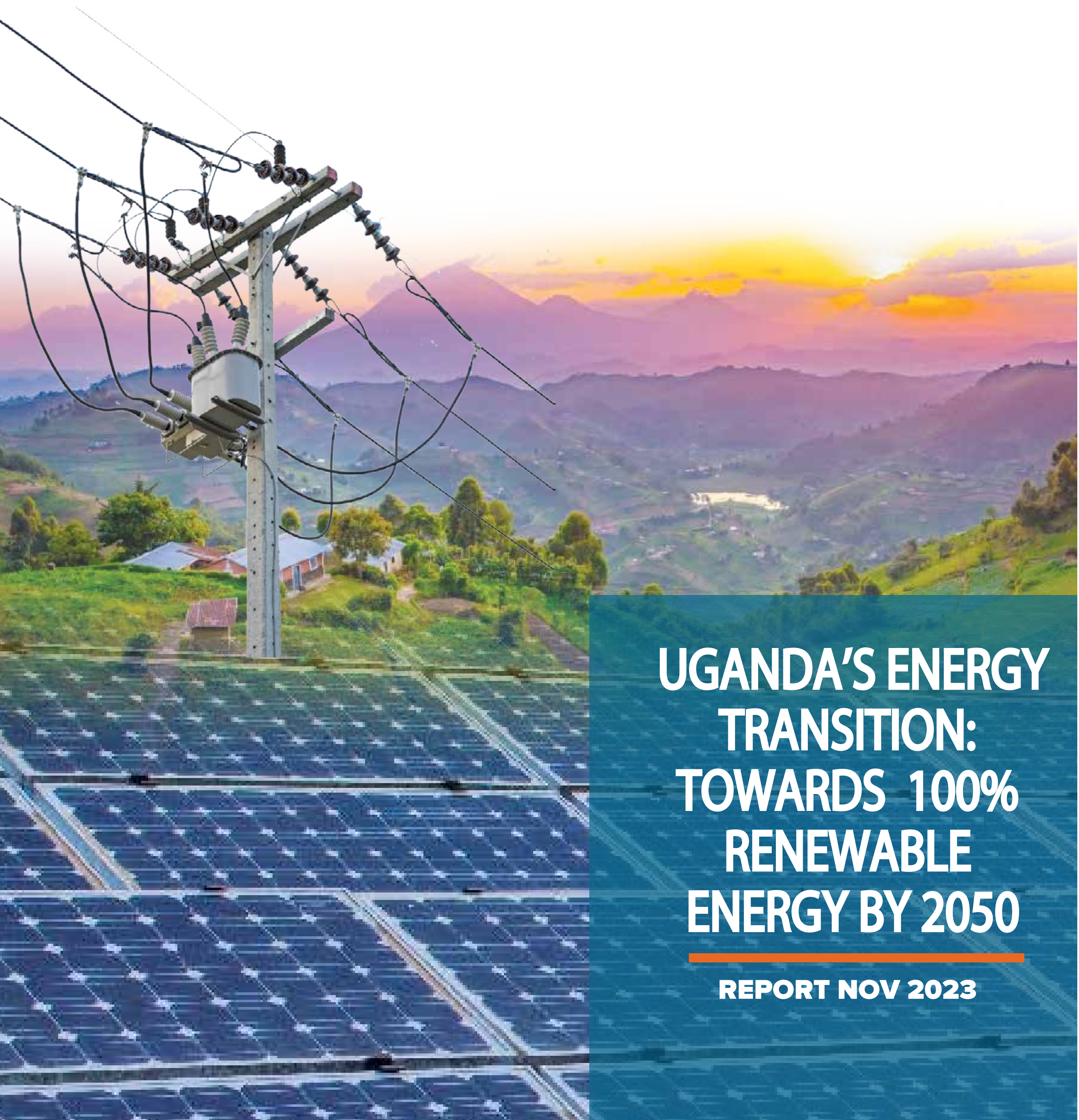
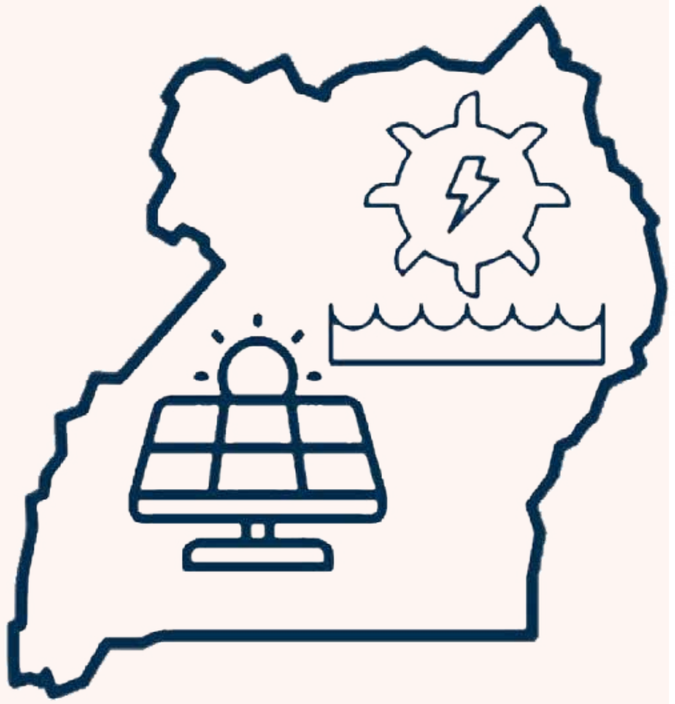
100%RE
multi-actor
partnerships



UGANDA'S ENERGY TRANSITION: TOWARDS 100% RENEWABLE ENERGY BY 2050

REPORT NOV 2023

UGANDA'S ENERGY TRANSITION: TOWARDS 100% RENEWABLE ENERGY BY 2050

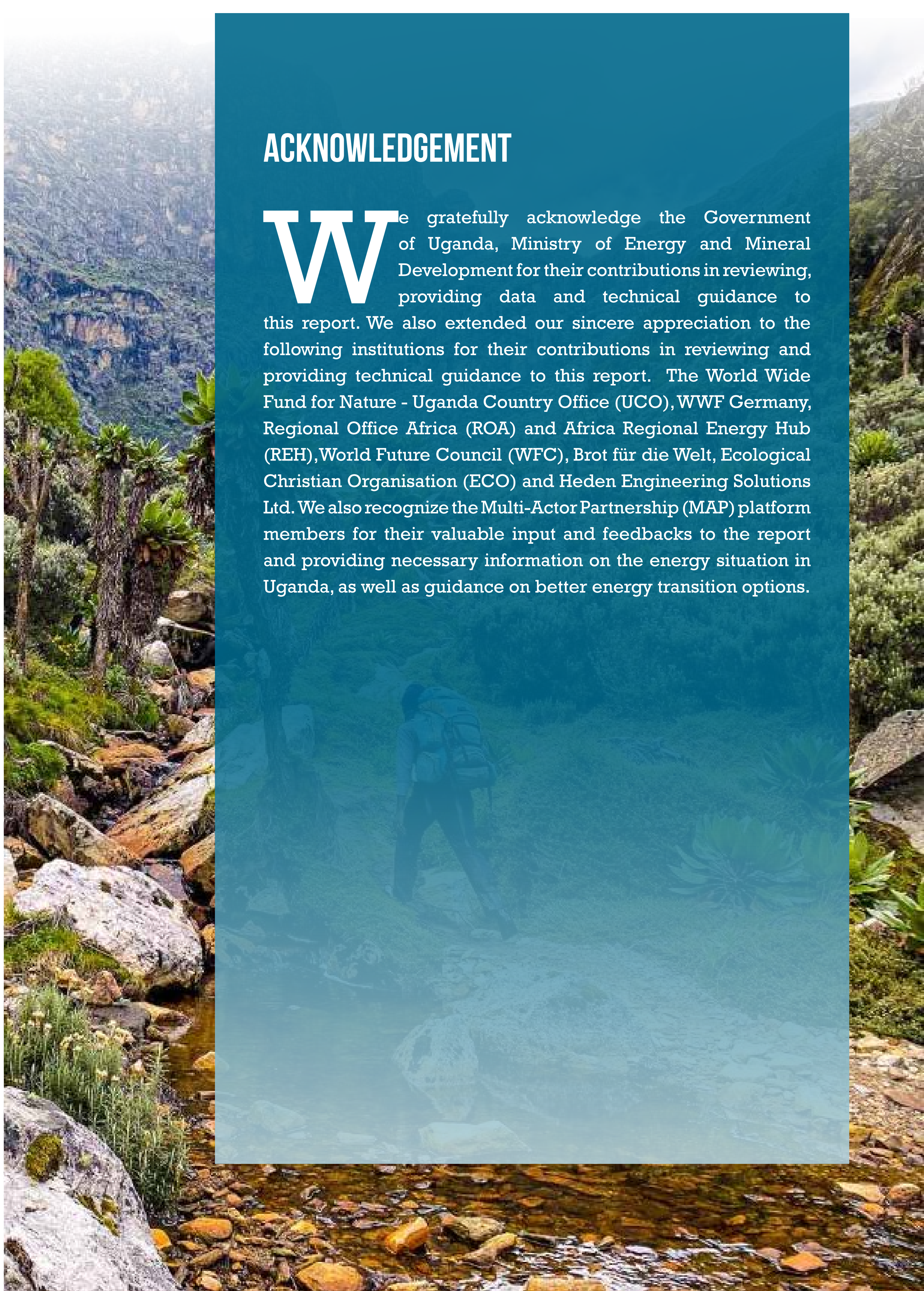


AUTHORS

Dr Caroline Möller
Catalina Peña
Ciara Dunks
Julian Fleischmann
Henry Hecker
Karoline Gerbatsch
Valentina Alvarez Villa
Dr. Paul Bertheau
Dr. Catherina Cader

> "THIS STUDY WAS CARRIED OUT BY A TEAM FROM REINER LEMOINE INSTITUT (RLI)- GERMANY ON BEHALF OF WWF, BROT FÜR DIE WELT AND WORLD FUTURE COUNCIL."

Reiner Lemoine Institut (RLI) is an independent, non-profit research institution whose mission is to find ways to achieve a sustainable energy system based on 100% renewable energy sources. RLI was founded in 2010 and has three research units: Off-Grid Systems, Transformation of Energy Systems and Mobility with Renewable Energy. Since the RLI was founded in 2010, the number of staff has grown steadily. Currently, there are over 50 highly qualified researchers (PhDs and Masters), professionals and administrative staff working in the areas Renewable Energy, Geographic Information Systems (GIS) & Satellite Imagery, Energy Engineering, Energy System Modelling, Energy Economics and Software Development.



ACKNOWLEDGEMENT

We gratefully acknowledge the Government of Uganda, Ministry of Energy and Mineral Development for their contributions in reviewing, providing data and technical guidance to this report. We also extended our sincere appreciation to the following institutions for their contributions in reviewing and providing technical guidance to this report. The World Wide Fund for Nature - Uganda Country Office (UCO), WWF Germany, Regional Office Africa (ROA) and Africa Regional Energy Hub (REH), World Future Council (WFC), Brot für die Welt, Ecological Christian Organisation (ECO) and Heden Engineering Solutions Ltd. We also recognize the Multi-Actor Partnership (MAP) platform members for their valuable input and feedbacks to the report and providing necessary information on the energy situation in Uganda, as well as guidance on better energy transition options.

THE 100% RE MAP PROJECT

The scale of the transformation ahead calls for collaboration and collective action. Inclusive alliances must be built that include people from all sectors, regions, and walks of life. New approaches must be implemented that facilitate innovative ideas to move us forward toward a renewable energy future. New business models must be developed that take the fast moving and shifting business conditions into account. We need a positive vision for our future, one that empowers change-makers and builds capacities across all sectors. By focusing on the opportunities related to 100% RE, rather than focusing on the fear related to the looming climate crisis, we can unlock the transformative power of renewables.

This work is part of the "Multi-Actor Partnership (MAP) for Implementing Nationally Determined Contributions (NDCs) with 100% Renewable Energy for All in the Global South (100% RE MAP)" project being implemented by WWF-UCO, Ecological Christian Organisation (ECO), the World Future Council, the World Wide Fund for Nature Germany (WWF Germany), and Brot für die Welt. The 100% RE MAP project aims to facilitate positive changes and advance the transformation necessary to ensure economic and social development in line with the Paris Agreement's climate target of 1.5 °C. By strengthening MAPs, we enable inclusive decision-making and unlock disruptive innovations for scalability. It is through partnerships that we can overcome short-term political interests, which can upend years of work when political power transfers take place. The project ensures strategic buy-in from opinion leaders, academia, civil society, government and think tanks, and is being implemented simultaneously in Nepal, Uganda and Vietnam. The 100% RE scenario covers state-of-the-art modelling technologies that highlight possible transition pathways towards 100% RE and enable comparisons to business-as-usual pathways.

PROJECT'S CONSORTIUM

The WWF Uganda Country Office main objective is to implement low carbon development pathways and increase resilience of the country's forest landscapes, wildlife populations and freshwater ecosystems to support biodiversity protection and socioeconomic, sustainable development.

WWF Germany is an independent, non-profit, non-artisan foundation, and part of the WWF network, which operates in over 100 countries and consists of national organizations and program offices.

Brot für die Welt is the globally active development and relief agency of the Protestant Churches in Germany. In more than 90 countries all across the globe, we empower the poor and marginalized and closely and continuously cooperate with local, often church-related partner organizations. Through lobbying, public relations and education we seek to influence political decisions in favour of the poor and to raise awareness for the necessity of a sustainable way of life

The World Future Council is a foundation based in Hamburg, Germany. Against the background of ever-increasing global problems that affect all areas of human life, a global group of experts have set up the World Future Council as a politically neutral and independent body. It brings the interests of future generations to the centre of policy making and addresses challenges to our common future and provides decision makers with effective policy solutions.

Federal Ministry
for Economic Cooperation
and Development

The project was supported by the German Federal Ministry for Economic Cooperation and Development (BMZ)

TABLE OF CONTENTS

FOREWORD

An energy transition based on renewables is urgently needed not just to accelerate economic progress and development, but also to cut emissions that are rapidly warming our planet and high deforestation rates which is a major threat to our biodiversity. Even though Uganda contributes less than 0.1% to global GHG emissions, the country is incommensurately affected by the impact of climate change on biodiversity, water supplies, food security and climate-related diseases, among others. As a party to the United Nations Conference on Climate Change (UNFCCC) and having ratified the Paris Agreement, Uganda was one of the first African countries to submit its Nationally Determined Contribution (NDC) with a commitment to mitigate climate change by limiting global warming to 1.5 °C. To achieve this, a complete decarbonization and shift to 100% Renewable energy (RE) in all emission sectors is necessary. In her NDC, Uganda has set a target to reduce GHG emissions by 24.7% by 2030, where one of the measures is to increase access to RE – targeting 3,200MW electricity generation capacity. This energy – climate nexus therefore provides an opportunity to implement policies and measures which may lead to increased energy security in a sustainable and less carbon-intensive way. I am therefore pleased to contribute the foreword for the report on Uganda's Energy Transition: Towards 100% Renewable Energy by 2050, a study that was commissioned by WWF Uganda Country Office (WWF UCO).

This report provides the possible transition pathways based on the current energy mix, energy plans and programs of the government of Uganda. These include: the business-as-usual (BAU) which considers national plans such as the Uganda vision 2040 with future developments of nuclear and peat energy; a high RE pathway (RE share of 80% with sustainable biomass limits), and a full RE pathway (100% RE with sustainable biomass limits), highlighting potential energy transitions by 2030, 2040, and 2050. These scenarios were developed considering the need for all Ugandans to access modern energy services, but also the need to ensure that energy demand is met by sustainable and renewable resources as opposed to non-renewable energy sources.

This report has been developed with consultations and engagement with members of Multi-Actor Partnership (MAP) platform formed under the project "Multi-Actor Partnerships (MAPs) for Implementing Nationally Determined Contributions with 100% Renewable Energy (RE) for All in the Global South". Special thanks to all those who contributed to preparing this report, especially, WWF Germany, World Future Council, Brot für die Welt, Reiner Lemoine Institute (RLI), Heden Engineering Solution Ltd and the German Federal Ministry for Economic Cooperation and Development (BMZ) who funded the entire project. It is my hope that the report offers inspiration to the Government, businesses, research institutions and other stakeholders in relevant sectors to look towards solving these energy related challenges and move boldly towards a future that entirely depends on Renewable Energy.

Ivan Tumuhimbise
Country Director, WWF Uganda

EXECUTIVE SUMMARY

Introduction

Uganda is at a turning point in its development: while it has a wide variety of natural resources, both renewable and non-renewable, it must make decisions about its energy future. Energy is a fundamental driver in the promotion of the country's development, having a direct impact on other sectors of the economy. Thus, it is essential that sustainability becomes an intrinsic element in the whole process, which will also support the country's actions regarding climate change.

Elaborating scenarios that help to envision energy alternatives and their effects in the coming years is useful to identify how the existing energy policy can be complemented and how a roadmap for an energy transition to the use of renewable energy (RE) in different sectors can be defined. For this reason, pathways and scenarios have been evaluated in this study to assess the potential of the available resources to set up an energy system based on 100% renewable energies. The aim of this research was to investigate the potential for a fully renewable energy system in Uganda, considering the rising energy demand and the availability of renewable resources in the country.

Energy supply and demand in Uganda

With a total population of around 45 million inhabitants, Uganda reported an energy consumption of 215 TWh in 2020. The primary energy source is biomass in the form of firewood for cooking. There is also a low share of oil products that are entirely imported. Moreover, Uganda's installed power capacity is primarily composed of hydropower plants, which constitute about 80% of the total capacity and produce about 90% of the electricity generated in the country (Electricity Regulatory Authority - ERA, 2022). However, according to the Uganda Energy Policy 2023, access to electricity is estimated at 57% of the country's population, where on-grid and off-grid contribute 19% and 38%, respectively. This highlights the need for sustainable energy technologies and mini grids to reach communities. The country's population density and projected economic development are expected to have an impact on energy supply and demand as the population continues to grow.

Challenges of Uganda's energy supply and demand

Just as the Ugandan energy sector is full of opportunities, there are barriers and challenges to overcome. Among the multiple challenges are the limited power supply, increasing demand due to economic and demographic growth, and the continued reliance on biomass, all of which face challenges in terms of resource scarcity and environmental sustainability.

Besides, the heavy reliance on biomass combined with limited access to clean cooking technologies not only affects the environment but also people's health. In addition, maintaining a reliable energy supply can be technically and economically demanding, and at the institutional level, promoting and achieving effective implementation of plans and policies is a critical challenge.

Pathways and Scenarios

Three pathways were developed to represent possibilities for Uganda's energy transition: the business-as-usual (BAU) pathway including national plans of developing nuclear and peat energy in the country; a high RE pathway (RE share of 80%, HighRE80 with sustainable biomass limits), and a full RE pathway (100%, FullRE100 with sustainable biomass limits). For each pathway, scenarios for the target years 2030, 2040, and 2050 regarding Uganda's current and future energy supply were evaluated using the energy system model. Each pathway starts with a representation of the status quo of 2021 (with the demand of 2019 to exclude the pandemic's impact on demand) as the baseline and then develops according to the pathway specific assumptions.

Methodology and key assumptions

The analysis of Uganda's energy supply pathways is conducted using the energy supply model, which is composed of two integral components: the energy demand model and the energy supply model. Initially, the energy demand model is employed to project sector-specific demand growth for the target years, and it subsequently calculates the effective end-use energy demand for each scenario. Assumptions for the demand model are informed by findings from a comprehensive literature review. The supply model is then used to simulate and optimize the allocation of energy resources, conversion technologies, and storage options, all aimed at efficiently fulfilling Uganda's demand, taking any limitations into consideration. The scenario inputs for the supply model are formulated from a literature review and the results from the energy demand model.

The model was established with a variety of energy supply and storage technologies, cooking technologies, and transport technologies and utilized to examine scenarios featuring increasing levels of RE utilization, up to and including full reliance on renewables. Figure 0-1 shows the superstructure of all components made available for modeling different pathways and scenarios for the energy systems of Uganda. Each technology was characterized with technical, economic and environmental parameters. The components were designed to describe the operational conditions of technologies, taking into account the specific characteristics of each resource, e.g., those with volatile sources include the variability in the form of a data series.

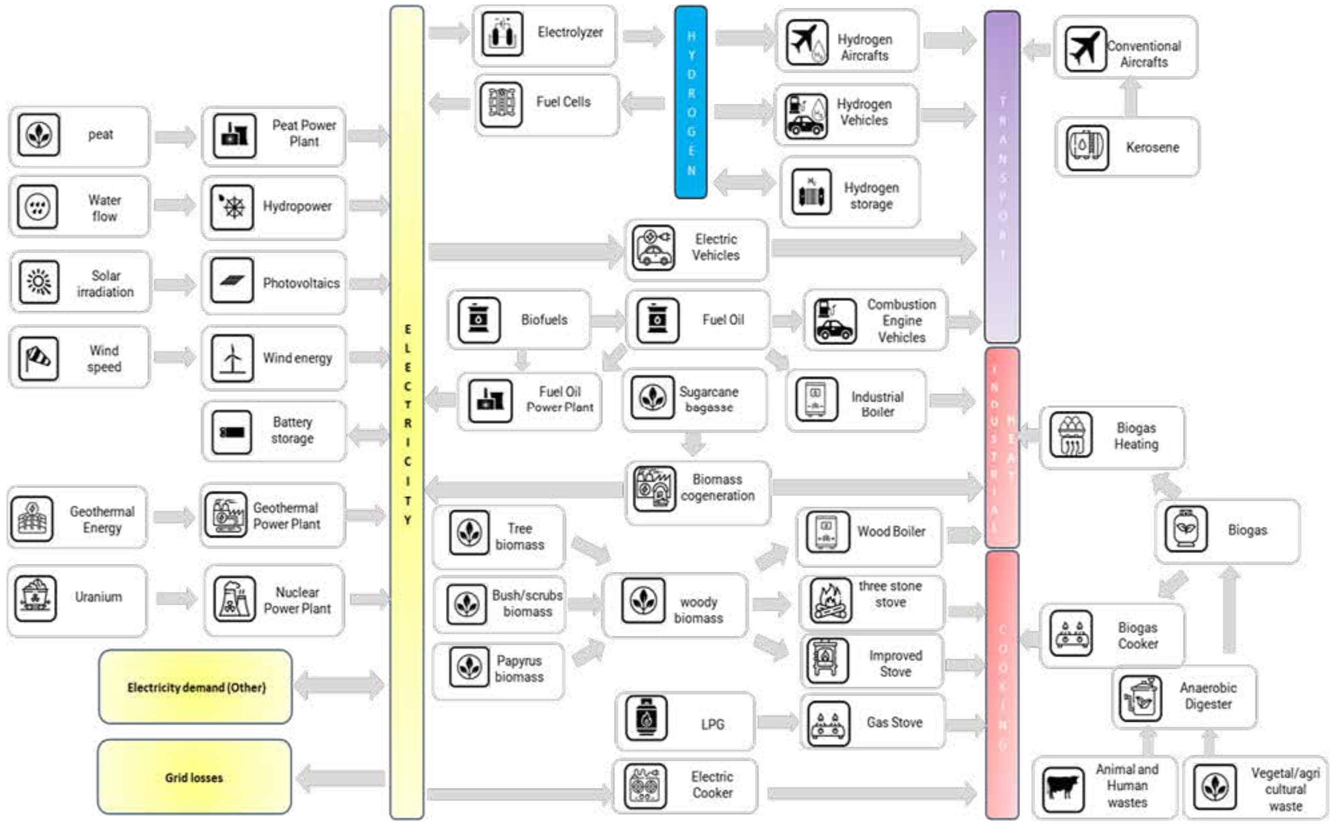


Figure 0-1: Superstructure of energy system models including electricity, H_2, heat, and cooking components

Results

The investments and capacities required to fulfil the energy demands for each pathway were investigated for 2030, 2040 and 2050 using the created energy system model. Post-simulation, the consequential direct annual emissions of Uganda's energy system were calculated. Figure 0-2 and Figure 0-3 show the installed capacities (existing plus optimized) of the electricity production units and the storage for each pathway and target year, respectively. In BAU, capacity extensions are comparably low, with nuclear taking the main share of installed capacity and generated electricity in 2050. In HighRE80, electricity supply is realized via photovoltaics (PV) panels, battery storage, hydropower, geothermal energy, and biomass cogeneration systems. In FullRE100, PV capacity combined with batteries or (from 2050 onwards) hydrogen (H2) storage and H2 electrolyzers are massively expanded. The PV electricity production is complemented with hydropower and biomass cogeneration.

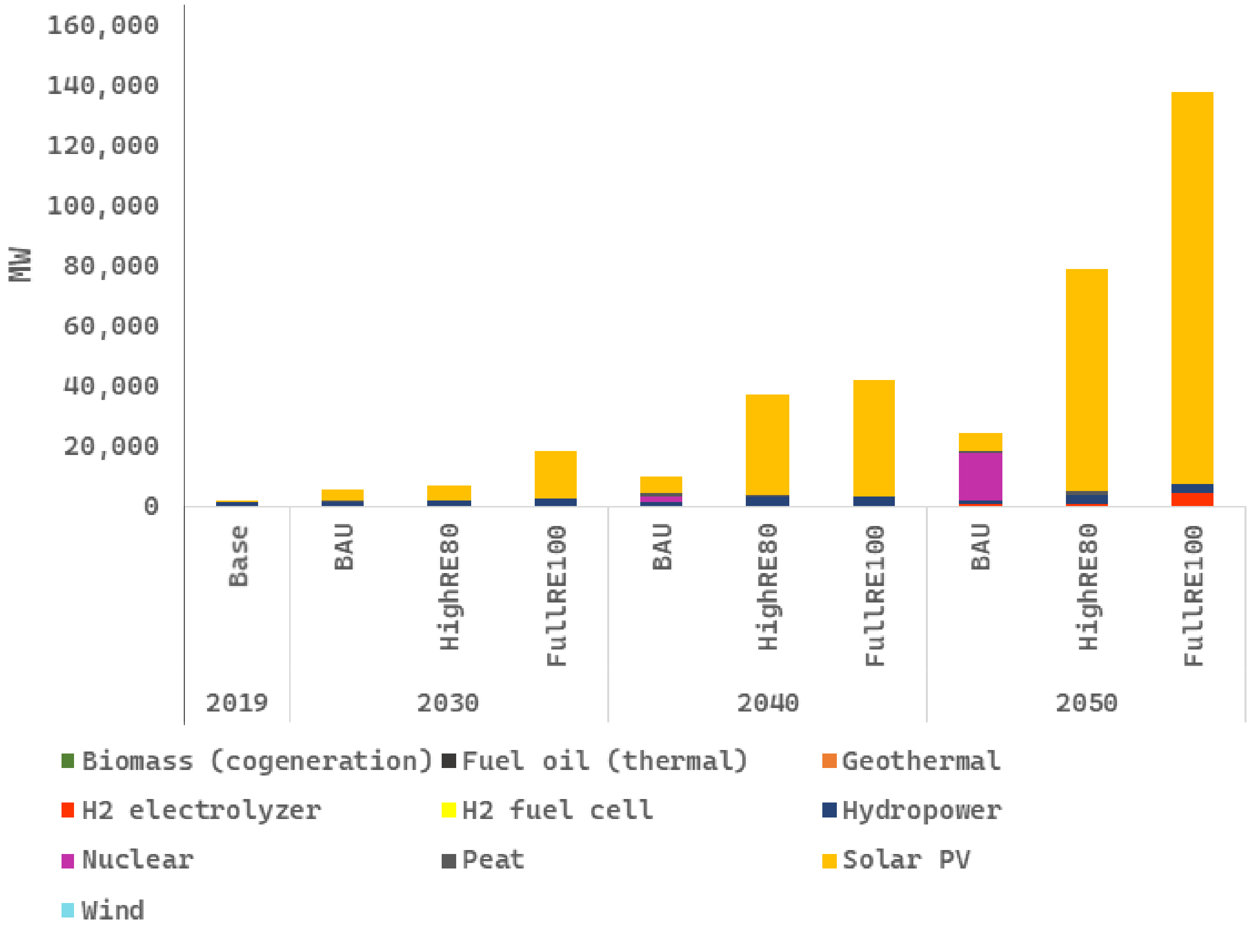


Figure 0-2: Installed power production capacities in the different pathways

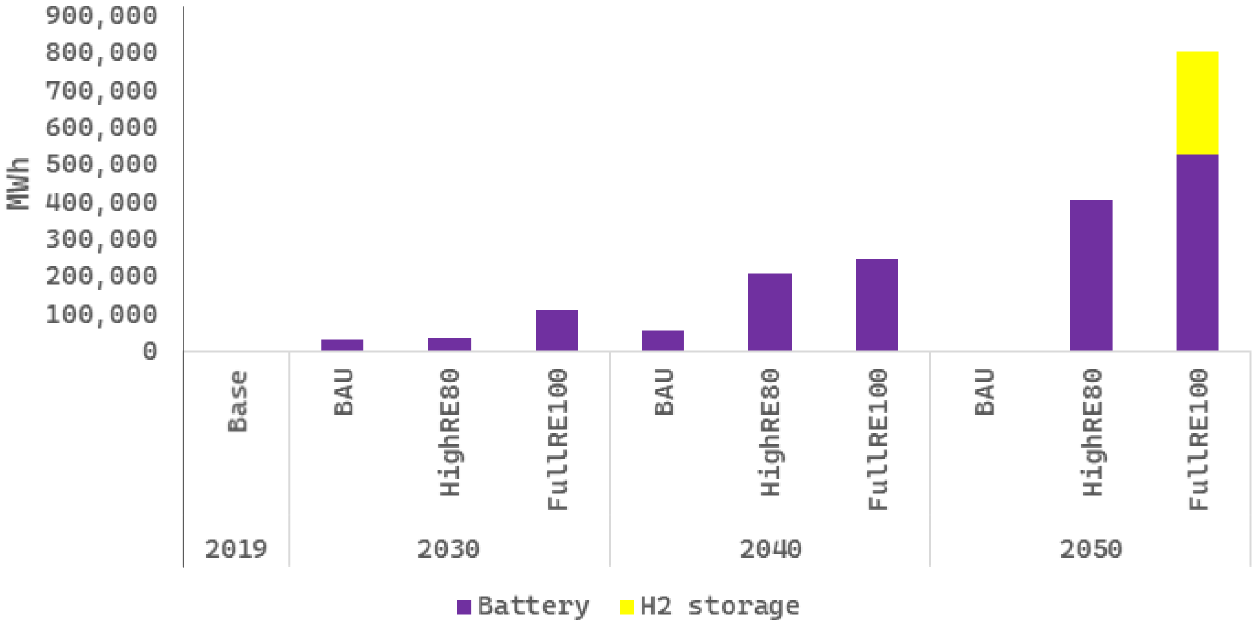


Figure 0-3: Installed storages in the different scenarios

After considering large parts of current biomass usage as unsustainable and thus non-renewable, the renewable share of the total energy system in 2019 is 36% (see Figure 0-4). In BAU, the renewable share rises until 2030, largely attributed to the affordability of PV panels and a relative reduction of biomass consumption due to the adoption of improved stoves. However, the BAU scenario witnesses a decline in renewables shares by 2040 and 2050, primarily due to the introduction of nuclear energy and the ongoing unrestricted use of unsustainable biomass. HighRE80 and FullRE100 increase their renewable share according to the defined trajectory. This increase is achieved through the deployment of large PV and storage capacities, as well as using electricity and H2 to replace unsustainable biomass use and fossil fuels in the transport, heat, and cooking sector.

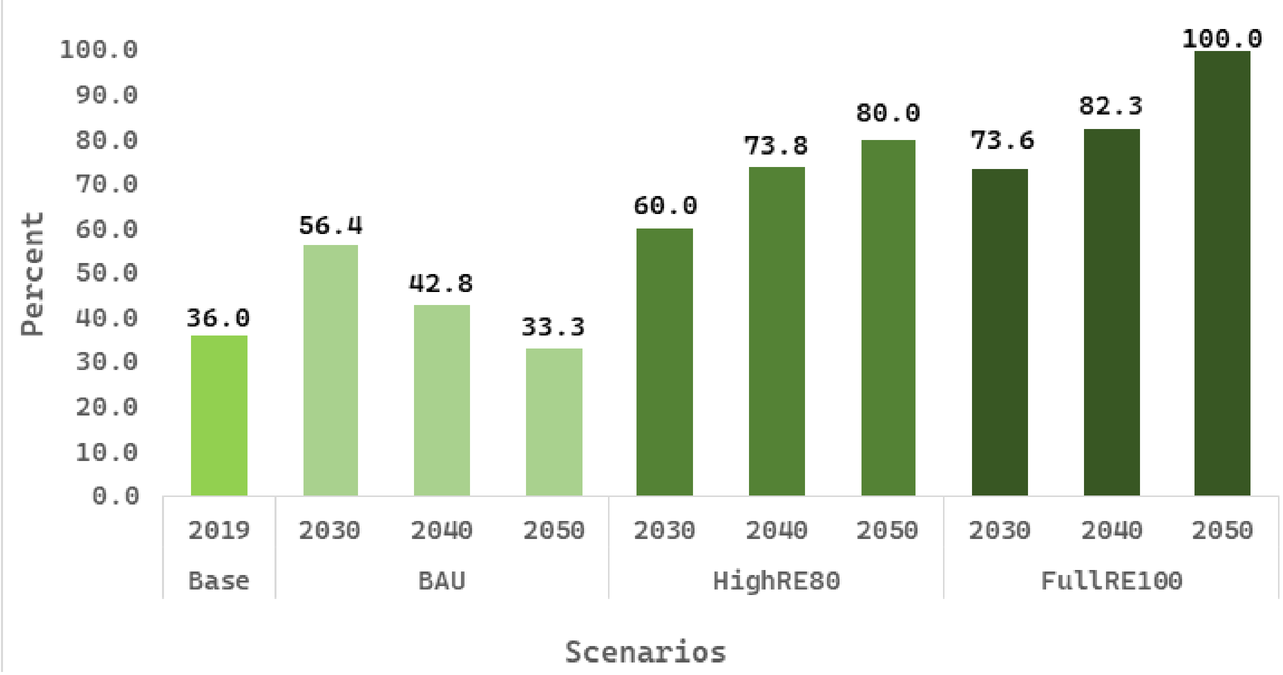


Figure 0 - 4: Renewable share of the energy system

Figure 0 5 shows the levelized cost of electricity (LCOE) for the defined pathways across various target years. In 2030, we observe a promising trend with consistently low LCOE values for all pathways, indicating an initial period of cost-efficiency. However, in the later target years where demand growth rates are considered, distinct patterns emerge. In 2040, the BAU pathway becomes more expensive than the renewable pathways, because of developments in nuclear and peat power plants. By 2050, the landscape further evolves. Due to large developments in nuclear, the BAU scenario is 255% more expensive than the HighRE80 pathway.

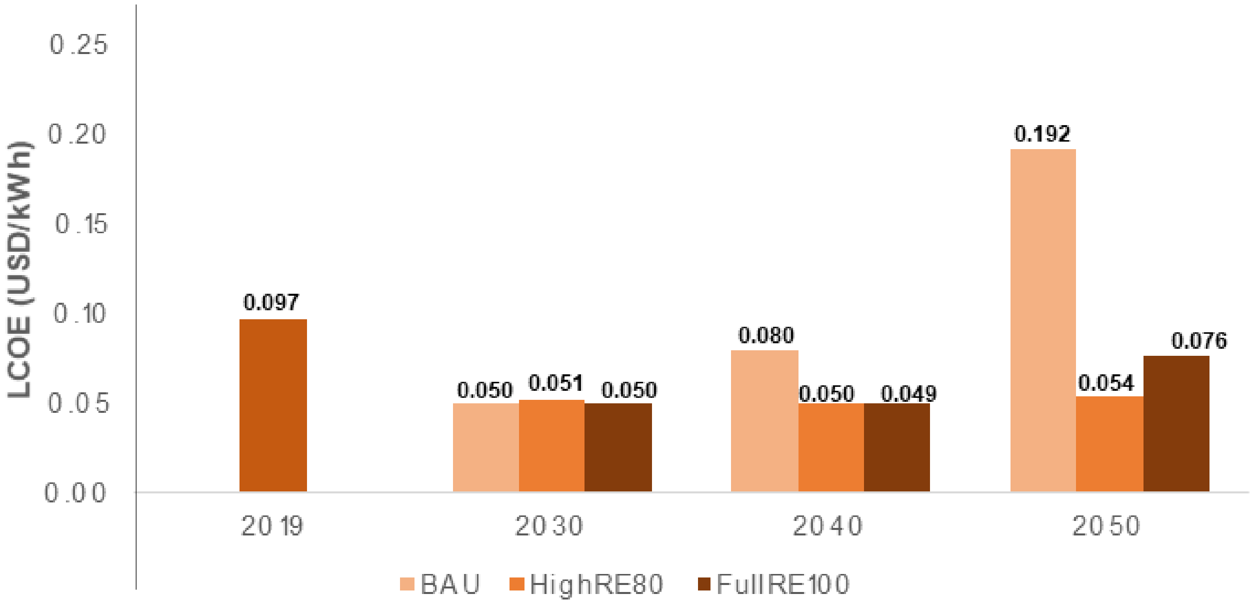


Figure 0- 5 : LCOE for the status quo and each scenario in the target years

Key Messages

The findings of this study contribute to the development of a targeted policy roadmap, known as 100% RE MAP. The results are intended to inform decision-makers, including opinion leaders, academia, civil society, government officials and think tanks on possible transition pathways towards 100% RE in Uganda.

- Growing energy demand and electrification, ongoing deforestation, and aimed decarbonisation to tackle climate change require the extension and transition to a reliable and sustainable energy system in Uganda.
- Government plans to meet the rising demand with nuclear power are less cost-competitive compared to renewable energy-based extension plans. By 2050, transitioning to a fully renewable energy system (FullRE100) is projected to result in a 60% reduction in the LCOE compared to the business-as-usual (BAU) plans. A high renewable energy system (HighRE80) could yield even greater savings, with a 72% LCOE reduction.
- The findings indicate that to achieve a cost-effective and sustainable transition, the focus should be on substantial increases in PV and battery storage capacities. For a transition to high or full renewable energy, investments ranging from 74 GW in the HighRE80 to 130 GW in the FullRE100 in PV capacity and from 404 GWh to 525 GWh in battery storage capacity are recommended as techno-economical optimum.

- A sensitivity analysis underpins the strong economic advantage of renewable energy-based transitions (HighRE80 and FullRE100) compared to a nuclear-based BAU scenario. Even when assuming that PV and battery storage prices are twice as high as the predicted 2050 prices, the renewable energy-based transitions still result in lower LCOE, with savings ranging from 27% to 43% compared to the BAU case. In reality, higher savings are expected.

- The HighRE80 pathway achieves an 80% renewable share with a 20% fossil share, resulting in a 29% reduction in LCOE compared to the FullRE100 pathway. This approach reduces required PV and battery storage capacities by 43% and 23%, respectively. The small fossil share provides grid stability and energy security, allowing conventional energy sources to strategically balance renewable intermittency, eliminating the need for over-sizing the system to cover low generation/high demand periods.

- The transition to a high or full renewable energy system requires substantial upfront investment costs, ranging from 245 to 393 billion USD, in contrast to the 132 billion USD in the BAU scenario. Nevertheless, these investments offer substantial long-term benefits, including potential annual cost savings of up to 80% due to reduced fuel costs. These savings may further increase in response to rising fuel prices.

- Choosing a BAU pathway for energy expansion will lead to a 24% increase in annual emissions by 2050 compared to the 2019 energy system. In contrast, opting for a high or full renewable energy pathway has the potential to reduce emissions from 60% to 100% by 2050.

- In the HighRE80 and FullRE100 pathways, it is essential to gradually replace conventional stoves with clean cooking technologies (such as electric and LPG stoves for HighRE80 and electric stoves for FullRE100) to ensure that Uganda's biomass usage remains within sustainable limits. This transition is crucial in preventing deforestation and biodiversity loss.

- Transitioning from combustion vehicles to electric vehicles is recommended for all pathways by 2030 due to high fuel oil prices. This recommendation holds true even at current fuel prices, but it becomes increasingly compelling with the anticipation of increasing fuel oil prices. In HighRE80 and FullRE100, envisioning solar-powered electric vehicles is especially promising for a sustainable and cost-effective solution for the future of the transport sector.

ABBREVIATIONS

CHP	Combined heat and power
CO2	Carbon dioxide
ECO	Ecological Christian Organisation
ERA	Electricity Regulatory Authority
GDP	Gross domestic product
GFMS	Global Flood Monitoring System
GRDC	Global Runoff Data Centre
GSEE	Global Solar Energy Estimator
H2	Hydrogen
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KIS	Kalangala Infrastructure Services
LCOE	Levelised cost of electricity
LPG	Liquefied petroleum gas
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MAP	Multi-Actor-Partnerships
NDC	Nationally Determined Contributions
oemof	open energy modelling framework
PV	Photovoltaic
RE	Renewable energy
RLI	Reiner Lemoine Institut
SME	Small and medium enterprises
UEB	Uganda Electricity Board
UEGCL	Uganda Electricity Generation Company Limited
UETCL	Uganda Electricity Transmission Company Limited
UNFCCC	United Nations Framework Convention on Climate Change
VWF	Virtual Wind Farm
WENRECO	West Nile Rural Electrification Company Limited
WWF-UCO	World Wide Fund for Nature Uganda Country Office

FIGURES

TABLES

1 | INTRODUCTION

How can Uganda's energy system be transformed into a system that runs on 100% renewable energy (RE)? This introduction gives an overview about the needs and gaps underlying this study, the scope of the research, and the methodology used.

1.1. Needs and gaps

One of the challenges facing Uganda is associated with population growth. In the last 60 years (from 1960 to 2021 to be precise) its population has increased by 502%, while in the same period the world's population grew by 160% (The World Bank, 2021). This upward trend is expected to continue. Meanwhile, the ongoing urbanization process has an impact on the dynamics of the economic sectors, which in turn must adapt to contribute to the country's development. A larger population implies a higher energy demand, which represents a considerable effort in terms of the efficient use of resources. Further, it is estimated that 57% of the population has access to electricity, leaving a substantial portion of the population without this service. The challenge is to ensure access to clean energy for the entire population and to provide this service in a reliable, sustainable and affordable manner.

On the energy supply side, majority of Uganda's population currently relies on biomass as their primary source of energy, amounting to 87.8% of the total energy consumption (UBOS, 2022b). This resource is mainly consumed at the household level (51%), followed by the commercial and industrial sectors (30% and 11%, respectively) (UBOS, 2022b). However, the resource is not being consumed in optimal conditions, since there is no general access to clean technologies that would avoid inefficiencies and health impacts on the population. At the same time, the reliance on biomass leads to deforestation and generates competition for the use of the land for agriculture. In parallel, the limited access to reliable electricity puts additional pressure on the country's natural resources, which are also vulnerable to the impacts of climate change.

In Uganda's electricity sector, there is a strong dependence on water resources. In recent years, about 90% of the electricity generated has come from hydropower plants, mostly run-of-river. Significant climatic changes then play an important role, since floods can cause damage to the elements of the electrical system, while droughts can also affect river flows. The diversification of the energy matrix is gaining importance, as it is necessary to mitigate dependence on a single technology and the risk associated with climate change and considering that the country is moving towards an economic growth that will require reliable and affordable energy supply.

Energy transition does not happen overnight, thus, energy planning and policy play a key role. The promotion of alternative energy sources and a sustainable energy matrix is possible in Uganda, which is a territory rich in natural resources. However, the current vision of the energy sector is not fully sustainable, and efforts are needed at the financial, planning and policy levels to make energy more affordable and climate-friendly. Taking into account the above, this analysis focuses on a transition to a fully renewable powered Uganda across all sectors.

1.2. Research scope and methodology

Renewable energy (RE) scenarios are typically developed using energy system models, which simulate the interactions between different energy sources, storage options, and demand sectors. These models take into account factors such as resource availability, costs, technology performance, and policy incentives, to estimate the penetration of different RE sources over time. They also consider the need for balancing supply and demand, including the use of storage and grid integration.

The primary objective of this study was to construct a model for Uganda's energy transition, with the overarching goal of formulating recommendations for a cost-effective and sustainable shift in the energy landscape. Three distinct pathways, with each offering a unique perspective on Uganda's energy future in 2030, 2040 and 2050, are modelled to characterize the energy transition. These pathways represent the existing governmental energy plans ("business-as-usual"), as well as ambitious RE transition plans to high and full renewable energy solutions.

The aforementioned pathways are based on a set of assumptions regarding economic, technological, and policy developments developed together with the MAP platform formed under the 100% RE MAP project in Uganda. The pathways are not a prediction of the future, but rather a tool to explore different possible future developments. The RE scenario specifically refers to a projection of future energy demand and supply based on a high penetration of RE sources, such as solar, wind, hydro, geothermal, and biomass. The scenarios allow for the evaluation of the implications of different assumptions regarding the energy system, such as the penetration of RE, the availability and cost of different energy resources, the evolution of energy demand and the implementation of policies, regulations, and technologies. The transition pathways are used as a reference in the decision-making route to develop high-impact strategies and policies in Uganda, which will support the systematic transformation process to become 100% renewable.

The defined pathways were analysed using an energy model which comprises of two components: the energy demand model and the energy supply model. The demand model was developed by collecting energy demand data from Uganda's statistical abstract as baseline and assuming annual energy demand growth rates based on (WWF, 2015; IATA, 2022; UIA, 2022). The energy demand was modelled in a sectoral approach and restructured to effective end-use sectors, namely, industrial heat, transport, cooking, and electricity (other end-uses besides transport and cooking). Key economic, social, and environmental information was collected in order to contextualize the pathways and scenarios and to identify drivers and barriers that may influence the development of renewables in Uganda. The input data collection was complimented with GIS based mapping methods providing data about population density, existing energy infrastructure, and RE resources.

The energy supply model was used to find the most cost-efficient energy supply solutions for each target year within each pathway. For modelling Uganda's energy system, a superstructure of relevant energy system components was developed based on the "open energy modelling framework" (oemof) (Hilpert et al., 2018) including energy resources, conversion technologies, storages, transport vehicles, cooking technologies, and demand models. Contextual information from a literature review was used to apply assumptions and constraints for each scenario, and techno-economic parameters were found and used as inputs in the model (Table 7 1). The results from the energy demand model were also used as inputs for the energy supply model. All scenarios are simulated and optimized using a linear optimization algorithm, with a requirement of fulfilling the energy demand at every hour of the year.

The modelling phase was followed by a post-processing phase. Based on the information from existing energy projects and plans under development, scenarios were analysed from a technical, economic and environmental perspective, seeking to identify an economically efficient and sustainable option that meets Uganda's growing needs. In carrying out the project, RLI worked with local stakeholders in Uganda including the WWF-UCO, Heden Engineering considering the assumptions and feedback of the MAP members. Finally, policy recommendations are further elaborated in the policy roadmap developed by Heden Engineering Solutions Ltd. The roadmap provides a framework to support the inclusion of renewables and the expansion of access to energy by all Ugandans.

The main processes of the study are organised into chapters. Chapter 2 provides a literature review regarding the current socioeconomic conditions, energy infrastructure and RE potential in Uganda, and the sustainable utilization of biomass and fuels. Then in chapter 3, the relevant pathways and scenarios developed to facilitate the study of Uganda's energy transition are outlined. Chapter 4 describes the energy model that has been developed and used to analyse the chosen pathways. These chapters can be used as a comprehensive guide to the methods used in the study, including assumptions and constraints that underlie the simulation results, allowing readers to understand and replicate the methodology. Chapter 5 presents the main results from the energy model, with chapter 6 providing a detailed discussion of the results. The key messages obtained from the study are outlined in the executive summary. The results chapters together with the key messages can be used to inform future policy decisions and research studies.

2 SITUATION ANALYSIS

This chapter presents a comprehensive literature review that serves as the foundational framework for the development of the relevant pathways and scenarios for Uganda's energy supply. Subsection 2.1 analyses the drivers that steer energy demand and supply, considering geographical, socioeconomic and accessibility factors. Subsection 2.2 outlines the RE potentials for various energy sources, and subsection 2.3 provides a detailed analysis of the sustainable utilization of biomass and fuels.

Understanding Uganda's socioeconomic context is crucial to grasp the country's current state, including energy supply and demand and the key factors shaping trends. As will be discussed in this Chapter, Uganda's population has grown considerably and is expected to continue to grow in the coming years. This population growth is accompanied by a shift in the population from rural to urban areas. The economic sectors have been adjusting to these demographic trends and will surely be a key part of the development that is expected in the country. Agriculture is certainly a fundamental activity in the country's economy and the service sector has been gaining relevance in recent decades; besides, the industrial sector has been growing and may play a key role in the urbanization process that is taking place. Energy supply cannot be separated from this framework, as it is the force that drives development in all sectors.

Therefore, the focus of this Chapter is also laid on identifying the status quo in the Ugandan energy infrastructure, supply and demand, as well as the availability of resources, and evaluating the possibilities arising therefrom. Figure 2-1 shows Uganda's final energy consumption by source in 2021 showing the current predominant role of biomass and subordinate role of electricity in the country. The excessive consumption of biomass is a major driver of deforestation and shall therefore be reduced through efficiency improvements in cooking devices and replacement of biomass with other energy sources. Figure 2-2 shows the final energy consumption by sector displaying the major roles of households, industry and agriculture in Uganda's energy demand.

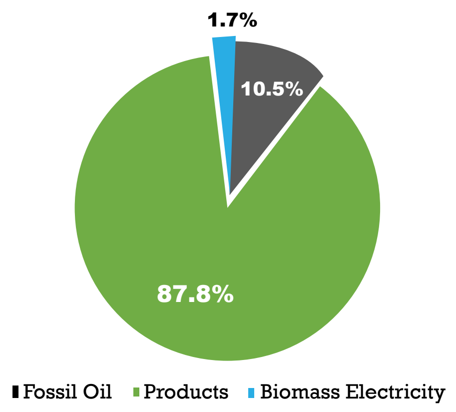


Figure 2- 1: Final energy consumption by Source 2021
Data Source: (UBOS, 2022a)

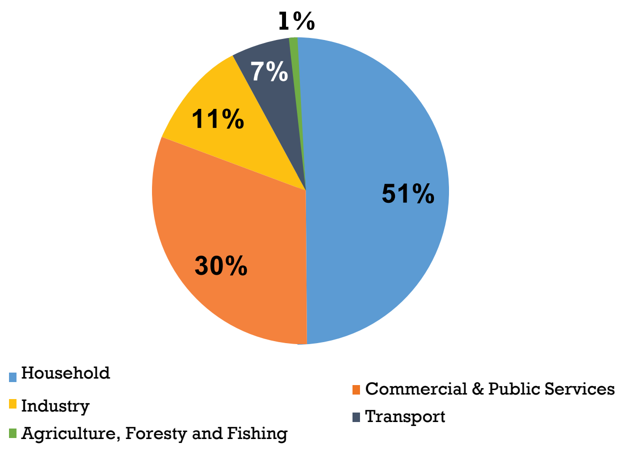


Figure 2 -2: Final energy consumption by sector 2021
Data Source: (UBOS, 2022a)

2.1. Drivers and status quo of energy resources and supply

There are various drivers of energy demand and factors which influence the energy supply. In the following sub-sections, they are categorized under geography, population, urbanization, GDP, economic sectors, social inequality, and poverty and explained. Further, current energy resource use, energy access, and the characteristics of the energy supply sector are described.

2.1.1 Geography

Uganda is one of the East African countries, which borders Kenya, South Sudan, the Democratic Republic of Congo, Rwanda and Tanzania. Lake Victoria is located in the southernmost part of Uganda and is considered the largest lake in Africa and one of the largest in the world. Lake Victoria is also shared with Tanzania (51%) and Kenya (6%) and is the source of the Nile River, one of the longest rivers in the world with an estimated length of 6,695 km. Additionally, most of Uganda's territory is in the Nile basin (Nile Basin, 2016). This equatorial country is endowed with a great variety of resources and a tropical climate, extending over different terrains between plateaus and mountains, home to different natural parks rich in biodiversity. The geographic influence is reflected in the diversity of resources available in the country, as it is described in the following sub-sections.

2.1.2 Population

Uganda has a population of 45.8 million, of which 74.4% are rural inhabitants, even though the urbanization process has been increasing in recent decades. Correspondingly, Uganda's urban population represents 25.6% of the total population, a low percentage compared to the rest of the Sub-Saharan Africa region, where the population in urban centers reaches 41.8% of the total national population. Considering the data reported since 2000, the average annual urban population growth rate in Uganda is 5.8% (The World Bank, 2021), and it has been estimated that the urban population will continue to grow in the coming years, reaching a share of the total population of 31.2% by 2030, 37.7% by 2040 and 44.1% by 2050 (The World Bank, 2022a), see Figure 2 3.

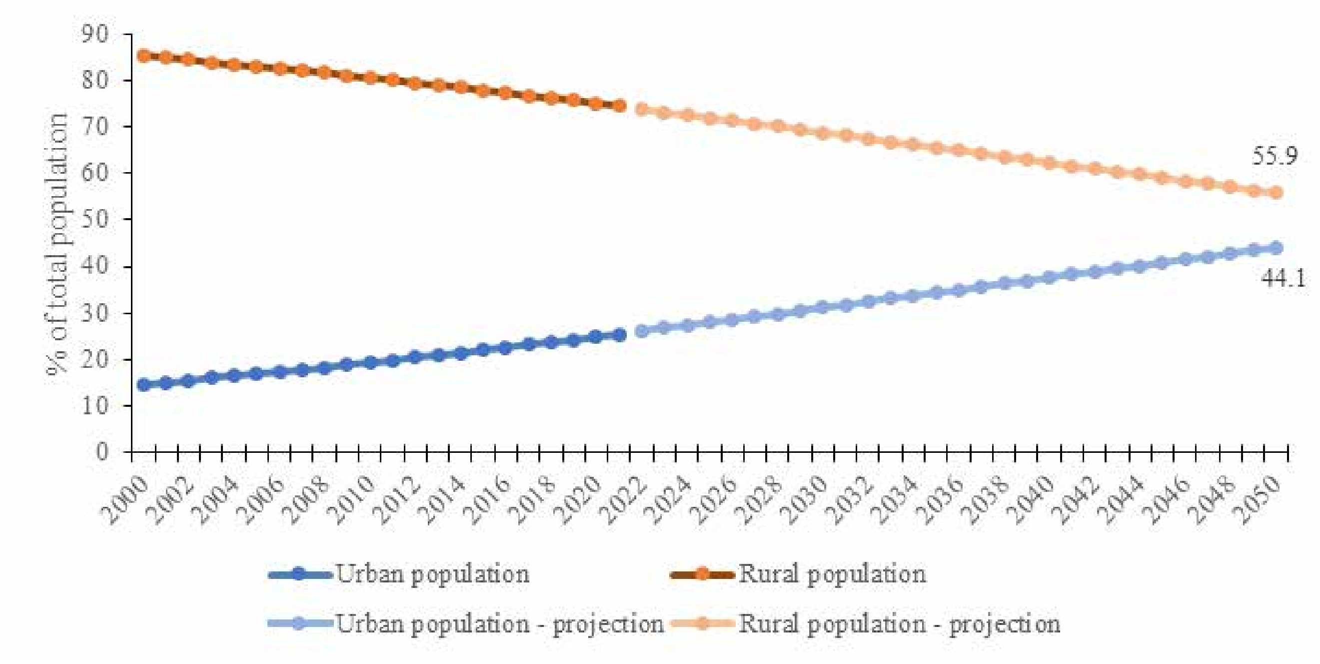


Figure 2- 3: Uganda's rural and urban population - realvalues and forecast data source: (the World Bank, 2021) and (the World Bank, 2022a)

Kampala and other cities have demonstrated rapid growth that has been changing the role played by large cities in the country's economy. The most urbanized region in Uganda is the central region, followed by the western region, according to data collected in the 2002 and 2014 censuses. This reflects the influence of the capital city, where the population finds greater opportunities for socio-economic development, such as employment and education (Tumwesigye et al., 2021). Other factors that contribute to this change are the natural increase in population, associated with a high fertility rate in the territory, and a reduction in infant and maternal mortality rates (Tumwesigye et al., 2021). Additionally, it is important to note that Uganda is one of the countries with the largest number of refugees, more than 1.5 million, mostly from neighbouring countries and from the region (The UN Refugee Agency - UNHCR, 2023).

Figure 2-4 shows the population distribution in Uganda by means of the population density. Most people live in Kampala, but also around other cities high population densities are visible. Northern Uganda is less populated than the rest of the country. Furthermore, the connection between natural resources and population patterns becomes clear. Most people live near greater bodies of water and seem to avoid drier or more mountainous areas. Figure 2-4 also shows operational and planned transmission lines as well as distribution lines and the strong connection to the population patterns.

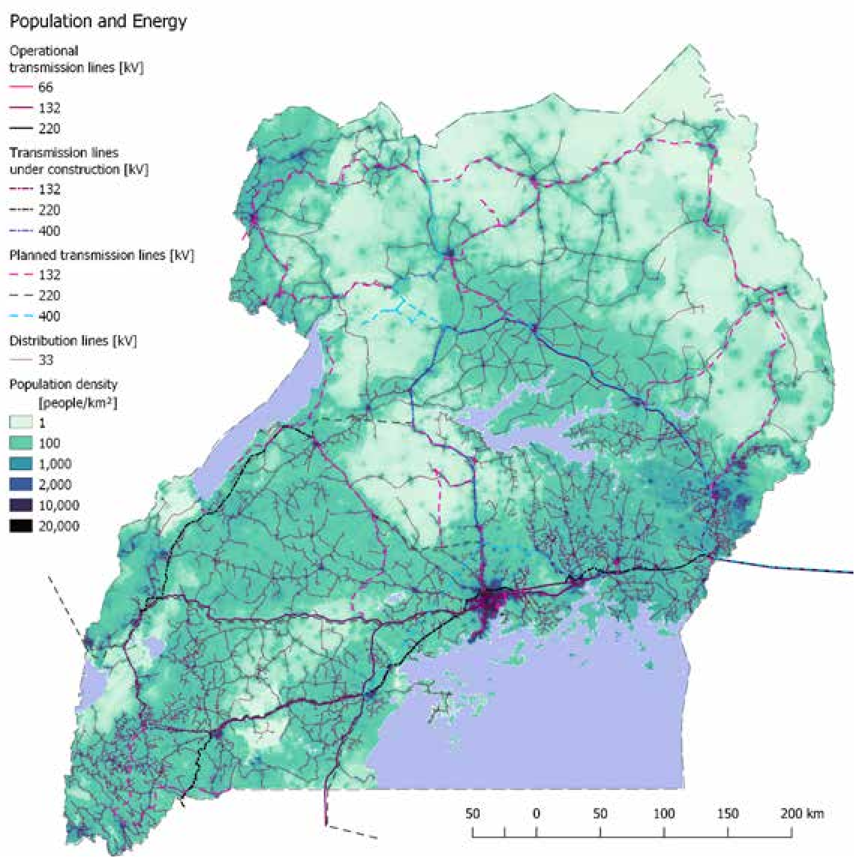


Figure 2 -4: Population density and transmission/distribution lines

2.1.3 GDP and economic sectors

The gross domestic product (GDP) in Uganda for the year 2021 was 40.53 billion USD and its annual growth rate was 3.54%, see Figure 2 5 (The World Bank, 2021). Considering that the world's GDP in the same year was 96.53 trillion US dollars, Uganda's economy represents 0.04% of that total value, placing it in the 93rd position in ranking. Putting these numbers in proportion to the population, the GDP per capita for Uganda in the year 2021 reached 884 US dollars (The World Bank, 2021). Extending on the sectoral perspective on final energy demand (Figure 2-2), Figure 2-6 shows the sectoral contributions to GDP, where for the fiscal year 2020/21 the services sector contributed 41.8% of GDP, followed by the industrial sector with 27.1% and the agriculture sector with 23.8% (UBOS, 2022a).

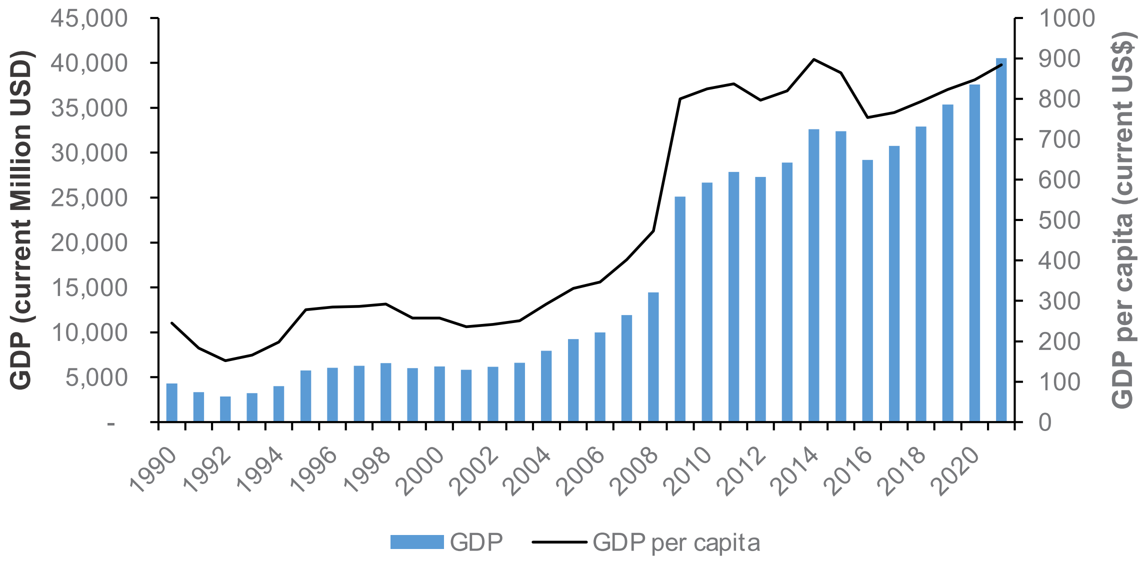


Figure 2-5: GDP absolute and per capita data source: (The World Bank, 2021)

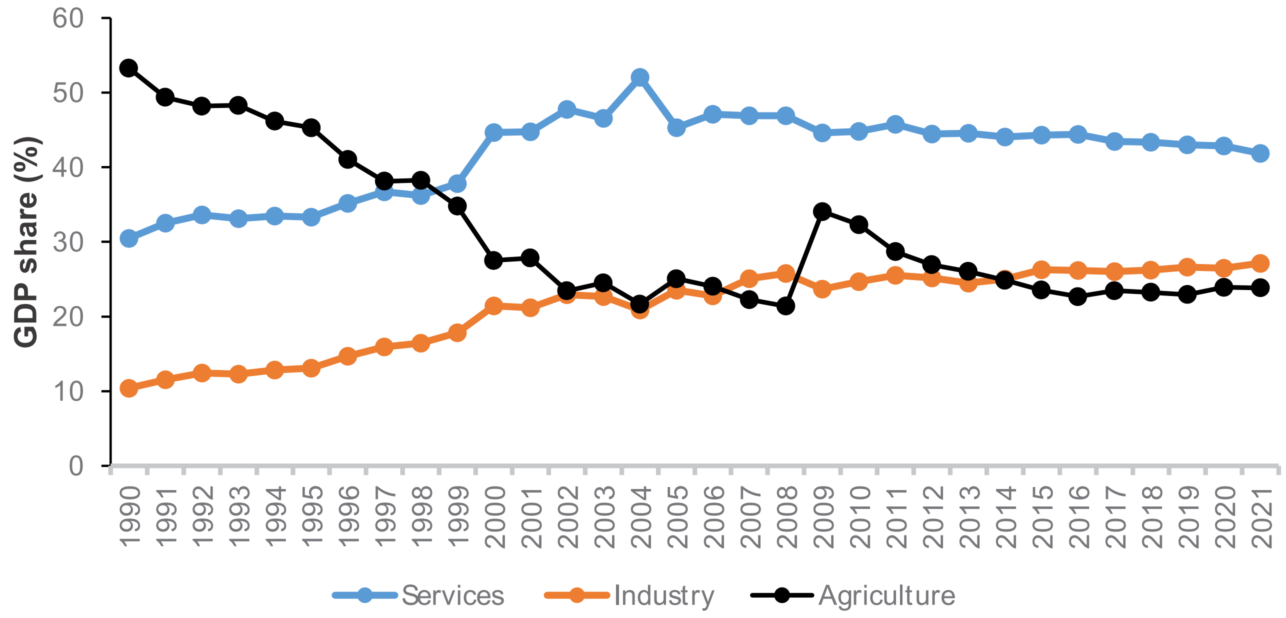


Figure 2-6: Sector contribution to the GDP data source: (The World Bank, 2021)

Agriculture is undoubtedly an activity that drives the economy in Uganda. According to the Ministry of Agriculture, Animal Industry and Fisheries, the agriculture sector accounts for nearly a quarter of the country's GDP, contributes half of the exports and generates direct and indirect employment for more than 80% of the population (MAAIF, 2021). According to the same source, traditional crops in Uganda include coffee, cotton, tea and tobacco, with coffee being the most profitable. Additionally, between 2018 and 2019 there was growth in maize, cassava, potato and plantain banana crops, the latter being the one with the highest increase. Livestock, as well as the volume of fish, showed an overall increase in the same period. Notably, during 2015 and 2019, chicken and goat production increased by 29% and 20%, respectively. The performance of this sector has a direct impact on food security in the country and linking this topic to that of urbanization, it could be stated that the availability of agricultural labour in the future may be affected.

Although agriculture is still an economic mainstay, the economic transformation that has been evident in Uganda in recent decades has reduced its share and given way to the growth of the services and industry sectors. The manufacturing sector's total value in Uganda accounted for 16% of the GDP in 2021, similar to the previous year (The World Bank, 2021). The segments with the greatest weight are Food Processing and Drinks and Tobacco, which between 2019 and 2020 decreased by 4.7% (UBOS, 2022b). In the same period, the highest growth rates were seen in the following sectors: Bricks and Cement (34%), Textiles (23.9%) and Chemicals, Paint, Soap and Foam Products (14.8%). In Figure 2-7, the size of the circles represents their weight in the manufacturing subsector, while their position on the y-axis represents their variation in the years from 2019 to 2020. Additionally, the country was ranked 115th out of 141 economies in the 2019 Global Competitiveness Index (World Economic Forum, 2019), with a score of 48.9, where 100 represents the maximum score to be awarded for competitiveness or the ideal state.

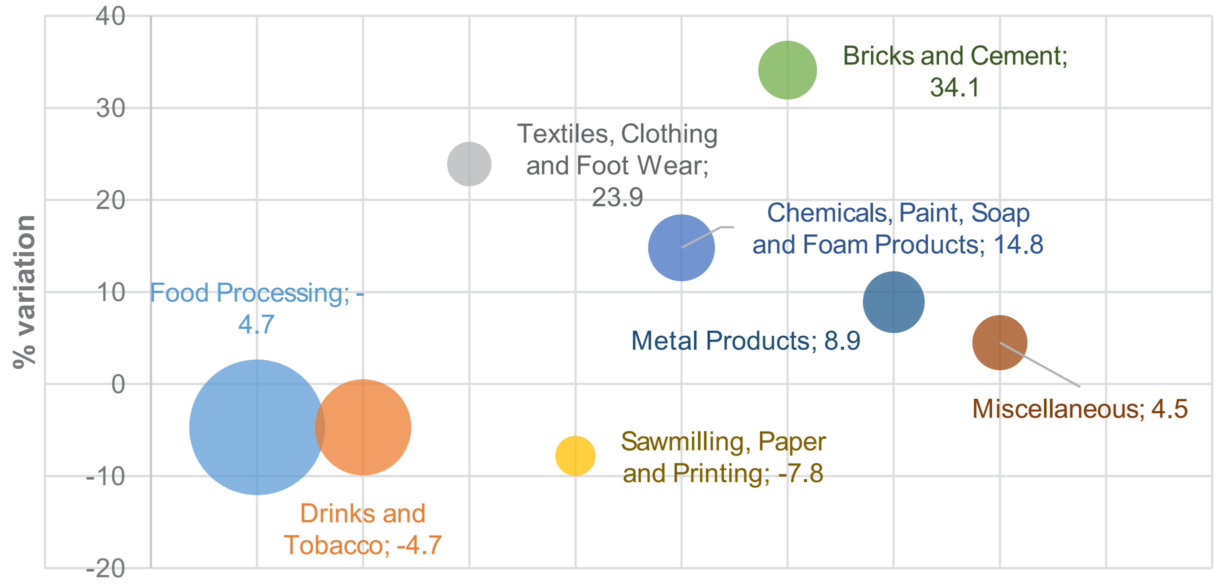


Figure 2 -7: Index of production 2020, data source: (UBOS, 2022b)

2.1.4 Social inequality and poverty

According to the World Bank methodology, Uganda is classified as a low-income economy, which means that its gross national income (GNI) per capita is below the established threshold of USD 1,085 for the year 2021 (The World Bank, 2023). By 2021, Uganda's GNI per capita, according to the World Bank's Atlas method, was USD 760 (The World Bank, 2021), which breaks down to a monthly average of USD 63. Moreover, the Gini index[1], which is a measure of inequality in income distribution was 42.7 in 2019 (The World Bank, 2022b).

As per the Uganda National Household Survey 2019/20 (UBOS, 2021), poverty in the country is at 30.1%, based on a national poverty line of USD1.77 person per day. However, under the threshold defined as the international poverty line (USD2.15 per day per capita), poverty reaches a rate of 42.2% (The World Bank, 2022b). Figure 2-8 shows different estimates of the percentage of the population living in poverty, under different considerations. In addition to the two indices already mentioned, there is the measure of poverty below the lines of lower middle income, upper middle income and multidimensional poverty, the last one considering, in addition to monetary poverty, non-monetary dimensions such as educational attainment, educational enrolment and access to electricity, sanitation and drinking water (The World Bank, 2022b). Other socioeconomic indicators considered in 2021 include: inflation, which stood at around 2.2%; unemployment at around 4.3% of the labor force (but with a vulnerable employment rate[2] of 73% (2019)); and foreign direct investment which accounted for 2.7% of GDP (The World Bank, 2021).

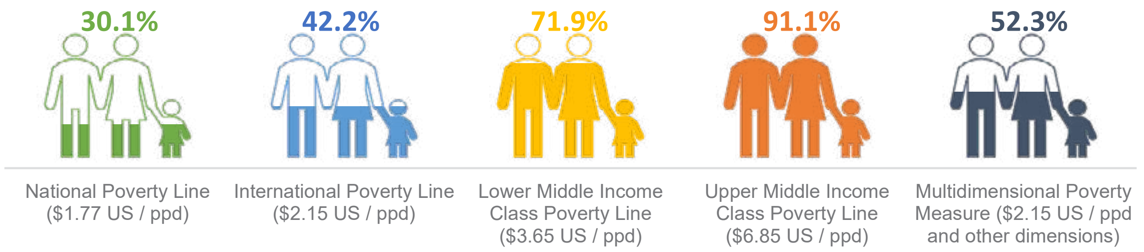


Figure 2-8: **Poverty in Uganda data source: (UBOS, 2021; The World Bank, 2022b)**

2.1.5 Energy resource use

Against this backdrop and its various changes over time, there is still a strong dependence on biomass[3] as a primary energy source, representing 88% of the energy consumption matrix in 2021 (UBOS, 2022a) due to its extensive use at the household level, to cook, and at the industrial level, in i) food, beverages and tobacco and ii) non-metallic minerals sub-sectors (UBOS, 2022a). Furthermore, oil products accounted for 10% of energy consumption in the same year, mainly in the transportation sector, followed by the industrial sector, with the iron and steel segment's activity (UBOS, 2022a). Lastly, electricity represents 2% of the total energy consumption, and is used to a large extent at the industrial level (UBOS, 2022a), see Figure 2-1 and Figure 2-9.

---

[1] *A Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality (The World Bank, 2021)*

[2] *Family workers and own-account workers as share of total employment.*

[3] *We refer to solid biofuels: wood fuel, bagasse, rice husks, other primary solid biofuels and charcoal, and waste.*

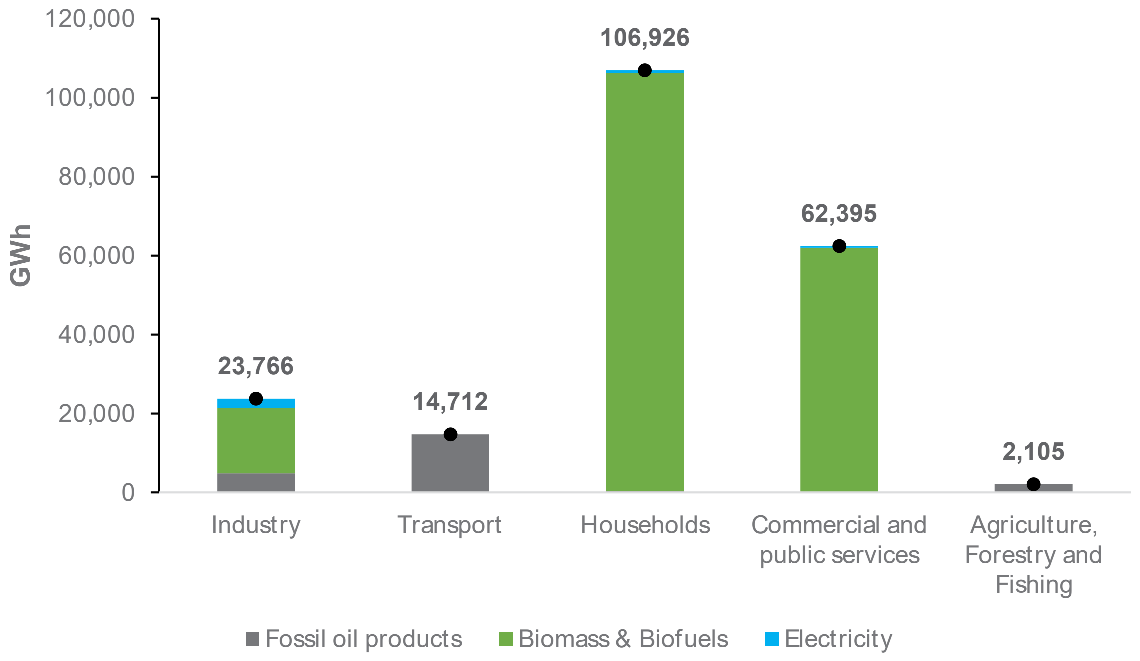


Figure 2 -9: **Energy consumption by sector data source: Ministry Of Energy and Mineral Development**

2.1.6 Energy access

It is estimated that in the Sub-Saharan African region, there are more than 600 million people without access to electricity and more than 970 million people without access to clean cooking fuels. Even more alarmingly, almost half of these people are concentrated in the Democratic Republic of the Congo, Ethiopia, Nigeria, Tanzania and Uganda (IEA, 2023a).

In view of the above, it is important to highlight that although Uganda has various energy resources that could be harnessed to provide electricity and clean fuels to its population, only 57% of its inhabitants have access to electricity (Uganda Energy Policy, 2023), corresponding to 70% of the urban population and 33% of the rural population (The World Bank, 2021), see Figure 2 10. Moreover, the World Health Organization has reported that in 2020, 0.5% of the population had a primary dependence on clean fuels and technologies for cooking[4] (World Health Organization, 2022). However, the value of energy as a driver in the transformation of the country has been recognized, and within the government's strategies set out in the document Uganda Vision 2040, it is expected to increase access to the national grid to 80% (National Planning Authority, 2013).

---

[4] *According to WHO, this includes households that primarily rely on electricity, biogas, natural gas, LPG, solar or alcohol fuels for cooking.*

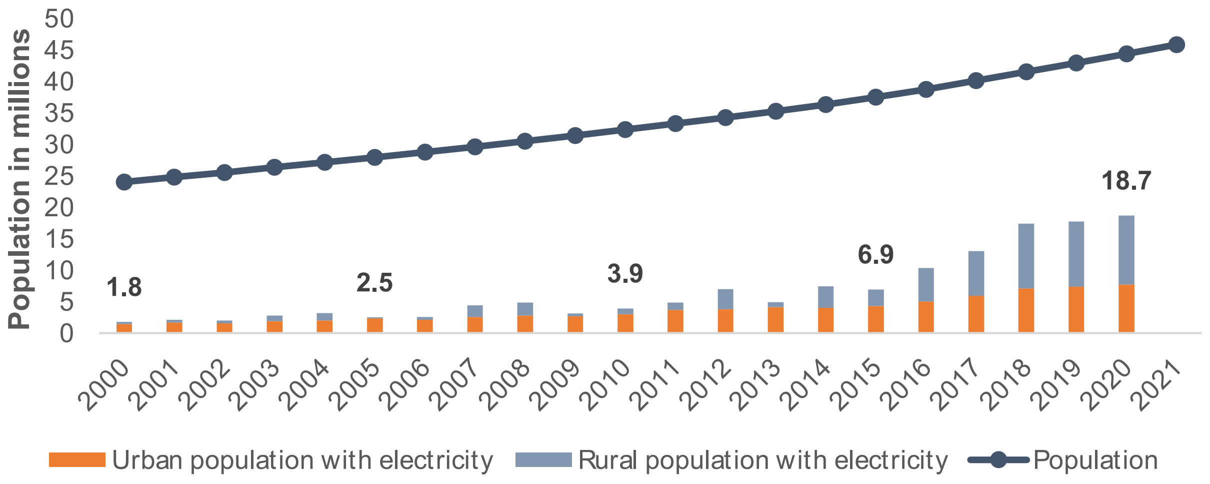


Figure 2-10: Access to electricity. Data Source: The World Bank, 2021

2.1.7 Energy supply sector

In Uganda's power sector, installed capacity has grown from 60 MW in 1954 to 1,347 MW in 2021, see Figure 2-11. Specifically, in 2021, hydropower plants accounted for 80% (1070 MW) of installed capacity, followed by combined heat and power (CHP) plants (8% i.e.,112 MW), thermal plants (7% i.e.,92 MW) and solar PV systems (5% i.e.,60 MW) (Electricity Regulatory Authority - ERA, 2022). For the coming years, several projects are planned for both generation and transmission sectors.

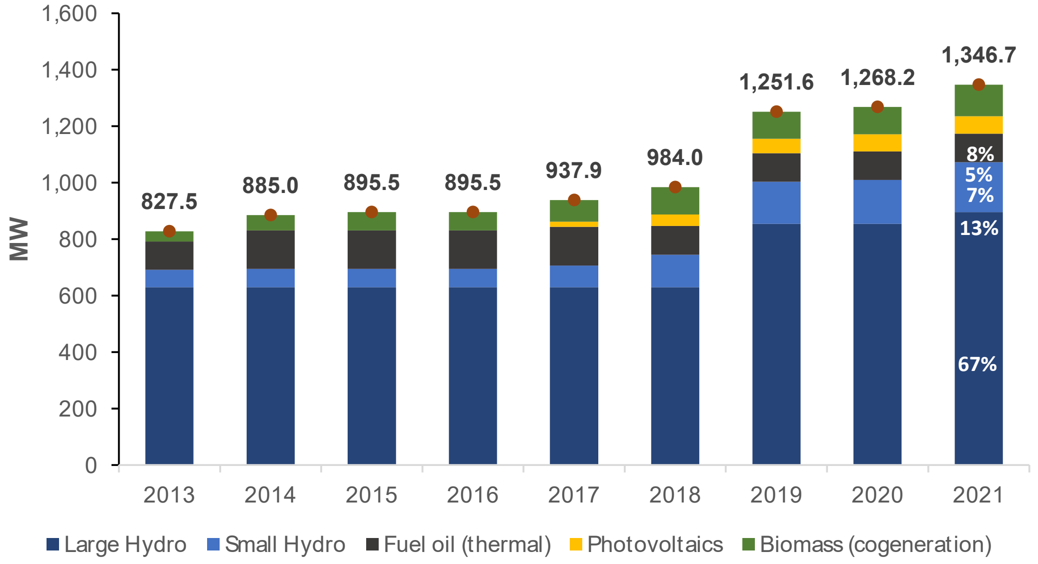


Figure 2-11: Installed capacity by technology. Data Source: Electricity Regulatory Authority-ERA, 2022

Electricity generation has maintained an upward trend over the years, reaching 4,749 GWh in 2021 (Electricity Regulatory Authority - ERA, 2022). In the same year, hydroelectric power plants generated more than 90% of the electricity and thermal plants less than 1%, see Figure 2-12. Based on these figures, it is evident how significant the share of renewable energies is in Uganda's electricity generation today.

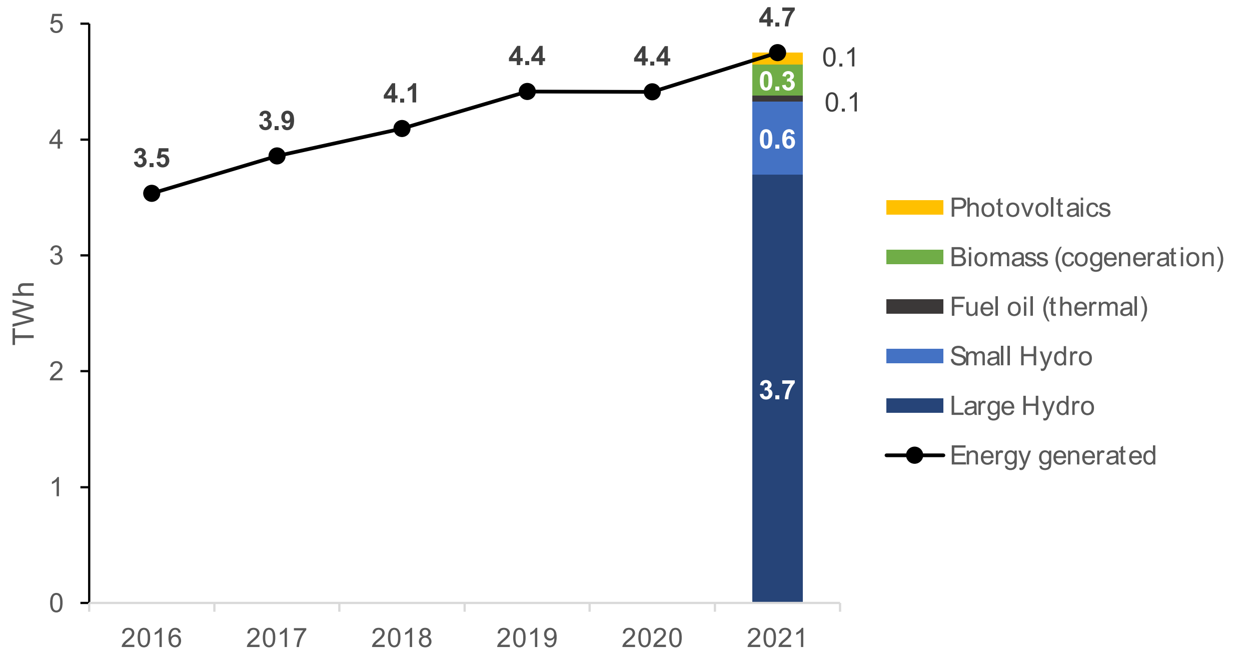


Figure 2-12: Electricity generation by technology. Data Source: Electricity Regulatory Authority - ERA, 2022

The expansion of transmission and distribution networks throughout the territory has been fundamental to reach more communities and with the commissioning of several projects between 2016 and 2021, the length of transmission and distribution lines has been increased by 111% and 90%, respectively (Electricity Regulatory Authority - ERA, 2022). Furthermore, a wide range of projects are expected in these two segments of the energy supply chain, to benefit both urban and rural areas, aiming to make it possible to evacuate energy from the power generation plants that will be incorporated and to accelerate rural electrification programs ((National Planning Authority, 2013) p. 74). Figure 2-13 shows all biofuel, bagasse, fuel oil, and solar power plants, which are in operation and planned as well as the transmission (operational, under construction, and planned) and distribution grid.

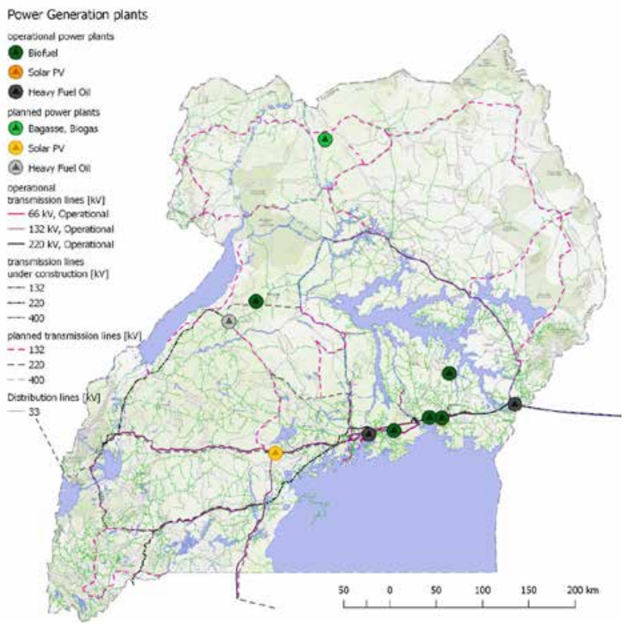


Figure 2-13: Power generation plants (operational and planned) with transmission lines (operational, under construction, and planned) and distribution lines. Data source: (Uganda Electricity Transmission Company Limited (UETCL), 2022)

Efforts are not only needed for areas connected to the grid. Off-grid electricity generation and distribution in Uganda is operated by two companies: West Nile Rural Electrification Company Limited (WENRECO), which supplies part of the West Nile sub-region (in North-western Uganda), and Kalangala Infrastructure Services (KIS) Limited, which operates on Bugala Island. As of 2021, there are around 11 off-grid plants with a total installed capacity of 14 MW, of which 65% are thermal plants reported (Electricity Regulatory Authority - ERA, 2022). With the off-grid generation of the same year, approximately 22 GWh, and some energy purchases made by WENRECO from UETCL (Uganda Electricity Transmission Company Limited), slightly less than 7 GWh, about 25.8 thousand off-grid users were supplied, where about 98% corresponded to households reported (Electricity Regulatory Authority - ERA, 2022) .

Similarly, electricity consumption figures show annual increases. In 2021, a total electricity consumption of 3.5 TWh by 1.76 million users was reported (Electricity Regulatory Authority - ERA, 2022), see Figure 2-14. In fact, large and extra-large industries alone (682 customers) accounted for 94.6% of the total customers, were responsible for 22% of the electricity consumption. Commercial users and medium industry have maintained a similar share in the distribution of consumption in recent years: commercial users' consumption oscillated around 12% of the total, while medium industry's consumption is around 15% (Electricity Regulatory Authority - ERA, 2022).

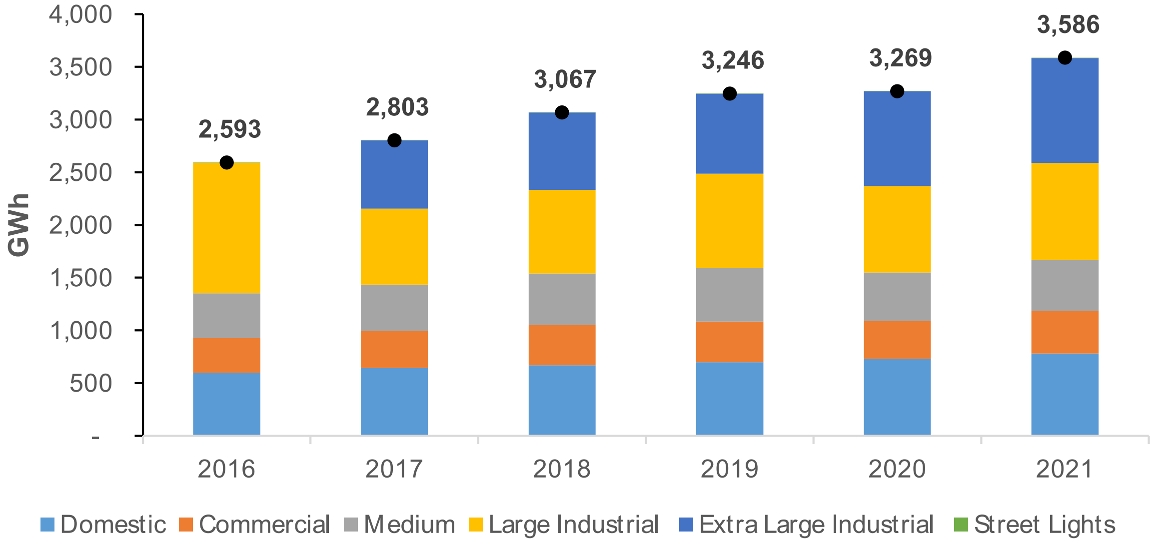


Figure 2- 14: Energy sales by customer. Data source: Electricity Regulatory Authority - ERA, 2022

Moreover, energy and electricity demand are expected to grow based on the country's developments and growing energy demands driven by domestic, institutional, industrial and transport needs. As stated by Uganda Investment Authority, electricity demand is growing at an annual rate of 10–12% (UIA, 2022). Therefore, in the Uganda Vision 2040 new hydropower, geothermal, nuclear, biomass cogeneration, solar PV and thermal plants are proposed with a total installed capacity of around 42 GW by 2040. Following the Uganda Vision and current plans of the government, It was assumed in the business-as-usual (BAU) pathway that nuclear energy capacities in Uganda would be developed i.e., 2 GW in 2040 and 15.6 GW in 2050 (Nhede, 2023). The expansion of energy supply capacities goes hand in hand with an 80% increase in access to the national grid (National Planning Authority, 2013).

In the current progress on the National Determined Contribution, the country is trying to improve the energy efficiency of firewood cook stoves, solar and liquefied petroleum gas (LPG) cookers. The excessive usage of firewood is putting pressure on natural resources as well as challenging climate change mitigation and maintaining an environmentally sustainable energy consumption. Out of the biomass options, charcoal is most commonly used in urban areas while firewood, agro-residues and wood wastes are generally used in rural areas. To diversify the energy system, Uganda is supporting some studies to replace biomass usage with electricity (Ministry of Water and Environment, 2021) as well as promoting RE projects under public and private partnerships.

2.2. RE potentials

The energy transition to a world powered mostly by RE is underway, and Uganda has all the potential to be part of this process. Referring to the potential of renewable resources for harnessing the power generation sector (12,700 MW)[5] envisaged by the Government of Uganda (National Planning Authority, 2013), the country has a yet untapped potential of about 11,400 MW. The purpose of this subsection is to review the resources available in Uganda, with special emphasis on those of a renewable nature. The identification of the resources available today and those expected to be available in the coming years allows for the outlining of the components included in the model. In this subsection, all renewable technologies that are either already in use in Uganda or are being considered in the alternative sarios in this study were included.

2.2.1. Biomass

Biomass energy supply involves using renewable organic material, such as wood chips, agricultural waste, or municipal solid waste, to generate heat or electricity. This can be done through a process called combustion, which involves burning the renewable organic material to create heat, and may also be converted to electricity through co-generation or gasification technologies. The main advantage of biomass energy supply is that it is a renewable source of energy that can help reduce dependence on fossil fuels. However, biomass energy supply is not always a clean source of energy, as the process of combustion releases pollutants and greenhouse gases into the atmosphere.

To reach the maximum level of sustainable biomass supply through firewood, there is a need for stronger and more efficient forestry management practices by the Ugandan authorities. One consequence of regulating and formalizing the harvesting of firewood and the production of charcoal would be an increase in sustainable output of biomass resources. Nevertheless, there might be some negative impacts that need to be investigated and taken into account. For example - a significant part of the rural population is dependent on biomass for cooking, and thus, for a living. Making it illegal, theoretically, would severely restrict this population's ability to make a living (WWF, 2015). See subsection 2.3 for details on sustainable biomass for Uganda, taking both supply and demand into consideration. For details on sustainable biomass usage in Uganda, taking both supply and demand into consideration, refer to subsection 2.3.1.

---

[5] *This figure includes: 4,500 MW (hydropower); 1,500 MW (geothermal); 5,000 MW (solar); 1,700 MW (biomass); and 0 MW (wind).*

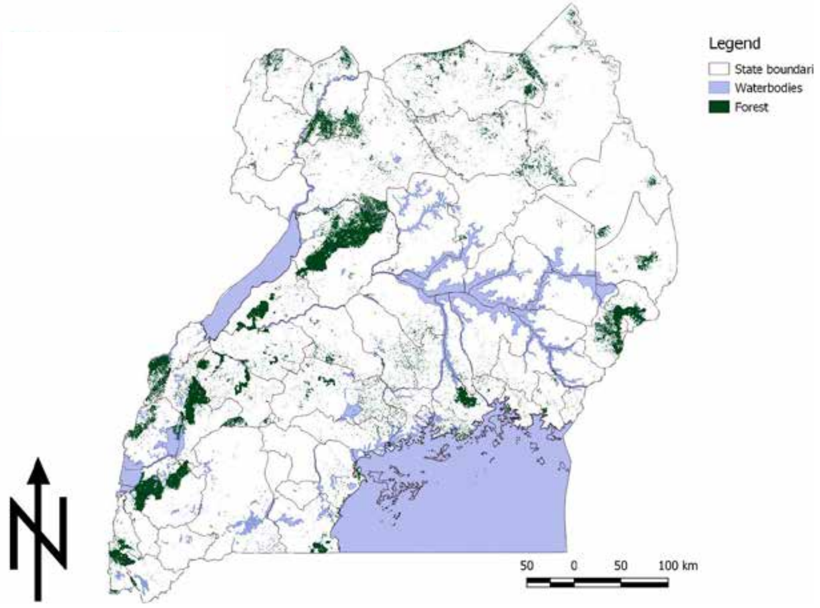


Figure 2 - 15: Uganda forest cover. Data sources: (Copernicus Global and Land Service, 2022), (Waterbodies-Openstreetmap; 2022) (GADM, 2022)

Most of the surface area of Uganda is not covered by forests which is shown in Figure 2-15; this is either because the environment is too arid to be suitable for forests or because it has been transformed to arable land by humans. Only a few larger forest areas exist in the country, located mostly in the Western part and in the North. Especially in national parks, the vegetation is protected and also in mountainous areas, forests are more common. In Central and Northern Uganda, small forested areas can be found.

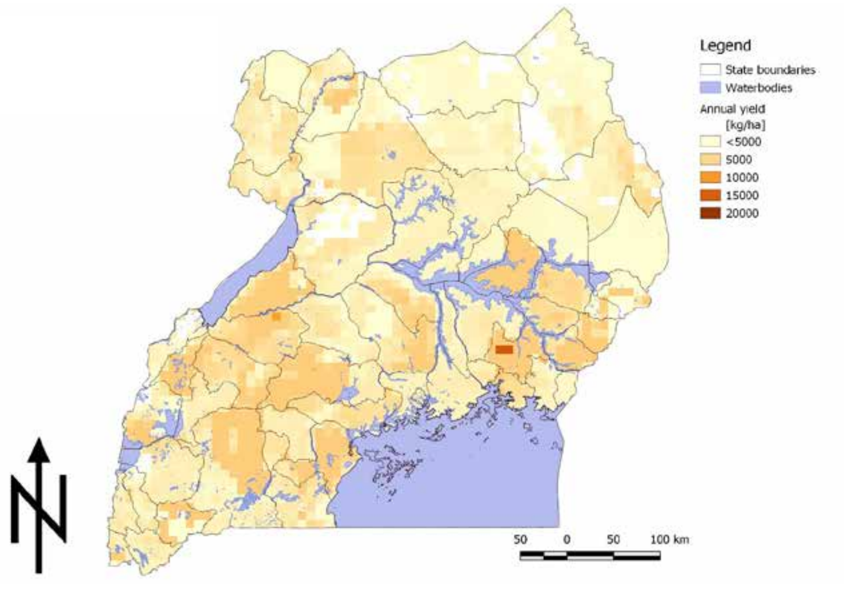


Figure 2-16: Uganda Maize Yields Data Sources: (International Food Policy Research Institute (IFPRI), 2019)

Figure 2-16 shows the annual yield of maize in Uganda. Maize is produced in most areas of the country. There are some higher yields in Central Uganda, up to over 15,000 kg per hectare per year. Near the river banks and around Lake Victoria, Lake Kyoga and other significant waterbodies the land is often more intensely used for agriculture. In the Southwestern and in Northern Uganda, the vegetation and arable land becomes scarcer, so the yield is lower. In forested areas, there is also no agriculture.

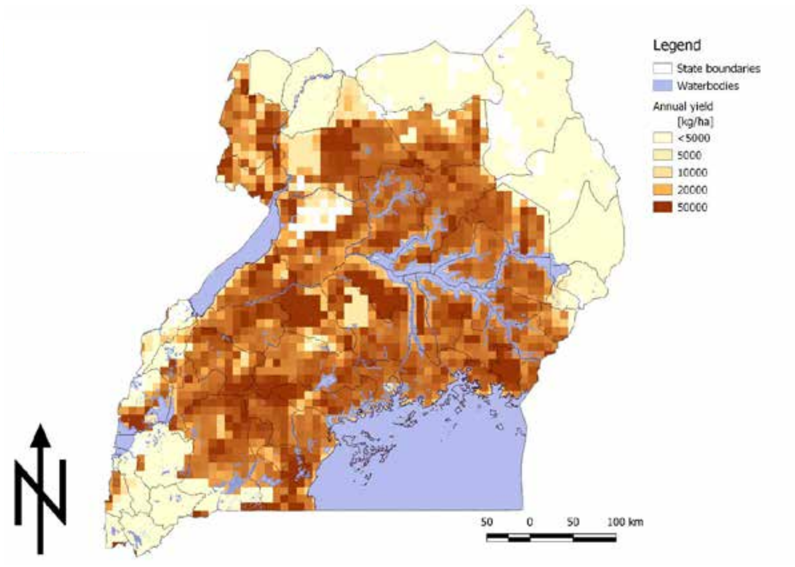


Figure 2-17: Uganda sugarcane yield. Data sources: International Food Policy Research Institute (IFPRI), 2019;GADM, 2022; 'waterbodies - openstreetmap', 2022

Figure 2-17 shows the annual yield of sugarcane in Uganda. There are huge differences in the distribution between Central Uganda and Northern and Southern parts of the country. In Central Uganda, yields beginning from 15 tons per hectare up to almost 50 tons are achieved. Outside the inner country, the yields are lower with an average of approximately 5 tons per hectare. Maize, sugarcane, oil palm, and jatropha are planned to be used as resource for biofuel production (Biofuels Act, 2020, 2020). Uganda Biomass Energy Strategy (BEST) estimates the sustainable biomass limit of the country for biofuel production to be at 1.2 million m^3 per year (MEMD, 2015). Estimates for future biofuel production by the MAP members exceed these limits and are considered in the BAU pathway.

2.2.2. Hydropower

Hydropower is a renewable energy resource that harnesses the power of water that is in motion to generate electricity. Hydroelectric power plants typically work by using turbines to convert the kinetic energy of falling water into mechanical energy, which is then used to generate electricity. Run-of-river power plants are a type of hydroelectric plant that uses the natural flow of a river to generate electricity, without the need for a large dam or reservoir. Hydro storage, on the other hand, involves using excess electricity to pump water uphill to a reservoir, which can then be released to generate electricity during periods of high demand.

The main advantage of hydropower is that it is a reliable, clean source of energy that can help reduce dependence on fossil fuels. Hydropower can also be highly efficient and can generate large amounts of electricity. However, the construction of large dams can be costly and can have a significant impact on local ecosystems and communities. Additionally, droughts and changing weather patterns can impact the availability of water, which can impact the reliability on hydropower as a source of energy.

Hydropower is a very common RE that is mature and cost effective to use in Uganda. The full scale of technically possible large-scale hydropower supply is estimated at around 4.5 GW. Considering small- and medium-scale plants, there is potential for a further 210 MW. Nevertheless, it is not recommended to explore the full potential of this source due to the high social and environmental impacts (WWF, 2015).

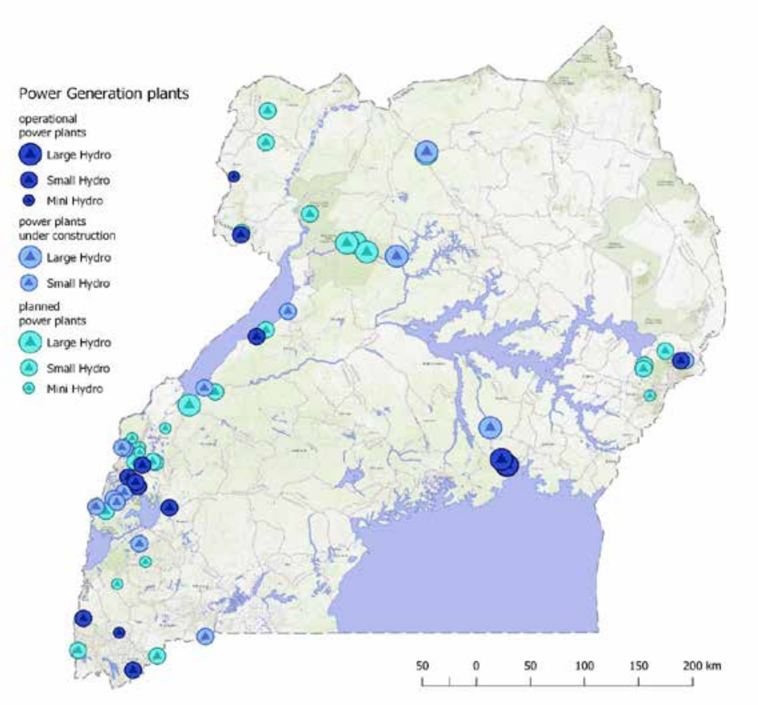


Figure 2- 18: Hydropower plants (operational, under construction, and planned), status march 2022. Data source: Uganda Electricity Transmission Company Limited (UETCL) 2022; " waterbodies-OpenStreetMap; 2022 Esri, 2022

Hydropower plants are located near water bodies, such as big rivers or lakes, as shown in Figure 2-18. Some power plants are near Lake Victoria or Lake Kyoga and some are planned on the River Nile. Most of the hydropower plants are found in the Western part of Uganda, from South to North. Especially around the Rwenzori Mountain range, numerous plants already exist or will in the future. Water that comes from the mountains is mostly used for power generation. Many of the power plants currently built are small hydro plants and some are large ones, while no mini hydro plants are currently under construction. However, more mini hydro plants are planned for the future.

2.2.3. Photovoltaics (PV)

Photovoltaics (PV), also known as solar power, is a technology that converts sunlight into electricity. It works by using solar panels made of PV cells, which absorb sunlight and generate a flow of electrons that can be captured and turned into usable electricity. The main advantage of PV is that it is a clean, and renewable source of energy that can reduce dependence on fossil fuels and lower greenhouse gas emissions. Additionally, PV rooftop systems can play an important role in the energy autonomy of some regions, providing a reliable and cost-effective source of energy that can reduce the need for electricity transmission over long distances. However, the technology requires a significant amount of space to generate large amounts of electricity. Especially Uganda's location, which is quite close to the equator, makes the potential of solar power enormous. With focus on Figure 2 19, the North-eastern region of Uganda seems to be perfect for the expansion of solar-based techniques.

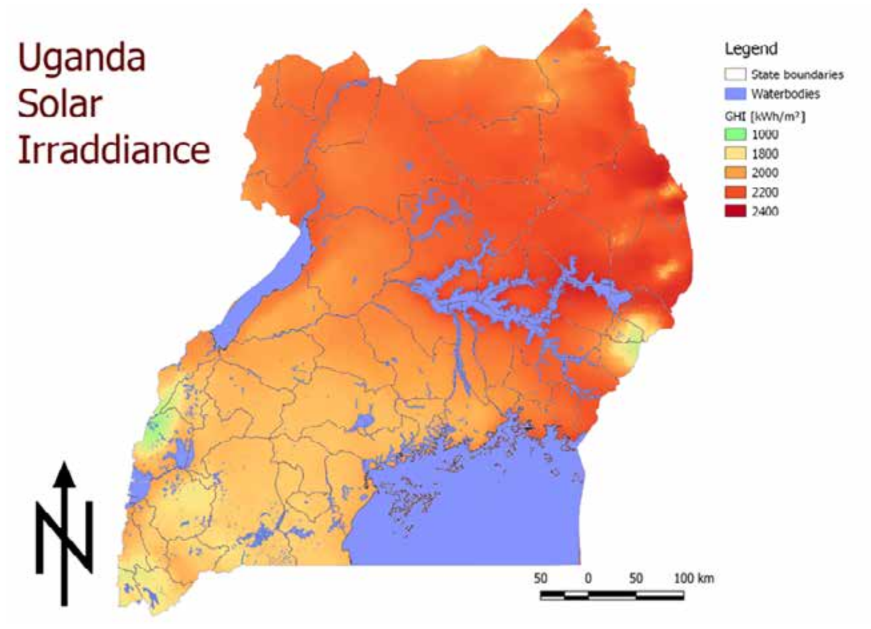


Figure 2-19: Uganda solar irradiance. Data sources: (gadm, 2o22; World Bank Group, 2022a; waterbodies - OpenStreetMap; 2022)

The solar irradiance shows different potential throughout Uganda. There are patches of higher solar irradiance, especially in the East of the country up to almost 2400 kWh/m²/yr. The Landscape in the North is scarcer and the vegetation is not as rich as in the South. Those areas occur naturally as semi-desserts, but oftentimes, this land is heavily influenced by human activities, such as agriculture. Therefore, the potential is higher in the North. Two patches, the Rwenzori Mountain Range in the West and the Elgon Mountain in the East, show values down to near 1000 kWh/m²/yr. Those areas are covered by dense forests.

2.2.4. Wind energy

Wind energy is a RE source that harnesses the power of the wind to generate electricity. Wind turbines are used to capture the kinetic energy of wind and convert it into mechanical energy, which is then used to generate electricity. The main advantage of wind energy is that it is a clean and renewable source of energy that can be used to power homes, businesses, and even entire communities. However, wind energy is dependent on wind patterns, making it less reliable than other sources of energy. Moreover, wind turbines can be visually disruptive to some landscapes.

Average wind speeds in Uganda are around 2-4 m/s (WWF, 2015) making the potential for large-scale wind power investments relatively low. Harnessing enough wind speed would only be possible with advancements in the field of low-speed wind turbines. With a look on Figure 2 20 the only reasonable region where the installation of high-speed wind turbines could be explored would be in the North-East – e.g. the districts of Karenga, Kaabong & Kotido (the Karamoja regions). It has also been suggested that wind speeds on the shores of Lake Victoria could be sufficient for the installation of wind turbines, as wind speeds of up to 6 m/s have been reported (Kamese, 2004). However, small-scale wind energy use could be feasible in other regions of the country.

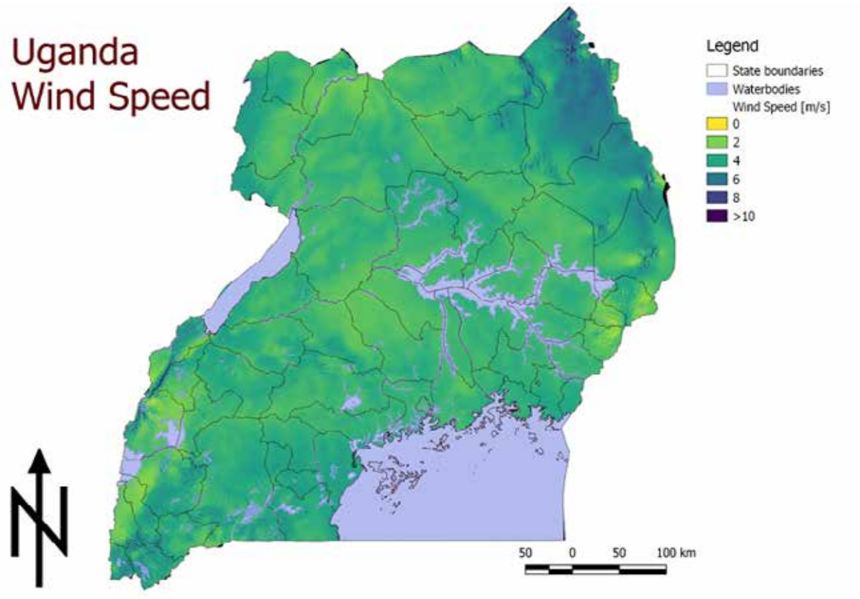


Figure 2-20: Uganda wind speed. Data sources: Wind Speed (GADM, 2022; World Bank Group, 2022b; 'Waterbodies - Openstreetmap', 2022)

The wind speed potential is influenced by the earth's surface, especially mountain ranges and dense vegetation. Areas with the highest wind potential are located in the North East of Uganda, values of 8 m/s in 100m height can be reached. Higher wind speeds, over 10 m/s, can only be measured in small areas high in the mountains. As mentioned above, in the biggest part of the country, the average wind speed is around 2 to 4 m/s.

2.2.5. Geothermal energy

Currently, geothermal water is used in Uganda as a source of salt, and in other places in hot springs as a tourist attraction associated with the cure of some diseases. However, no further application has yet been developed for the use of geothermal energy in Uganda, but some pre-feasibility explorations have been carried out that confirm the availability of this resource in the country. The main areas where potential has been found are located in the Western Rift Valley, on the border between Uganda, the Democratic Republic of Congo and part of Rwanda (Bahati and Natukunda, 2020).

Indeed, the top four prospects in this area are called Katwe, Buranga, Panyimu and Kibiro (Bahati and Natukunda, 2020). In the first three zones, subsurface temperatures have been estimated to be between 110 °C and 150 °C, while in the last one the estimated temperature ranges between 150-250 °C. These temperatures are suitable for a variety of uses, including the power sector, agriculture, industry and as a tourist attraction (Bahati and Natukunda, 2020).

According to the "Uganda Vision 2040", the potential of this resource to be harnessed in the coming years would reach 1,500 MW. However, the government is aware that these figures are subject to feasibility studies (National Planning Authority, 2013) and in the prospective areas, only surface explorations have been carried out and there are still no exploratory wells to quantify the power in MW that can be installed there (Bahati and Natukunda, 2020).

This resource would apparently offer great potential for the region in terms of energy. For Uganda, specifically, it is seen as a complement to its current electricity system, since it is located in the Western part of the country, complementing the hydropower generation in the Eastern part of the country, along the Nile. It has even been estimated that the installation of 150 MW of geothermal power plants could supply electricity to approximately 3 million people in rural areas of western Uganda (Mutumba, Echegu and Adaramola, 2021). Currently, GIDS Consult Limited is carrying out exploration and evaluation activities of the geothermal resource for the construction of a 100 MW power plant in Buranga, one of the four identified prospects (Uganda Investment Authority, no date).

Nevertheless, although Uganda recognizes this resource in its energy policy, there are several barriers and challenges before this technology can be implemented, which is why this study did not consider this technology in the energy mix of the alternative scenarios in comparison to the Uganda Vision 2040. Barriers include high investment costs, both in the exploratory stage and during development and a lack of expertise on the technology in the country, which is necessary for the operation and maintenance of the plants. Further, land conflicts may arise with other activities such as agriculture, people may be affected and have to be relocated, which may generate resistance from the communities, and large-scale projects may affect biodiversity as some of the projects are located in protected areas (Mutumba, Echegu and Adaramola, 2021).

2.2.6. Peat energy

Peat is not exactly a renewable resource (Electricity Regulatory Authority - ERA, 2022), because its extraction rates are not offset by its recovery rates in nature, so it is a finite resource. Nonetheless, it was included in this subsection in order to delve into its availability as an energy resource in Uganda.

It has been estimated theoretically that Uganda has about 250 Mtoe of peat, located in the Western and Southwestern of the country. Considering factors such as its quality

Energy Limited in South-western Uganda and is a pioneer in conducting studies for the use of peat as a source of electricity generation. The project is categorized as being in an advanced stage of its implementation and consists of a 33 MW power plant; it is estimated to cost between US$60 and US$70 million (Uganda Investment Authority, no date).

According to the most recent report on the case published on Electricity Regulation Authority (ERA)'s website (ERA (Electricity Regulatory Authority (ERA), 2022), dated January 2022, the company has submitted an application for a licence to generate and sell electricity from the hybrid project (33 MW peat and 80 MW solar PV). Considering that no further information has been found, it seems that ERA is still evaluating the application. In the BAU pathway it was assumed that 400 MW of peat would be installed in 2030, 800 MW in 2040, and 800 MW in 2050. This study did not consider the development of PEAT energy as an option in the RE pathways due to its sustainability concerns.

2.3. Sustainable usage

2.3.1. Biomass

Biomass is a crucial component for Uganda's sustainable energy transition, but the limitations of how much biomass supply can be considered sustainable needs to be evaluated for a 100% RE study. From approximating the limit of how much sustainable biomass Uganda is able to supply, the remaining current or predicted demand for biomass must find an alternative source of energy supply. For the HighRE80 or FullRE100 scenarios in this study, any demand from biomass that is considered unsustainable is instead fulfilled by the electricity sector. This sub-section provides the results of literature research regarding a sustainable biomass supply for Uganda. It includes the availability of different biomass resources as well as possibilities to reduce the biomass demand.

As already indicated in the status quo of Uganda's energy supply (subsection 2.1), there is a huge non-electricity demand which is almost completely covered by biomass (88% of energy supply is biomass, see Figure 2-1). The challenge therefore lies not only in transforming Uganda's energy supply to 100% RE, but also in transitioning to sustainable biomass usage. Figure 2-21 describes two aspects of sustainable usage of biomass that must be taken into account: the supply and demand of biomass. Opportunities exist on both sides for modifications that will impact the sustainability of biomass. On the supply side, all of these actions would decrease the amount of currently consumed tree biomass, whereas on the demand side all of these actions would decrease the demand for biomass.

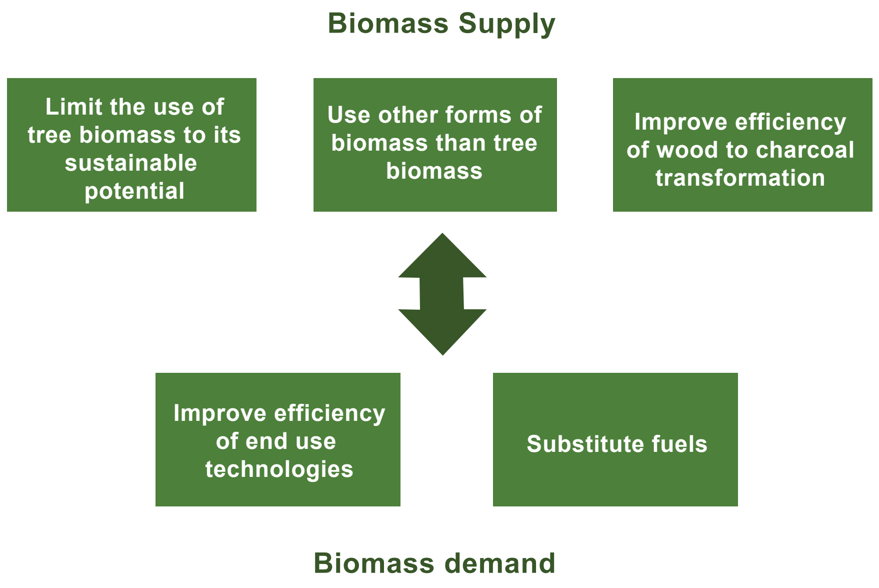


Figure 2-21: Two aspects of a sustainable biomass Use. Data Source: (UBOS, 2022b)

2.3.1.1. Biomass demand

In 2013, Uganda's total energy demand across all end-use sectors amounted to 136 TWh. These sectors can be categorised into the four general sectors: 'households', 'commercial', 'industrial', and 'transport'. Household energy consumption accounted for the largest share, making up 66.2% of the total energy demand, followed by the commercial sector at 14.3%, industry at 12.8%, and the transport sector at approximately 6.2%. However, it is worth noting that a significant portion of household energy usage is attributed to cooking needs. When focusing solely on electricity demand, the industrial sector alone accounts for approximately 60% of the overall supply (WWF, 2015).

Seven out of ten households (73%) used firewood for cooking, while two out of ten used charcoal (21%). Therefore, wood fuel use constituted 94%. The rest splits between electricity and fossil fuels like kerosene, gas and other fuels. The ratio changes when urban and rural areas are considered. In urban areas, the majority (57%) used charcoal compared to 9% in rural areas. There are many reasons for that. Safety may be the most pressing reason. Charcoal is considerably safer in closed buildings or denser cities due to air circulation (UBOS, 2021). Other energy forms of cooking fuels – such as LPG and electricity – are mainly exclusive to high-income groups in the urban areas (WWF, 2015).

The commercial sector mainly represents restaurants, bakeries and other service enterprises whereas the institutional sector represents schools and prisons, etc. When considering all energy consumption across different end-use sectors, firewood and charcoal make up to 98%

of the energy used. A substantial portion of this energy is utilized for cooking, particularly in residential and household sectors (WWF, 2015).

The largest part of the industrial sector is made up of small and medium enterprises (SMEs) that are mostly located in the agricultural segment (WWF, 2015). The industrial sector also relies heavily on biomass – mainly firewood and agricultural residues. Biomass contributes over 80% of energy consumption in the industrial sector. The main fields of use are brick burning, tea drying and lime production. Diesel generators are sometimes used as a stable energy backup or as the main energy source for industries that must rely on constant quality of their electricity supply. Insufficient physical infrastructure and unreliable power supply hinder establishment of industries in some locations. Poor network transmission reliability is often due to the fact that the network is built in a radial rather than a ring network (Tesfamichael et al., 2022).

Energy efficiency is often ignored as a factor when trying to achieve a 100% RE scenario. To achieve 100% RE, it is of course necessary to make the energy supply as green as possible. However, by increasing energy efficiency and enabling a greater number of households or individuals to be supplied with the existing available energy supply, a significant impact can be achieved in terms of access to electricity. Across sectors, the same three end-use technologies are responsible for at least 59% of final energy consumption: lights, refrigerating devices and televisions. Depending on the sector and the location in terms of whether it is in an urban or rural area, the usage within these three areas varies. In on-grid urban and rural sectors, an average of almost 50% electricity can be saved by replacing the outdated technology (Katutsi, Dickson and Migisha, 2020).

A pathway for the transition from traditional to modern fuels for cooking in Uganda was proposed by Katutsi et al. (2020). This pathway is characterized by a progression from fuels with high availability, low cost, and low safety, to fuels with low availability, high cost, and high safety. Firewood, which is widely available and inexpensive, but poses significant safety risks, particularly in enclosed spaces, is considered a traditional fuel. Charcoal and kerosene, which are more widely available and offer improved safety compared to firewood, but are more expensive, are considered transitional fuels. Finally, LPG, biogas, and electric cooking stoves, which have lower availability and higher costs and offer the highest level of safety, are considered modern fuels.

2.3.1.2. Biomass supply

Biomass – especially firewood and charcoal – dominates Uganda's primary energy supply with an overall share of 89%. Biomass counts as a RE resource, but the forest management is not centrally regulated, and unsustainable deforestation is happening across Uganda. Between 1990 and 2010, the forest area lost approximately 47% of its covering. The current demand for wood is estimated around 44 million tons/year whereas the Biomass Energy Strategy Uganda (MEMD, 2015) considers the consumption of up to 26 million tons/year as sustainable. As Uganda lost one quarter of its forest coverage in the period from 2000 to 2020 alone (globalforestwatch.org, no date) and currently has one of the highest annual forest reduction rates in the world (World Bank, 2019), the study suggests a more conservative sustainable biomass limit to protect the remaining forest and its biodiversity, and reduce the negative effect of deforestation on the local and global climate. The substantial difference between wood demand and sustainable biomass limits contributes to the ongoing deforestation, a pressing issue that continues to persist. Accordingly, it is important to limit deforestation, foster restoration, and lower pressure on the forest with a renewable and reliable energy supply.

Due to its high energy density, charcoal is a very popular fuel – especially in urban regions. Its production is estimated at 1.8 million tons/year and is derived inefficiently from around 16 million tons/year of firewood (WWF, 2015). Considering these numbers, it follows that nearly 1/3 of the firewood production goes straight into charcoal processes. The topic of energy efficiency is particularly important in this area, because it allows for a much higher yield of charcoal to be achieved with the same firewood supply (WWF, 2015).

Agricultural and forest wastes are a further source for biomass. The largest share of vegetal waste comes from the forestry industry in the form of tree waste, wood chips, and sawdust. From the agricultural industry, the largest share of waste comes in the form of coffee husks, peanut shells, and rice husks. In 2015, the industrial sector alone consumed 2.4 million tons of plant waste with a total energy content of 39 PJ - tendency increasing. The industrial sector's move towards using plant waste as a thermal energy source instead of fuel oil and wood highlights the need for careful planning and management of biomass procurement. This will ensure a secure and efficient supply while minimizing any potential negative impacts on the environment and nearby communities. Although consumption in other sectors is presently relatively low, this will change as prices in the fossil fuel sector rise. In rural areas, cassava stalks, maize stalks, sorghum stalks, and coffee waste are mainly used (MEMD, 2015).

Cogeneration is used at every sugar industry site in Uganda to produce electricity and heat. Practically, every phase of sugar production (juice extraction, drying, juice purification & evaporation) energy is needed in the form of heat. The by-product of this heat generation is electricity, some of which can be used directly in the plant - for lighting or running electric motors, for example. On average, it can be said that all plants with cogeneration use about 1/3 of the produced electricity internally and supply 2/3 to the national grid. In 2021, a total of 96.2 MW of capacity was installed as cogeneration plants.

2.3.2. Fuels

Along with considering how to transition away from dependence on unsustainable biomass, there is also a need to transition away from fossil fuel dependence in the transport sector for a full RE Ugandan energy supply. The transport sector in Uganda is divided into five subsectors: road, rail, air, inland water and other modes. Most of the vehicles used in Uganda are from Japanese manufacturers and are sold as refurbished vehicles. The mean age of the vehicles purchased by individuals in Uganda is 5 years. The current vehicle fleet is comprised of about 1.4 million vehicles with an advanced average age of 15 years. By far the largest subsector for greenhouse gas generation is road transport with 84% (MEMD, 2015).

The production of biofuels is basically divided into two generations. The first generation of production is based on biomass types that are normally used for food - for example corn, soy or sugar. The second generation of biofuels is based on non-food biomass, such as perennial grass and fast-growing trees (WWF, 2015; Nagler and Gerace, 2020).

In principle, many different feedstocks can be used to produce biofuels. In Africa, sugarcane or molasses to produce ethanol and jatropha for the production of biodiesel receive the most attention. By 2015, there was no large-scale biodiesel or ethanol production in Uganda (WWF, 2015) (Mitchell, 2011). Currently, several industries such as sugar industries are producing biofuels and are in the process of blending.

In 2007, Uganda started commercial production of ethanol from sugar millet with technical support from the International Crops Research Institute. Sugar millet, however, does not grow very widely in Africa, hence, research is still needed to improve the varieties. One of the major challenges with millet is the need for rapid processing. The crop must be processed within a few weeks of harvest and cannot be stored in its harvested state (Mitchell, 2011).

Unlike bioethanol, biodiesel production is based mainly on fats. Used cooking fats, animal fat and vegetable oils are used. If available, algae can also be considered for production. Generally, oil palm trees and soybean are currently grown and used for biodiesel production in Uganda. Although little research has been done so far, the Jatropha plant may also be a good alternative. Compared to the previous two biofuel feedstocks, Jatropha does not compete with the food production and, due to its high resistance, can be cultivated in places where other energy crops would not grow (Scarlat and Dallemand, 2011).

3 | PATHWAY AND SCENARIO DEVELOPMENT

This Chapter focuses on the process of pathway and scenario development. Subsection 3.1 defines the pathways and scenarios that were developed for this study, and subsequently used in the energy system model. In subsection 3.2, the underlying assumptions integrated into the energy system model are described. This includes the assumptions governing the formulation of energy demand and supply for each scenario, as well as the assumptions defining sustainable biomass limitations for each scenario.

3.1. Pathways outlines

The study defined three pathways for the energy transition in Uganda up to 2050:

- Business-as-usual considering government's Nuclear, Peat and Biofuel extension plans and not limiting unsustainable biomass usage (BAU)
- High RE share (80%) and fully sustainable biomass usage until 2050 (HighRE80)
- Full RE share (100%) and fully sustainable biomass usage until 2050 (FullRE100)

Each pathway comprises four distinct scenarios, representing key milestones: the 2019 baseline, and subsequent years in 2030, 2040 and 2050. These scenarios are implemented in the energy model (detailed in section 4) and optimized, based on cost minimization tailored to the specific target years. Each pathway is characterized by unique definitions of capacity extension plans, resource use constraints, and adaptable technologies, all individually tailored to suit their respective objectives. The baseline energy system, which remains consistent across all pathways, includes 112 MW of biomass cogeneration, 92 MW of fuel oil, 1,070 MW of hydropower, and 60 MW of solar PV to meet the national electricity demand (Electricity Regulatory Authority (ERA), 2022). Furthermore, technological consistency is maintained across scenarios by considering the typical operational lifetimes of various technologies. For example, in the 2030 scenario, existing hydropower plants with long lifetimes remain in operation, while unimproved cooking stoves with shorter lifetimes may be replaced as part of the simulation.

3.1.1. Business-as-usual (BAU)

The BAU pathway represents current nuclear energy, peat energy, and biofuel extension plans and unrestricted use of biomass. Nuclear energy capacities are assumed to go on-grid in 2040 with 2.6 GW and 15.6 GW in 2050 (Nhede, 2023). Peat energy is assumed to be developed with a capacity of 400 MW by 2030 and 800 MW by 2040 (Electricity Regulatory Authority (ERA), 2022). Biofuel production is assumed to be extended, growing up to 2 million m^3 in 2030, 3 million m^3 in 2040, and 4 million m^3 in 2050. The use of biomass is not restricted in this pathway. Besides these specs, the energy system is optimized for minimum annual cost to meet the annual energy demand.

same limits as suggested in Uganda BEST were applied. For simplification, the study does not differentiate between thermal energy yield of charcoal produced from fuel wood or direct use of fuel wood, as it assumes that improved stoves balance out energy yield advantages of charcoal (Keita, 1984). Further, the study considers biomass usage exceeding the limits a form of non-RE consumption. This assumption reduces the renewable share in total energy calculations drastically.

3.1.2. High RE share and fully sustainable biomass usage (HighRE80)

The HighRE80 pathway aims to reach a renewable share in energy production of at least 80% and only allows for sustainable biomass usage within the defined limits by 2050. Investments in nuclear, peat energy, and new fuel oil power plants are not restricted. The minimum renewable share is set to 60% in 2030, 70% in 2040, and 80% in 2050. All other biomass use is limited according to the sustainable biomass limits in Table 3 1 in all scenario years. Woody biomass usage is restricted to 30.975 million tons in 2030, 20.65 million tons in 2040, and 10.325 million tons in 2050.

3.1.3. Full RE system and fully sustainable biomassusage (FullRE100)

The FullRE100 pathway aims to reach a fully renewable-based energy system and only allow sustainable biomass usage given the defined limits by 2050. Investments in nuclear, peat energy, and new fuel oil power plants are not allowed in this pathway. Woody biomass usage is restricted to 30.975 million tons in 2030, 20.65 million tons in 2040, and 10.325 million tons in 2050. All other biomass usage is limited according to the sustainable biomass limits as presented in Table 3-1. Further, a successive lowering usage limits for fuel oil and LPG is set out in this pathway. Finally, all fossil fuel resources and technologies are fully phased out by 2050 and replaced with RE based alternatives including PV, CHP plants, battery storages, green H2 storages, electric vehicles, electric cookers, green H2 aircrafts, and improved stoves using sustainable biomass.

3.2. Assumptions used in the energy system model

This subsection summarizes the assumptions taken in modelling the energy transition pathways for Uganda.

3.2.1. Sustainable biomass and renewable share assumptions

Based on the background information, sustainable biomass limits used in this study were set (Table 3 -1). The study set sustainable biomass for tree, bush and papyrus biomass to 25% of the limits estimated by Uganda BEST (MEMD, 2015). For vegetal wastes, biogas, and biofuel, the

Table 3-1: Sustainable biomass limits used in this study (inspired by (MEMD, 2015))

	Limit set sustainable biomass	Sustainable biomass in our study [million tons]
Tree biomass	0.25	6.575
Bush biomass	0.25	2.625
Papyrus biomass	0.25	1.125
Agro processing vegetal waste, bagasse	1	1.4
Agro processing vegetal waste; maize cobs, rice husks, coffee, husks etc.	1	1.2
Grass, forbs	1	1
		[million m^3]
Biogas based on animal	1	1
Biogas based on human waste mainly institutions	1	1
Biofuels e.g. ethanol, bio	1	1.2

3.2.2. Demand assumptions

For each pathway, energy demands are projected based on considerations of population and economic growth. It is important to note that these energy demand projections are consistent across all pathways. This uniformity is possible because effective end-use energy demands are established and forecasted. These effective end-use demands are independent of the specific energy resources employed and the technologies used for conversion, as detailed in subsection 3-1.

3.2.3. Supply assumptions

Within the model, equivalent annual costs for each technology within the energy system were calculated. These costs represent the investment expenses for each technology, computed as annuities. Considering a key message of the African Energy Outlook 2022 (IEA, 2023a), a price drop of PV's equivalent annual costs by 46.4% and wind turbines' equivalent annual costs by 14.4% from baseline to 2030 was assumed. For simplification and due to missing data, all other cost parameters were assumed to be constant until 2050 at investigated levels (Table 7-1). Furthermore, the costs of off-grid and on-grid energy systems were assumed to be equal. Although on-grid systems are typically perceived as more cost-effective, it is important to note that in remote areas of Uganda, the expenses associated with grid connections are significantly high in comparison to household incomes. In such cases, off-grid solutions may present a more cost-efficient alternative. By assuming equivalent costs for on-grid and off-grid systems, the study effectively accounts for the situations where the cost-effectiveness of these options varies.

As a baseline for energy infrastructure, the study considered the installed capacities in 2021 according to ERA (Electricity Regulatory Authority - ERA, 2022), as depicted in Figure 3-1. The installed heat devices in the baseline scenario are depicted in Figure 3-2. Figure 3-3 illustrates installed cooking devices in the baseline scenario 2019.

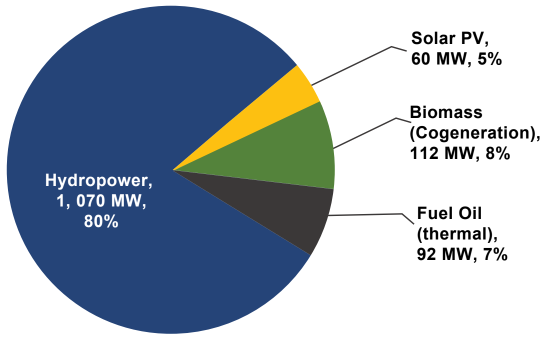


Figure 3-1: -Installed electricity production capacities in MW, 2021 (Electricity Regulatory

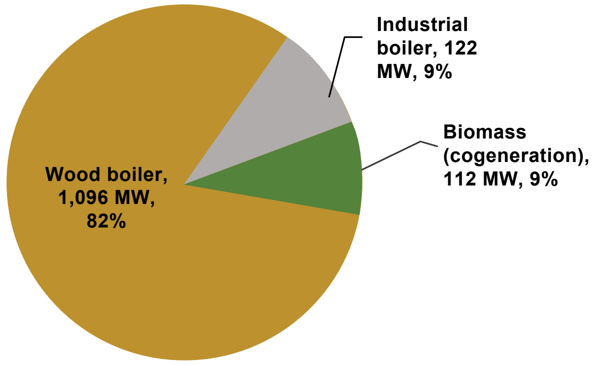


Figure 3-2: Installed industrial heat devices in MW rated power, 2019

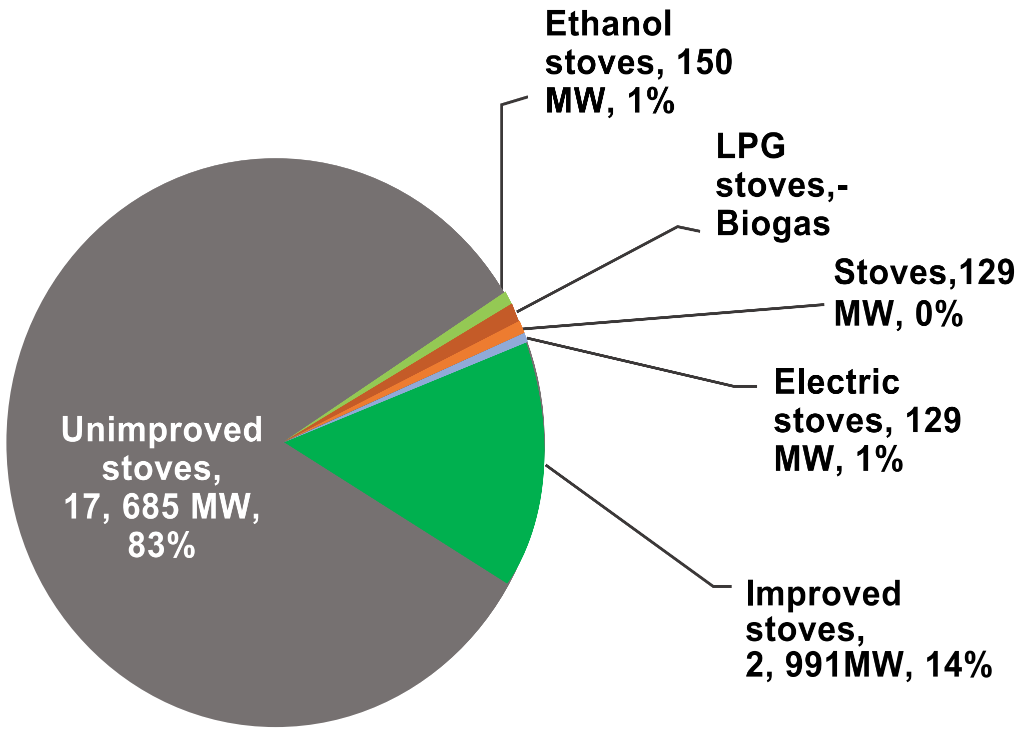


Figure 3- 3: Installed cooking devices in MW rated power (2019)

4 | ENERGY MODEL

The energy model is used to analyse the various pathways for Uganda's energy supply (as outline in section 3). The model comprises two components: the energy demand model and the energy supply model. First, the energy demand model is deployed to project demand growth across sectors for the target years, ultimately calculating the effective end-use energy demand for each scenario. These results are then employed as inputs for the energy supply model. The methods used for the energy demand model are described in subsection 4.1. The energy supply model, as outlined in subsection 4.2, is then applied. The supply model is used to simulate and optimize the allocation of energy resources, conversion technologies, and storage options, all aimed at efficiently fulfilling Uganda's demand, taking any limitations into consideration.

4.1. Energy demand model

In this subsection, an energy demand model for Uganda is developed. In general, energy demand is assumed to be growing in Uganda due to population growth, reduction of poverty and concomitant lifestyle changes, economic growth, and further industrialization. The energy demand is forecasted for the years 2030, 2040, and 2050 applying investigated growth rates. Further demand profiles for electricity, cooking, and transport are presented.

4.1.1. Demand model structure and demand forecast

The demand model was created by applying growth rates taken from the literature to a baseline year. A baseline for the demand model is provided in the Energy Balance 2019 by the Statistical Abstract of Uganda 2019 (UBOS, 2020). 2019 was chosen instead of 2020 to avoid irregularities in the energy demand due to influences of the COVID 19 pandemic that may have influenced the data for 2020. In 2019, the final energy consumption (177 TWh) was predominantly met by biomass (66.8% fuelwood, 6.8% vegetal wastes, 12% charcoal), as can be seen in Figure 4-1. Households were the biggest energy consumers being responsible for 61% of the final energy consumption, followed by Industry (21%); Transport (9%), Commercial &Public Institutions (8%), and Agriculture (1%) (see Figure 4-1).

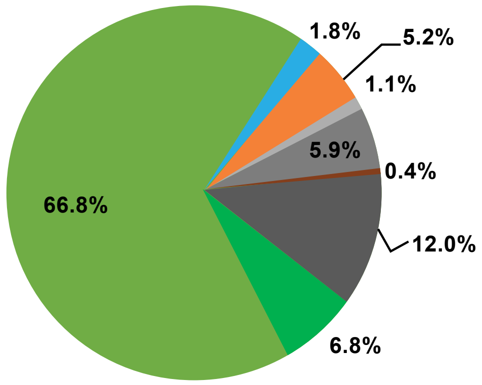


Figure 4-1: Final energy consumption by fuel (2019)

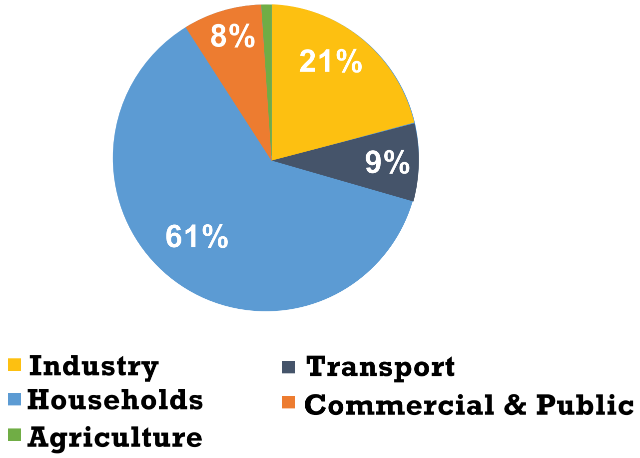


Figure 4-2: Final energy consumption by sector (2019). Data Source: UBOS, 2020

The demand forecasting was based on the annual growth rates by sector (WWF, 2015). Further, a growth rate of electricity demand other than demand of electric mobility and electric cooking was included in the model. Therefore, the electricity demand growth rate assumption of the Ugandan Investment Authority (10%-12% annual growth, UIA, 2022) was used and electricity demand growth which was assumed in electric cooking and electric mobility was subtracted. Table 4-1 shows the assumed growth rates. The growth metrics taken into account are the population growth, the urbanization process and the constant economic growth of the country. A slight annual decrease in annual growth in all sectors was assumed over time, as population growth is expected to slow down and energy efficiency is expected to increase.

Table 4-1: Annual growth rates by sector

	2025	2030	2035	2040	2045	2050	Source
Household	3%	2.6%	2.5%	2.2%	2.0%	1.7%	(WWF,2015)
Commercial	4%	3.4%	3.5%	3.3%	3.3%	2.9%	(WWF,2015)
Industrial	4%	4.6%	4.4%	4.4%	3.9%	3.5%	(WWF,2015)
Transport	7%	6.0%	6.0%	6.0%	6.0%	6.0%	(WWF, 2015)
Transport (Aviation	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	(IATA, 2022)
Electricity (Other)	9.0%	8.0%	7.0%	6.0%	5.0%	4.0%	(UIA, 2022), own assumption

In the supply model, energy demand data that is independent of the energy source was required. This data is referred to as "effective energy end uses". These effective end uses represent the actual usable energy that serves a specific purpose, such as the energy transferred to a cooking pan (thermal energy yield) (Keita, 1984), or the energy used for the motion of a vehicle, excluding conversion losses. To obtain these effective end energy uses, the final energy consumption data from the Energy Balance 2019 (UBOS, 2020) based on different end-use categories (electricity, transportation (air), transportation (boat & road), cooking and industrial heat) was recognized. This was done by considering the sector-wise distribution (industry, commercial, household and transport) of resource use (UBOS, 2020). Subsequently, efficiency factors to each end use based on the technology and fuel used to calculate the effective end-use demand was applied:

$$EEUD_i = \sum_j EUD_j * S_{i,j} * \eta_{i,j} * \delta_{i,j}$$

$EEUD_i = Effective\ demand\ for\ end\ use\ i$
$EUD_{i,j} = End\ use\ demand\ \ for\ fuel\ j\ (from\ the\ Energy\ Balance\ 2019)$
$S_{i,j} = Share\ of\ fuel\ j\ in\ the\ end\ use\ i$
$\eta_{i,j} = Average\ efficiency\ factor\ for\ technology/fuel\ j\ in\ end\ use\ i$
$\delta_{i,j} = Share\ of\ industrial\ heat\ in\ the\ industrial\ sector's\ demand\ for\ fuel\ j.$
$For\ end\ uses\ i\ other\ than\ industrial\ heat, \delta_{i,j} = 1.$

The "effective end-use demand" is independent from its energy origin and serves as an input to the supply model and for the creation of different energy system transformation pathways. The energy demand restructured by end-use for the 2019 baseline year is shown in Figure 4-3. Applying the demand growth rates (see Table 4-1) on the effective end use demand, forecasts, which are displayed in Figure 4-4, showing the projected demand for each target year were generated.

Focusing on the electricity demand, Figure 4-5 illustrates the expected development of per capita electricity demand for non-cooking and non-mobility applications, such as lighting, computers, cooling, and machinery. Notably, the figure excludes electricity demand for cooking and mobility, as these are contingent on Uganda's energy transition choices and potential government policies, such as subsidies for clean cooking technologies and measures to reduce unsustainable biomass use. These demands were factored into the model within the separate cooking and mobility demands.

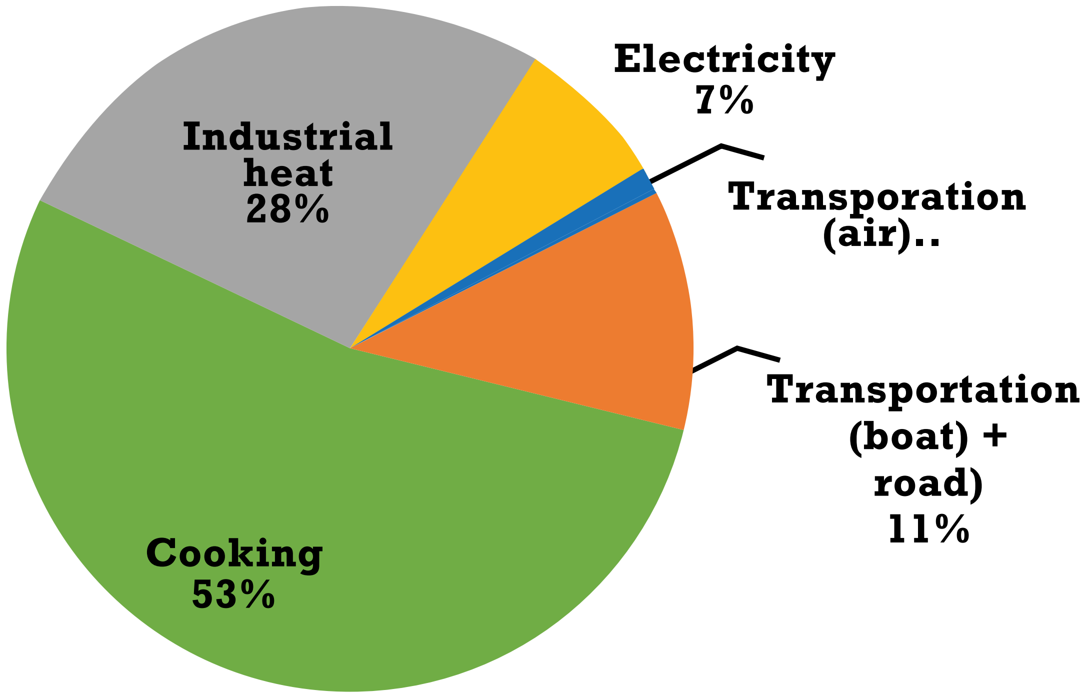


Figure 4-3: Energy demand restructured by End-Use (2019)

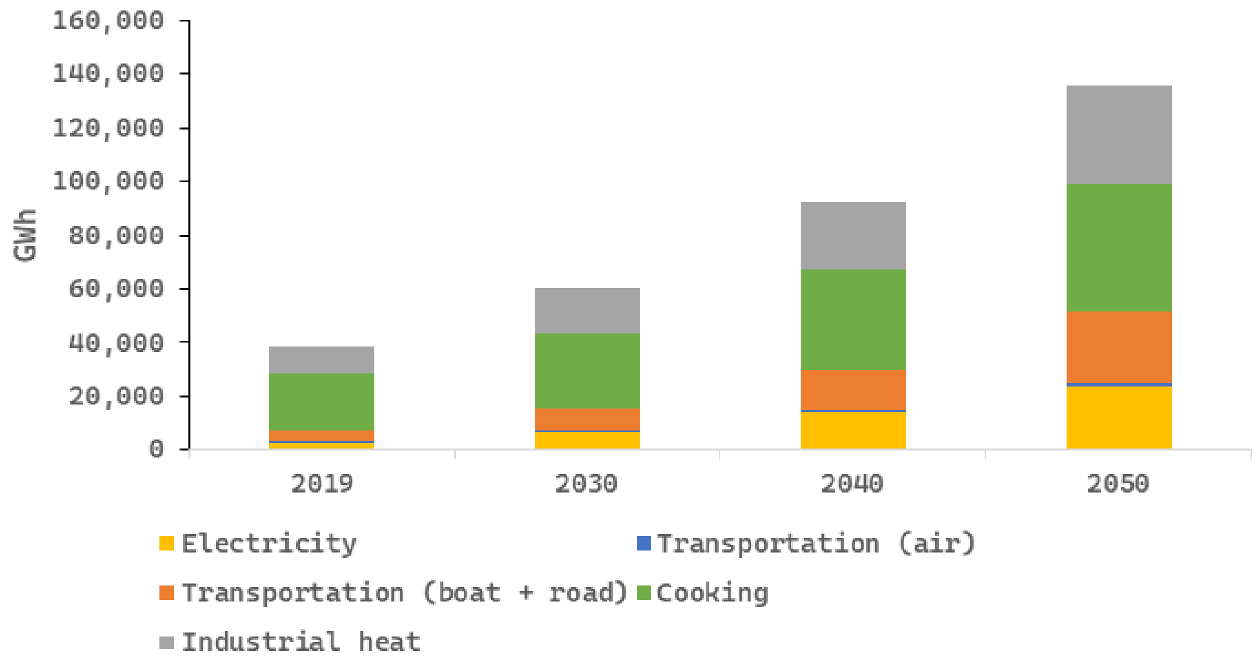


Figure 4-4: Effective energy end-use demand (2019 - 2050)

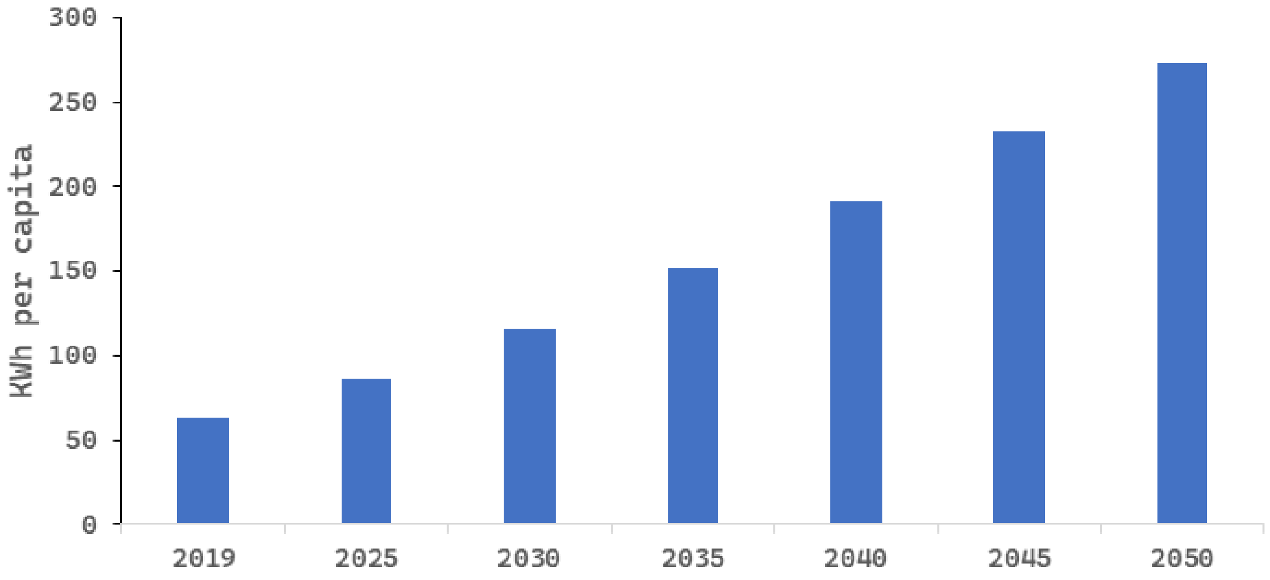


Figure 4-5: Electricity demand per capita excluding electricity demand for mobility and cooking (2019 -2050)

4.1.1.1. Energy demand profiles

As previously mentioned, demand curves reflect energy consumption habits. These habits are influenced by several factors, including the predominant economic activities (i.e., whether it is an economy with greater industrial influence or one in which the residential sector predominates), access to various appliances, and even the application of hourly energy tariffs. The energy model and, consequently, the energy profiles, are designed with a one-hour temporal resolution to account for the daily fluctuations in RE generation and energy demand.

4.1.1.2. Electricity demand profile

The demand profile for electricity was based on the work of Lombardi (Lombardi et al., 2019). The original hourly profile was processed through a probability normalization, where the sum of all the values of the profile was adjusted to equal 1. This means that the values represent a proportion or percentage of the total demand. The model utilizes this sum-normalized profile and the defined total demand (in MWh) for each pathway to generate the actual demand profile, which was used in the model. To visualize the load curve over a day, a peak-normalized profile was employed (where the peak value was scaled to 1), as shown in Figure 4-6.

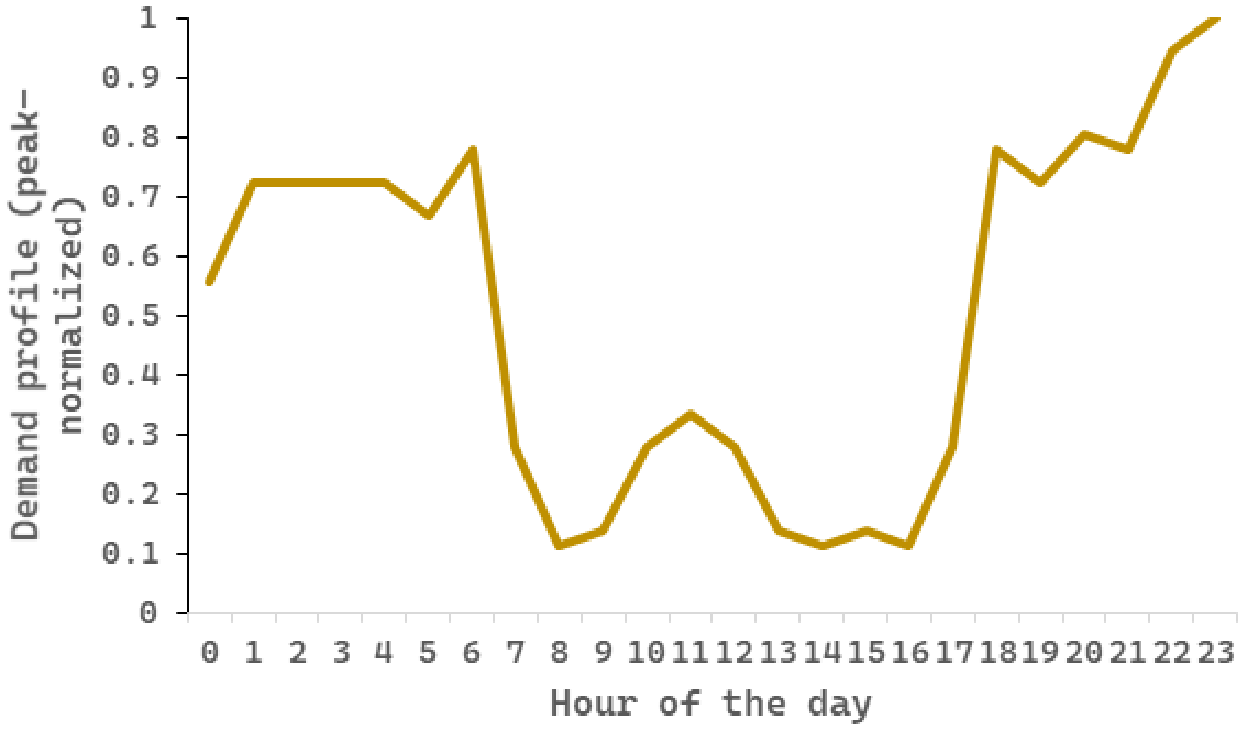


Figure 4-6: Peak-normalized daily electricity demand profile

4.1.1.3. Cooking demand profile

The cooking demand profile was based on the techno-economic analysis of a system in Tanzania powered by renewable sources to provide access to electricity and clean cooking (Lombardi et al., 2019). The study, was able to estimate a cooking profile (from the region) by subtracting the "base load" curve, which includes conventional electricity loads, and the "Full cooking" curve, which represents the behavior when making the transition from traditional biomass cooking to e-cooking, in order to identify the profile corresponding only to e-cooking. Figure 4-7 shows the peak-normalized daily profile where it is clear that there are two important demand peaks: in the morning, around 6:00 am, and in the afternoon, around 5:00 pm.

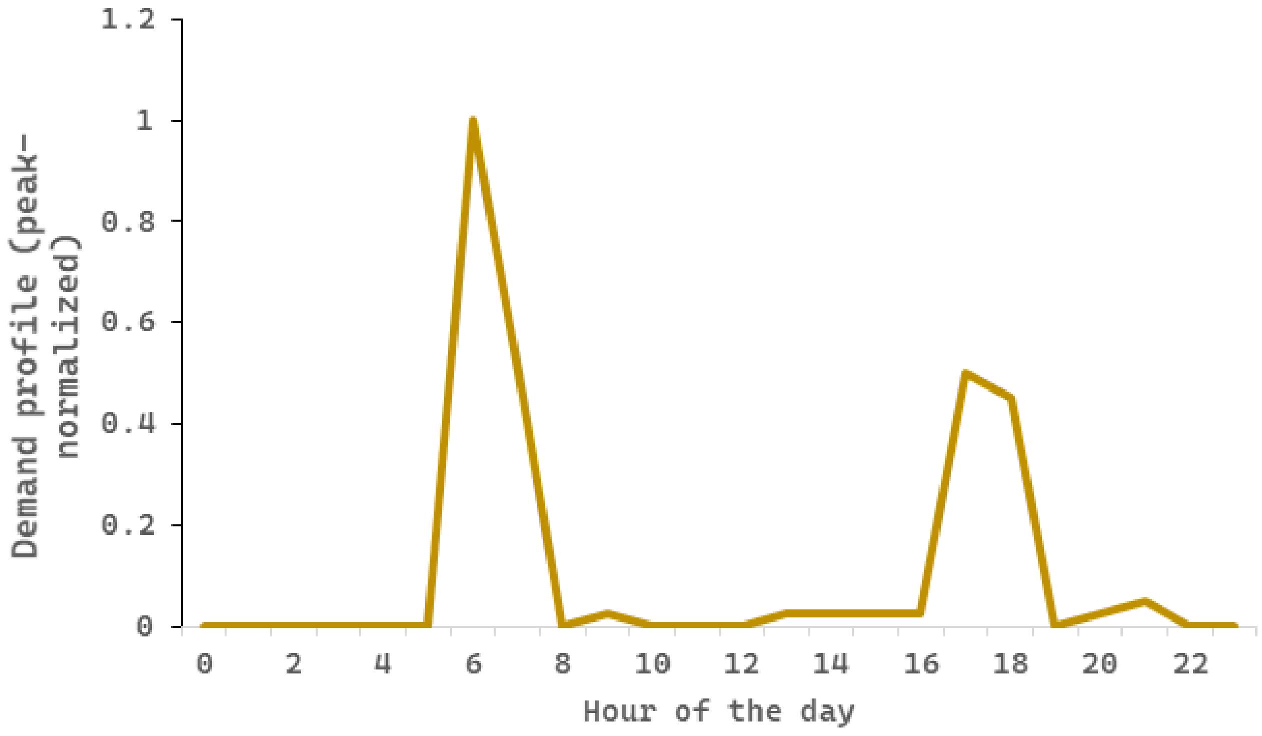


Figure 4-7: Peak-normalized daily e-Cooking demand profile

4.1.1.4. Transport demand profile

The demand profile of electric mobility was retrieved from Prina et al. (2020). The demand profile for fossil-fuel and H2-based mobility was negligible as it was assumed free and infinite storage of petroleum and H2. The e-mobility demand profile (Figure 4-8) shows highest demand at night, typically when people have their vehicle recharging at night and local peaks from 10 to11 am and 1 to 2 pm when many people are working and have their vehicles recharging meanwhile.

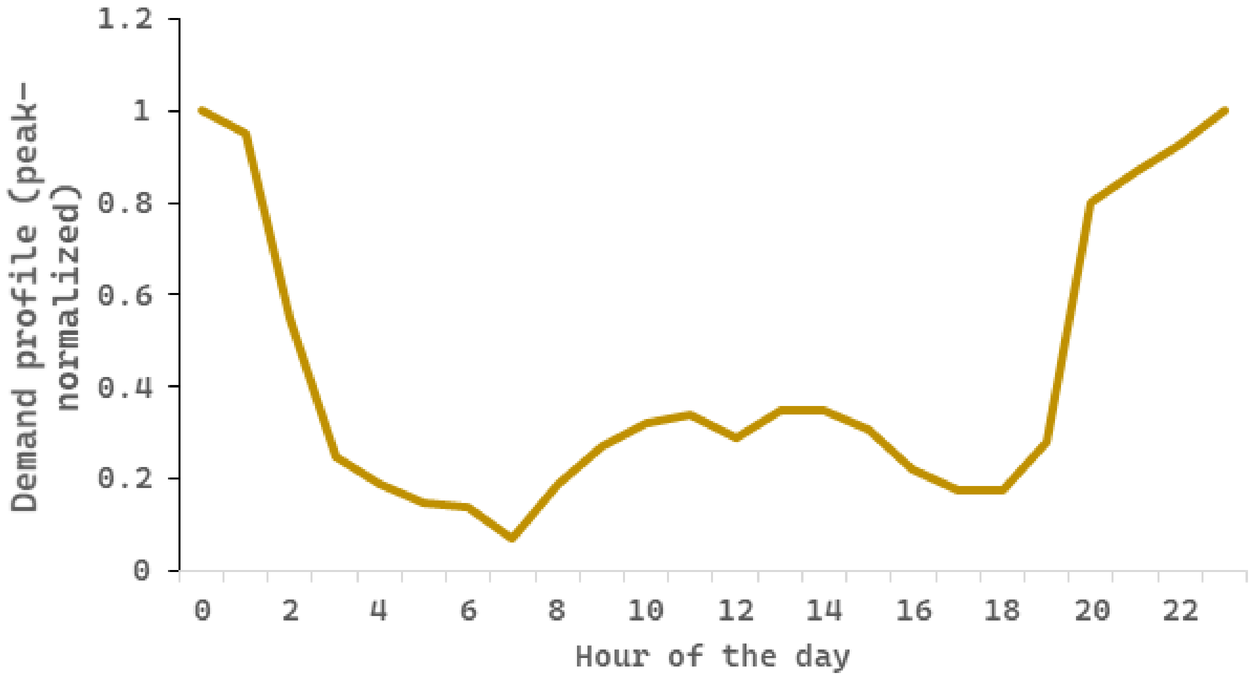


Figure 4 - 8: Peak-normalized daily e-mobility demand profile

4.2. Energy supply model

This section describes the energy supply system model used to simulate and optimize the energy dispatch between different energy sources, conversion technologies, and storage options to meet Uganda's energy demand. It provides information about the model structure, the assumptions, and constraints to optimize the size of different RE sources and the inputs and outputs of the model. The core methodology to develop energy transition pathways for Uganda is an energy supply system model simulating and optimizing various energy resources, conversion technologies and storage system configurations to reduce the total system costs. The energy system model was set up with various supply and storage technologies and their specific costs and technical parameters (Table 7-1).

4.2.1. Model structure and sector coupling

To set up the model of the energy system of Uganda, the oemof framework was used (Hilpert et al., 2018; oemof Documentation, n.d.,). oemof is an open-source software toolbox for energy system modelling and optimization. It is composed of flexible modules to represent the capabilities of various energy system technologies and can be used to create and solve linear optimization problems. Specifically, the study used the oemof-solph package for the energy system modelling and optimization and oemof-tabular for the model structure, which allows csv files as inputs. A least-cost optimization to calculate generation and storage capacities for various scenarios and target years was performed. The simulations were based on linear optimization and hourly time steps (increments of time). The time-step-approach allows, compared to a purely annual accounting approach, the possibility of storing fluctuating energy generation to be mapped in the energy system. The code repository for simulating and optimizing the energy system can be found on github (Dunks et al., 2023).

To create energy system models for the different pathways, a comprehensive superstructure encompassing all potential components of the Ugandan energy systems was constructed (Figure 4-9). The components include resources, energy conversion technologies, energy storage technologies (batteries, and H2 storage), industrial heater, transport vehicles (combustion-engine, H2, electrical), aviation and cooking devices. The fluctuating RE technologies are represented by hydropower, PV and wind energy. They were characterized by their dependence on weather conditions, which directly impacts the amount of electricity they generate. The dispatchable renewable and fossil technologies were represented by biomass cogeneration, fuel oil, geothermal energy, nuclear energy and peat. These technologies are flexible enough to adjust their output to match changes in demand, allowing them to be dispatched to meet the electricity demand. Energy storages were represented by batteries and H2 storage in our model. These technologies help to balance supply and demand, by storing excess energy when it is produced and releasing it when it is needed. This allows for the integration of the fluctuating RE technologies into the energy mix, by smoothing out the variations in output. The H2 storage technology was complemented by electrolyzer and fuel cell to produce H2 and electricity. Finally, energy losses were included in the electricity grid via a further demand component, counting as 25% of the annual demand and having the same demand profile as electricity demand.

4.2.2. Objective function: minimization of energy system cost

To find the most cost-effective combination of energy conversion technologies and storage solutions to meet the energy demand, a linear programming algorithm was employed. The algorithm minimizes the overall energy system cost for target years, while component costs (CAPEX, fixed O&M and variable O&M) were considered as annuities. This approach distributes the investment cost over the operational lifetime of each system component using the capital recovery factor. The explanations and the units of the used cost parameters are stated in Table 4-2. The following equation outlines the objective function applied to minimize energy system cost:

$$min \sum_{i} \left(Capex(i) * CRF(i) + Opex_{fix}(i)\right) * P_{inst}(i) + \sum_{i} \sum_{t} Opex_{var}(i) * E_{gen}(i,t)$$

Whereby the capital recovery factor (CRF) was calculated as follows:

$$CRF(i) = (\mathrm{wacc} * (1 + \mathrm{wacc}) ** \mathrm{n(i)}) \,/\, ((1 + \mathrm{wacc}) ** \mathrm{n(i)} - 1)$$

Table 4-2: Explanation of cost parameters

Cost Parameter	Explanation	Unit
$Capex$	Capital expenditure	[USD/kWp]
CRF	Capital recovery factor	-
$Opex_{fix}$	Fixed operational expenditure	[USD/(kWp*a)]
$Opex_{var}$	Variable operational expenditure	[USD/kWh]
P_{inst}	Capacity of component	[kWp]
E_{gen}	Generated electricity per timestep	[kWh]
i	Index of system components	-
t	Index of time steps	-
$wacc$	Weighted average cost of capital	[USD]
$n(i)$	Operation lifetime of	[a]

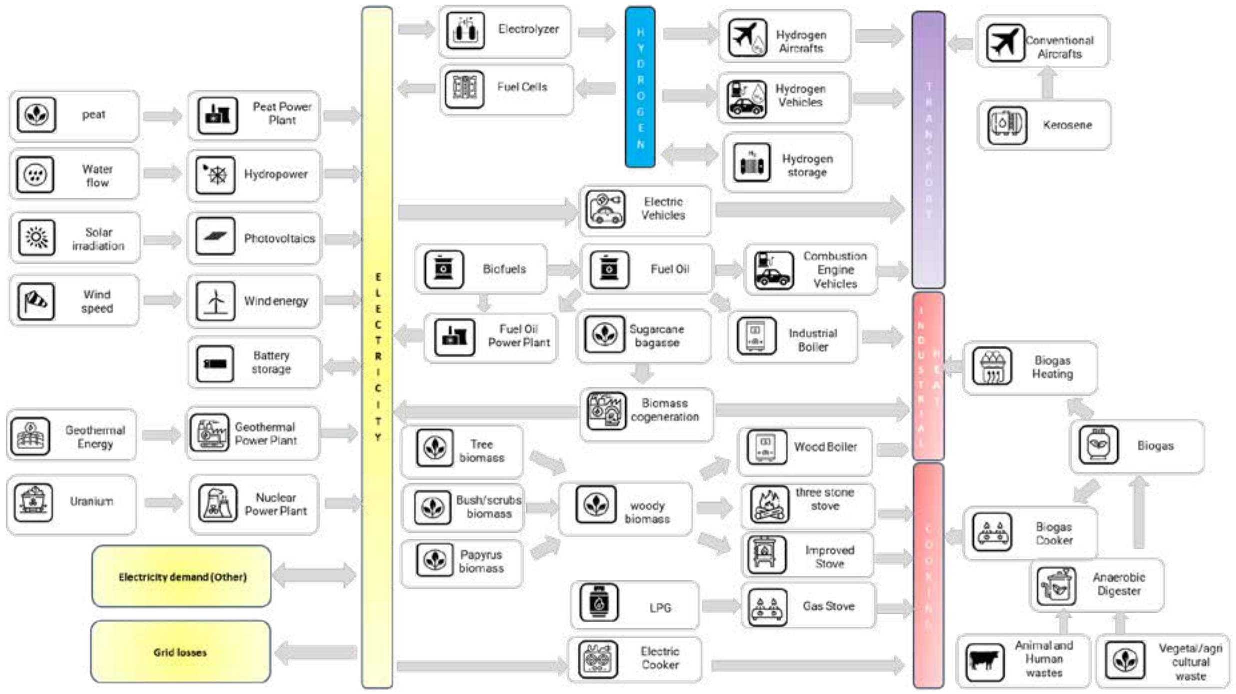


Figure 4-9: Superstructure of energy system models including electricity, H_2, heat, and cooking

4.2.3. Parametrization of the supply model

This subsection describes the data collected to parametrize the supply model. It is divided into several sub-sections, which outline how the annual RE production profiles were generated (to be used as inputs for the energy system model). By using oemof, it is possible to characterize the energy system by components. These components are in turn parametrized to describe the behaviour of the different technologies, enabling the tool to optimize the generation of energy from the different resources that constitute the energy matrix.

Just as there are parameters that can be represented by a specific value under certain assumptions, it is also necessary to consider variations in the patterns of behaviour that other parameters regularly show. The model parameters were represented in two ways:

1) by means of constant values, which depict an average condition or a value within a reasonable and possible range; for example, the efficiency of a conversion technology, capacity expenditure, fixed and variable operation cost

2) by time series, which reflect the fluctuations of the values within the year given by the characteristics of the modelled component or by external factors, such as meteorological conditions.

In order to define the variables that characterize the components associated with dispatchable renewable and fossil technologies, a market analysis was performed to define the typical values of each technology, and if possible, the typical values of technologies in the region. These technologies are energy sources that, with the required fuel, can produce energy according to the needs of the grid or demand. This methodology also applies in the case of storage systems, since typical variables are defined for the equipment that would be available on the market to incorporate these components into the energy system. The techno-economic parameters for each modelled technology including reference are listed in Table 7-1.

Conversely, time series allowed the representation of the fluctuations that occur in renewable resources, which in turn impact the availability and generation of energy. This applies to modelling of hydroelectric, solar and wind power plants. Likewise, the demand curve provides information on energy consumption habits, and therefore it was meaningful to consider its variations on an hourly basis.

4.2.3.1. Hydropower profile

Water resources in Uganda are abundant and widely used for power generation, as mentioned in chapter 2. In order to obtain the hydropower profile, the hydropowerlib library (Hörsch and Chloe, 2019) was used. This tool allowed the estimation of the electrical outputs of hydropower turbines, based on parameters such as turbine and generator efficiency, water density, standard gravity, nominal head of water and water flow.

For this purpose, the online tool Global Flood Monitoring System (GFMS) (University of Maryland, no date) was used to obtain the streamflow [m3/s] in Uganda, specifically at the point with coordinates 0.444887 latitude, 33.18552 longitude. In order to represent the behaviour of the hydropower plants, a location at the beginning of the Nile River was selected, considering that there are hydropower plants located along its course, which account for more than 60% of the total installed capacity and about 76% of the installed capacity of hydropower plants. Additionally, by using this data source, some months were taken as a reference to model the variability of water resources in electricity generation.

The curve obtained was adjusted considering the average monthly discharges from GRDC Data Portal (The Global Runoff Data Centre, no date). This source has measurement stations in different rivers and not only in Uganda. To maintain consistency with the previously selected point, the Owen Reservoir gauging station was selected, for which there are records available for the years 1973 to 1982. Based on the above inputs the water flow that feeds the hydropower turbines, see Figure 4-10, was defined.

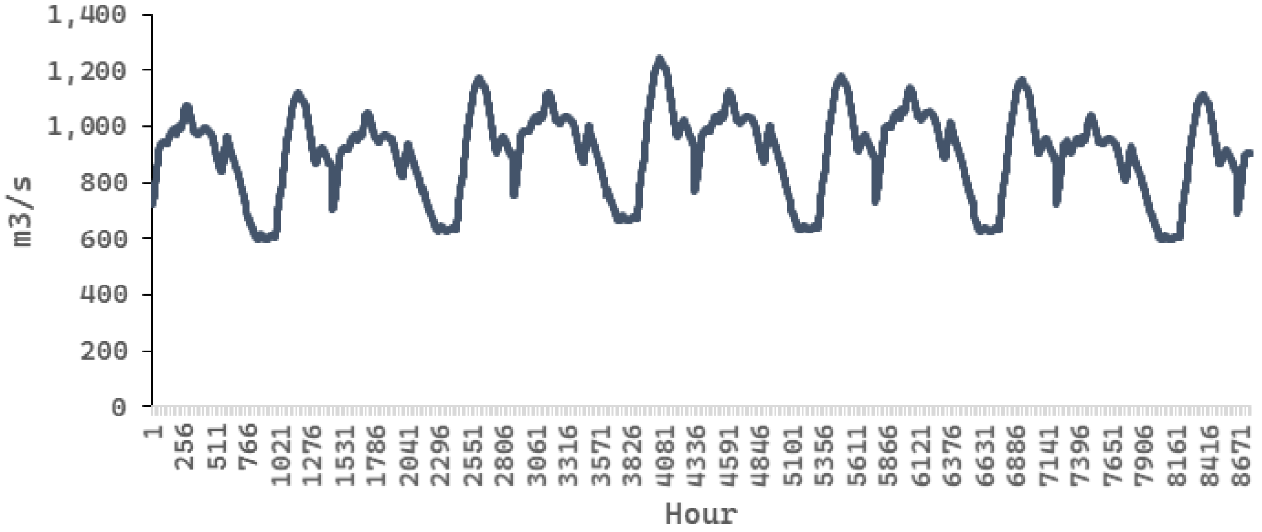


Figure 4-10: Water flow for hydropower analysis

Returning to the calculation with hydropowerlib, having the flow series already defined, it was necessary to define additional parameters to characterize the power generation along the river, such as the turbine type used and the head of water. According to (Katutsi et al., 2021) (Katutsi et al., 2021), the Nalubaale hydropower plant uses Kaplan turbines and the head of water is around 19 meters. With the parameters set, the conditions were ready to run a hydropowerlib simulation. Once the resulting profile had been normalized in relation to the maximum value, it could be included in the model in oemof. The full-load hours for hydropower was 6,700.

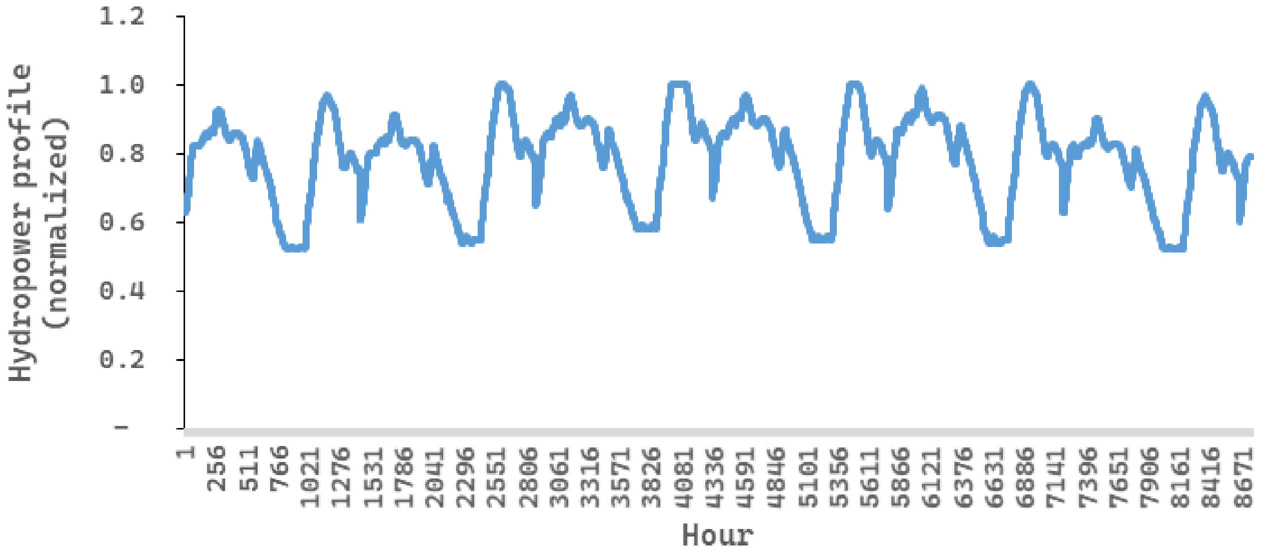
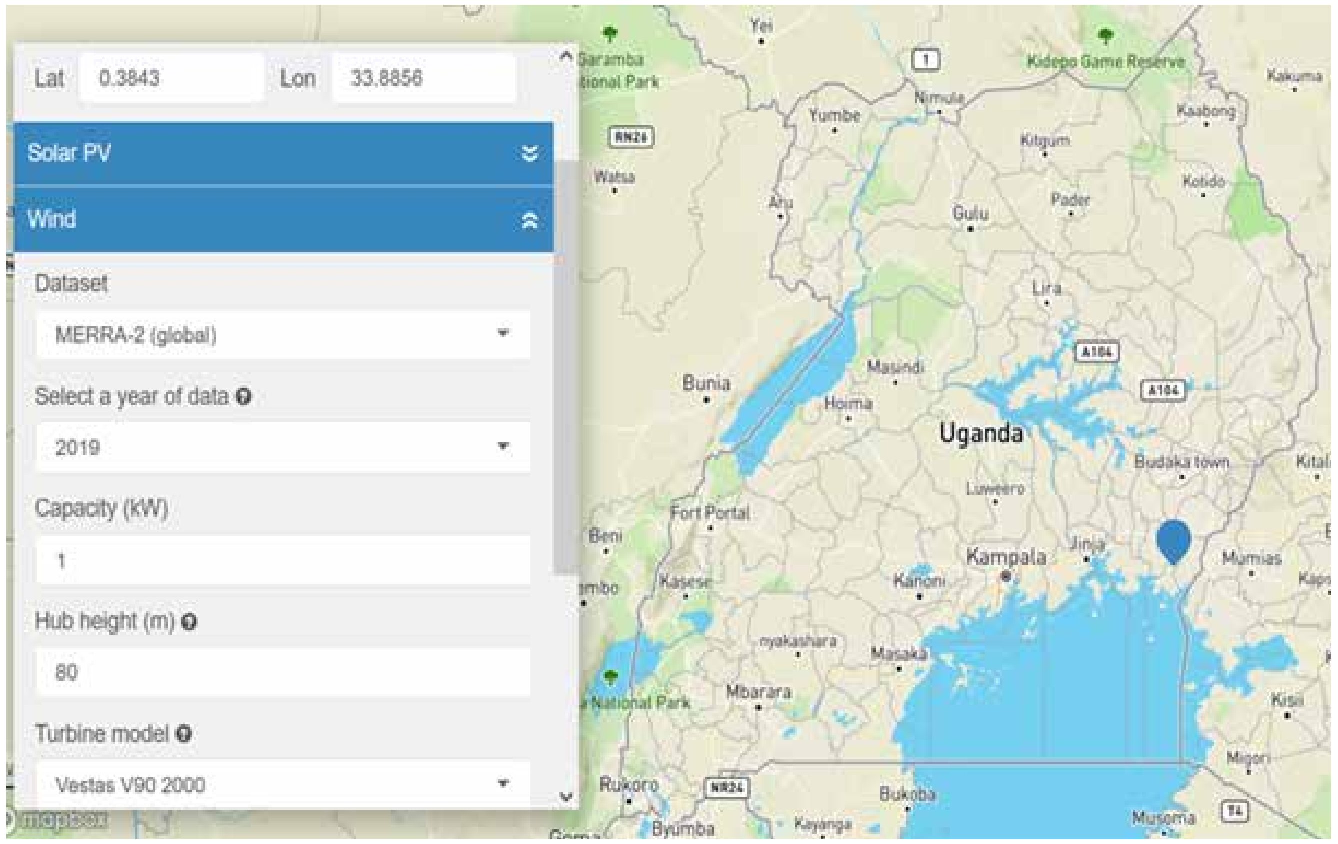


Figure 4 -11: Hourly hydropower profile

4.2.3.2. PV profile

The hourly power generation profile of solar PV sources was obtained from the online tool "Renewables.ninja". This source takes weather information, in this case specifically solar irradiance, and converts it into power output with help of the GSEE model (Global Solar Energy Estimator) (Pfenninger and Staffell, 2016).

The site with coordinates 1.9591 latitude, 34.4855 longitude was selected as a representative point (see Figure 4-12). As can be seen from the map in Figure 2 19 (solar irradiance) in section 2.2.3, the north-eastern part of Uganda has promising areas for the installation of PV systems.



Lat 0.3843 Lon 33.8856

Solar PV

Wind

Dataset: MERRA-2 (global)

Select a year of data: 2019

Capacity (kW): 1

Hub height (m): 80

Turbine model: Vestas V90 2000

Figure 4-12: Reference point for the PV system profile. Data source: Stefan pfenninger and Iain staffell, n.d

To obtain the profile, the chosen dataset is MERRA-2, since it contains available information in the area of analysis for the year 2019. The parameters Tilt (35°) and Azimuth (180°, southwards facing because the latitude is greater than zero) was set up with their default values. As a result, the output profile obtained (kW) corresponds to a 1 kW PV system with losses of 10%. Furthermore, the full-load hours for this zone were 1,600.

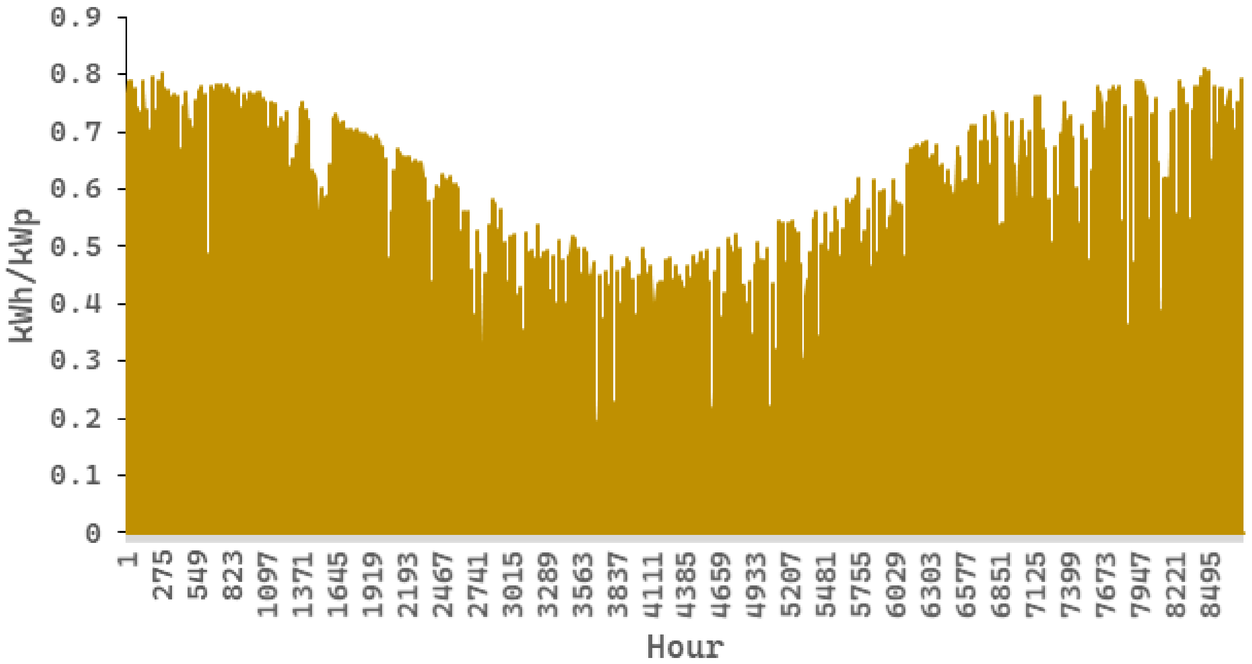


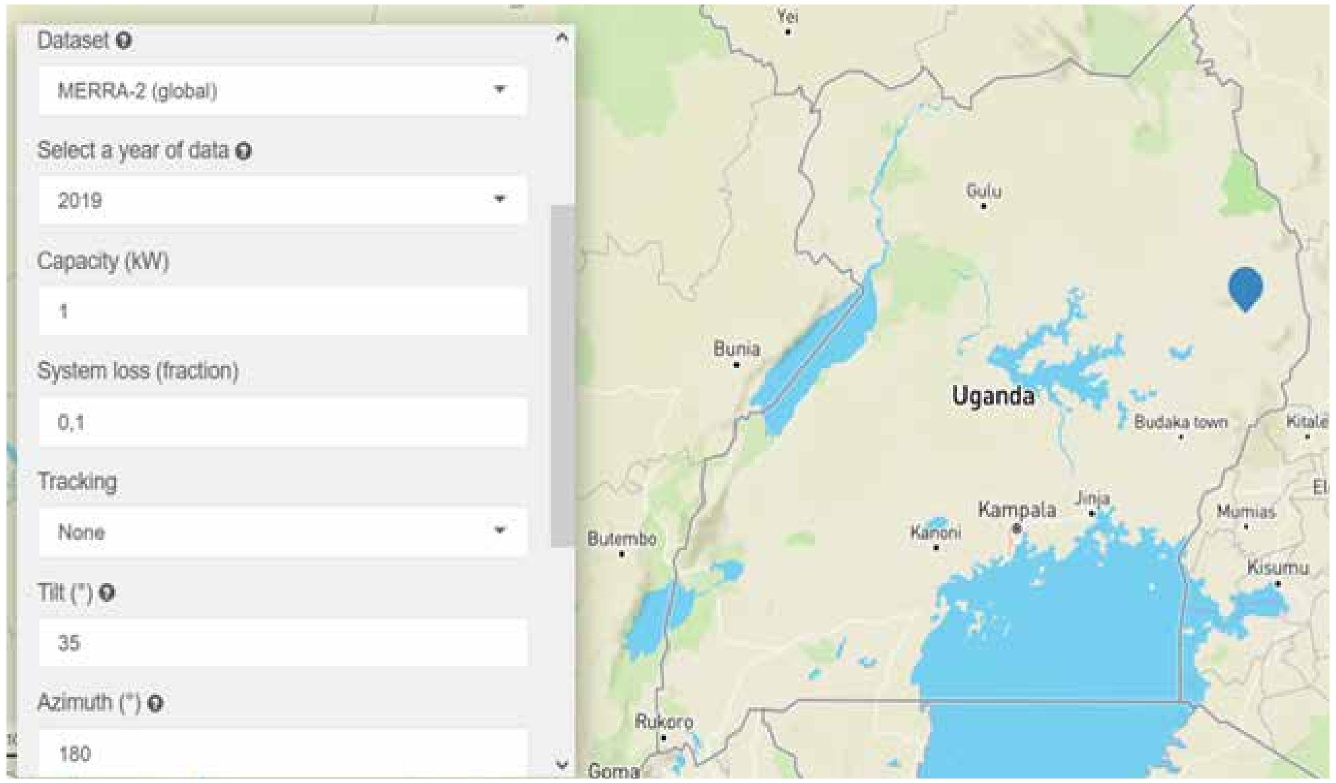
Figure 4-13: Hourly solar PV generation profile. Data source: Stefan Pfenninger and Iain staffell, n.d.

4.2.3.3. Wind energy profile

The wind turbine power generation profile was also obtained from Renewables.ninja. For this technology, the wind speeds from MERRA-2 (Gelaro et al., 2017) for the year 2019 was transformed into power output using some manufacturers' power curves, with the Virtual Wind Farm (VWF) model (Staffell and Pfenninger, 2016).

As mentioned in section 2.2.4, the wind speed distribution in Uganda is relatively uniform throughout the country and for large-scale uses, it would seem to have low potential; on average the wind speed fluctuates around 2 m/s to 4m/s. A point that describes the average wind potential in the country was selected.

For this analysis, 0.3843 latitude and 33.8856 longitude was used as a reference point (see Figure 4-14). According to Figure 2-20 in section 2.2.4, this zone is at the average level of wind speeds in the country. Additionally, its geographic proximity to Lake Victoria could favour the presence of higher wind speeds (Wabukala et al., 2021). In this same region, in eastern Uganda, the potential for the development of wind projects was considered. In 2016, a 20 MW pilot project was planned to be developed by MSS XSABO Power, but could not be carried out due to problems associated with a licence to construct, own and operate the power plant (Wabukala et al., 2021).



Dataset: MERRA-2 (global)
Select a year of data: 2019
Capacity (kW): 1
System loss (fraction): 0,1
Tracking: None
Tilt (°): 35
Azimuth (°): 180

Figure 4-14: Reference point for the Wind Turbines Profile. Data Source: Stefan Pfenninger and Iain Staffell, n.d.

As additional parameters to obtain the profile, default values were assigned in the case of hub height (80 m) and turbine model (Vestas V90 2000), capable of operating at a rated power of 2 MW and a minimum height of 80 m (Vestas, n.d.). The corresponding profile is shown in Figure 4-15. Moreover, the full-load hours in this case were 600.

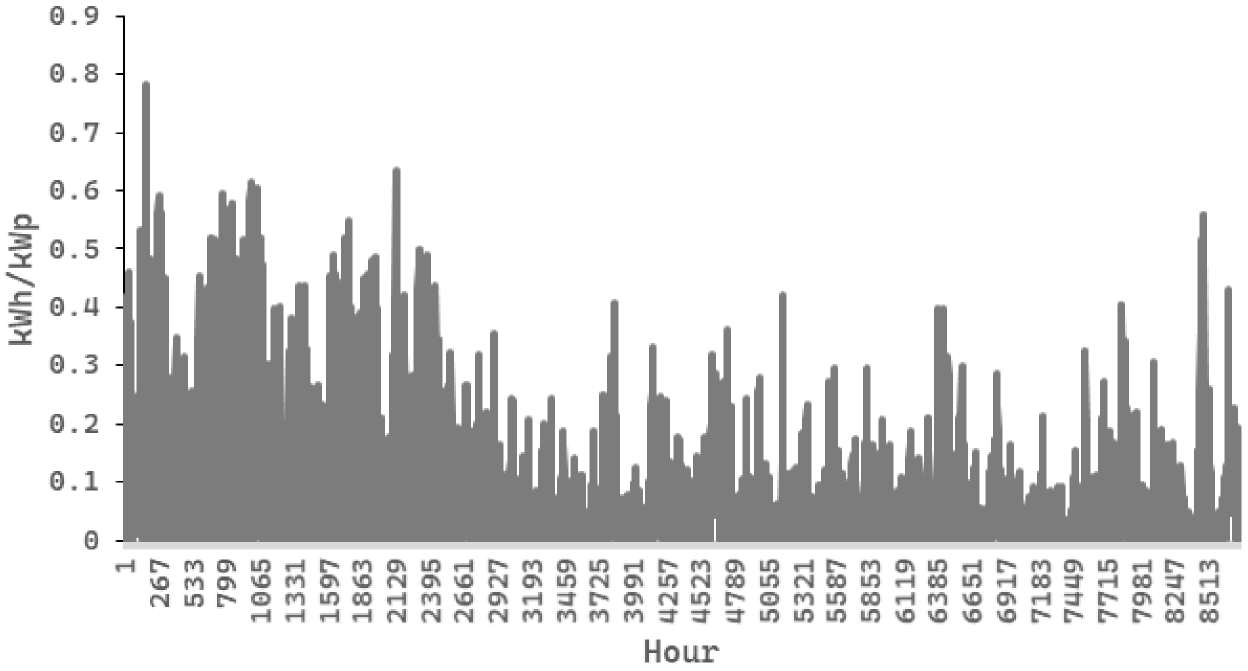


Figure 4-15: Hourly wind power generation profile. Data source: Stefan Pfenninger and Iain

5 | RESULTS

This chapter presents results on:

- installed capacities of each technology included in the energy system (the already existing capacities and the additional optimal capacities that are yet to be installed)
- energy production and flows between the technologies at each timestep, and the electricity deficit if the supply is insufficient to meet the energy demand.
- LCOE and upfront investment costs
- renewable share of the energy supply

The results from each scenario are presented and compared in section 5.1. Next, in section 5.2, a sensitivity analysis was deployed on two key cost parameters for RE transitions: PV panels and batteries. Additionally, the CO2 emissions reduction potential was calculated post-simulation based on the results of the energy system model for each working scenario, using the direct emissions of each technology in the energy system – these results are presented in section 5.3.

5.1. Installed capacities and system costs

The following subsection shows the results of the three pathways (BAU, HighRE80, FullRE100) for the target years 2030, 2040 and 2050 from the optimization, compared to the baseline scenario (scheduled to the year 2019 for demand and 2021 for installed capacity). The optimization results provided the optimal additional capacities required to fulfil the electricity, transport, cooking, and industrial heat demand, as well as the optimal dispatch for each technology in the energy system.

5.1.1. Electricity and H2

Figure 5-1 and Figure 5-2 show the total installed capacities (existing plus optimized) of the electricity production units and the storage for each pathway and target year, respectively. In BAU capacity extensions are comparably low, with nuclear taking the main share of installed capacity and generated electricity in 2050. In HighRE80, electricity supply is realized via PV panels, battery storage, hydropower, geothermal energy, and biomass cogeneration systems. In FullRE100, PV capacity combined with batteries and (from 2050 on) H2 storages and H2 electrolysers are massively expanded. The electricity production is complemented with hydropower and CHP plants. Figure 5-3 shows the corresponding electricity generation of all pathways.

Figure 5 4 shows the LCOE for the defined pathways across various target years. In 2030, a promising trend with consistently low LCOE values for all pathways, indicating an initial period of cost-efficiency was observed. However, in the later target years where demand growth rates were considered, distinct patterns emerged. In 2040, the BAU pathway becomes more expensive than the renewable pathways, as a result of developments in nuclear and peat power plants. By 2050, the landscape further evolves. Due to large developments in nuclear, the BAU scenario is 255% more expensive than the HighRE80 pathway.

The FullRE100 pathway becomes 41% more expensive than the HighRE80 pathway in 2050. This is because from being fully renewable necessitates larger capacities and storage solutions to meet demands during periods of high demand but low electricity production. This requirement leads to the oversizing of capacities, contributing to the higher LCOE in 2050 for this pathway. In contrast, the HighRE80 pathway consistently demonstrates cost-effectiveness, offering a compelling energy supply system throughout the examined years.

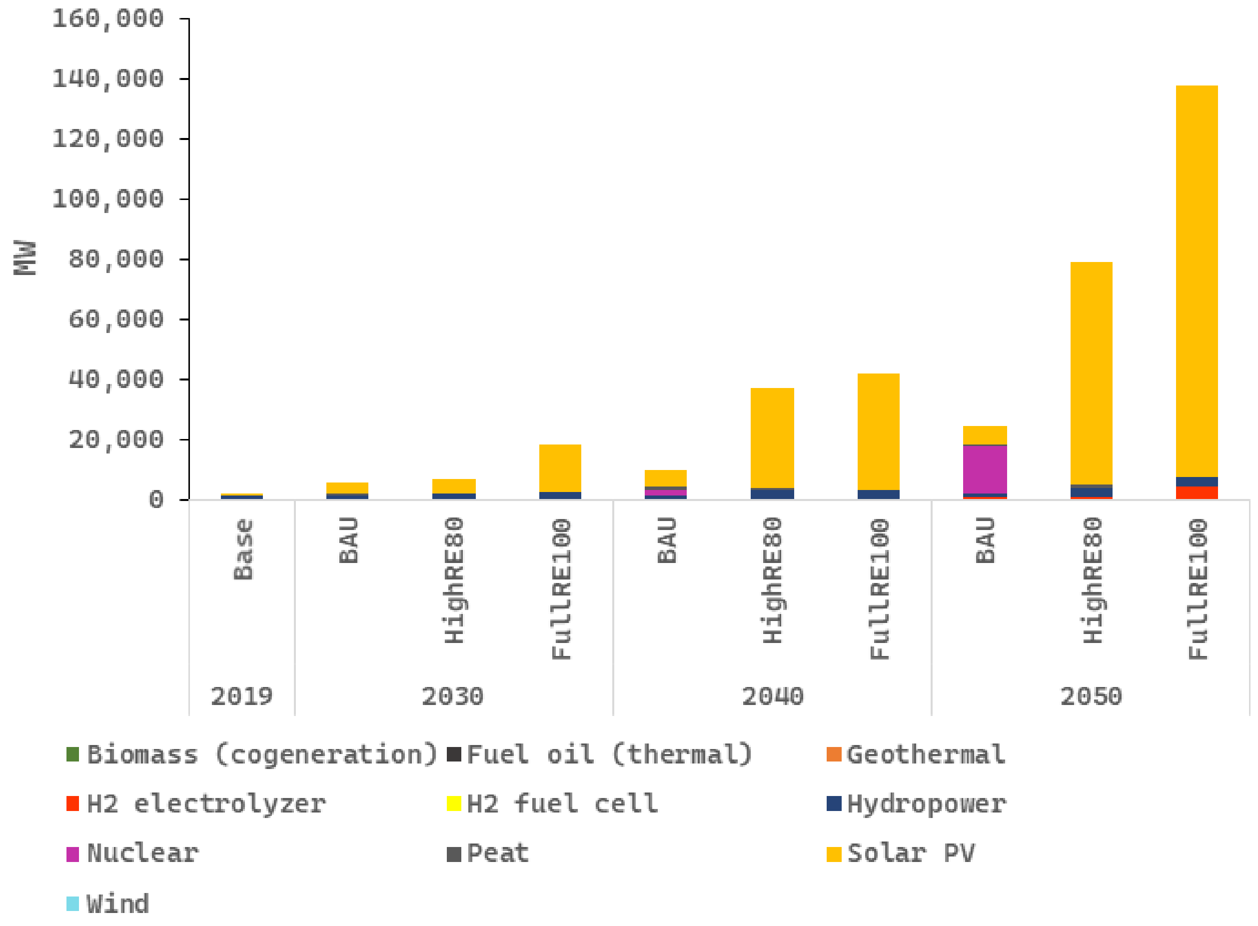


Figure 5-1: Installed power production capacities in the different pathways

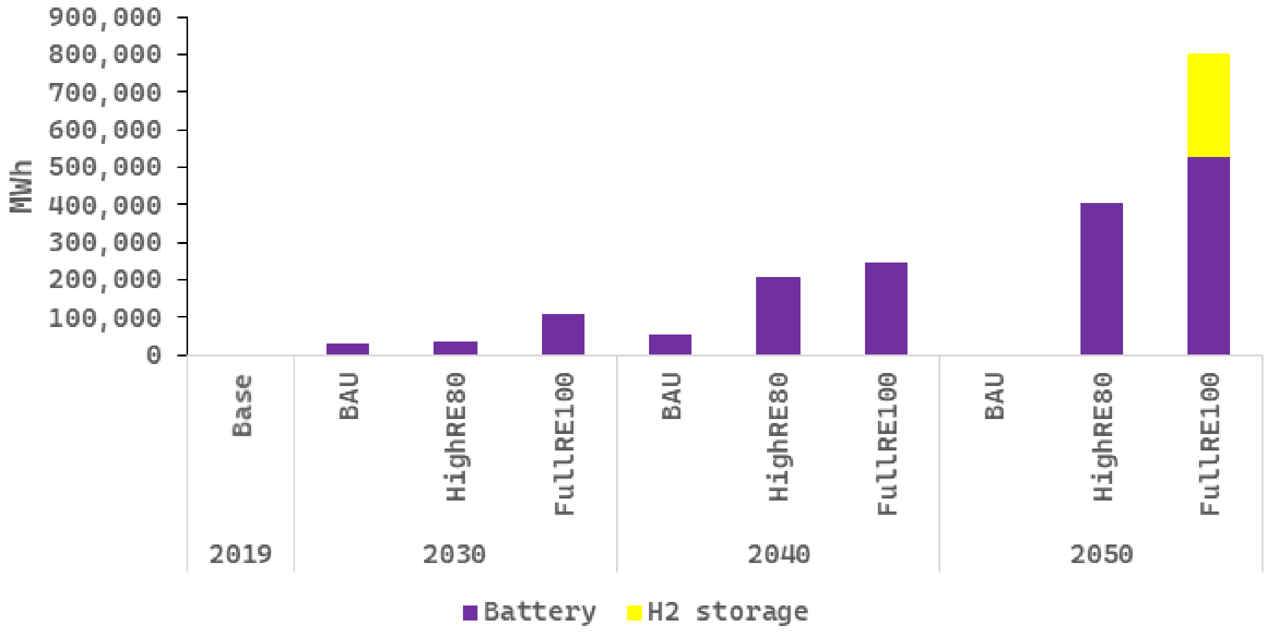


Figure 5-2: Installed storages in the different Scenarios

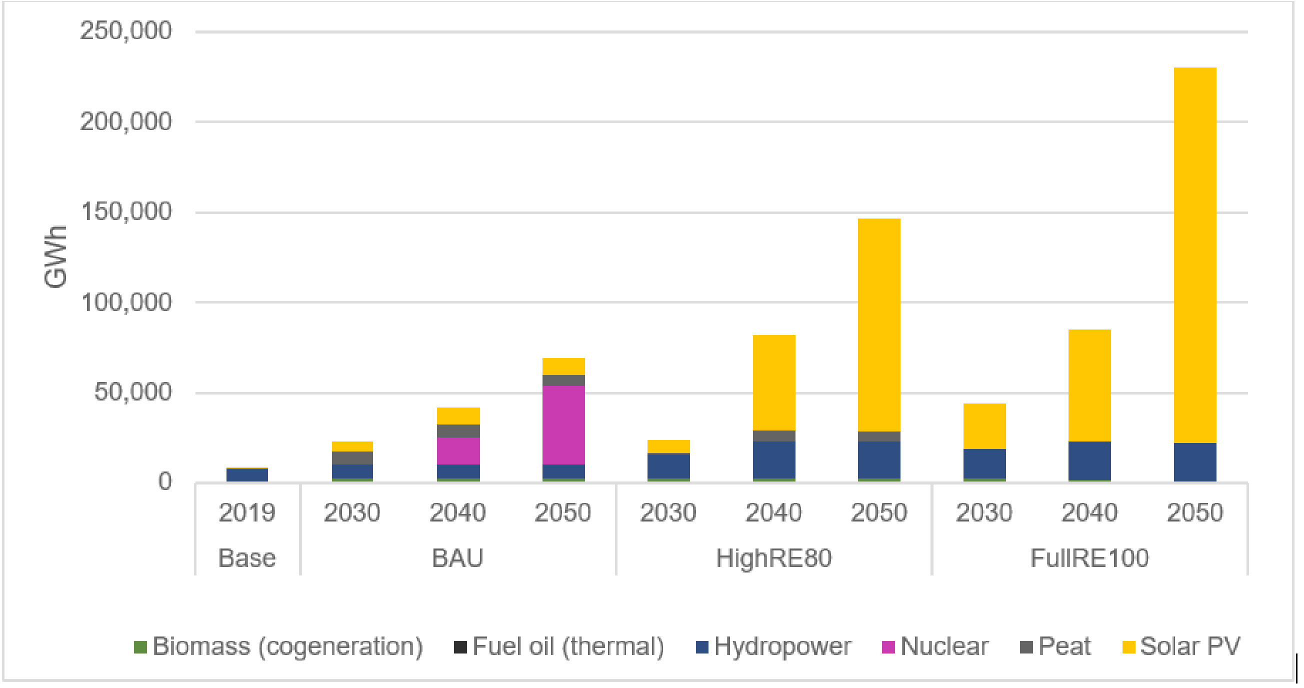


Figure 5-3: Electricity generation for each pathway and target year

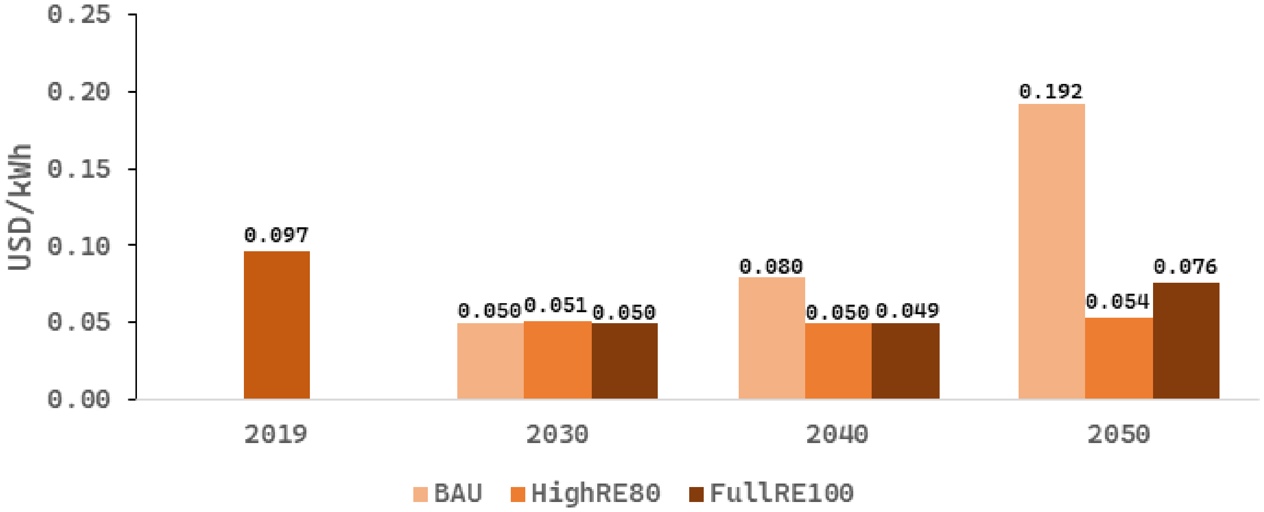


Figure 5-4: LCOE for the defined pathways and target years

5.1.2. Industrial heat devices

Figure 5 -5 provides an insightful overview of the industrial heat sector's evolution within the specific pathways and target years. After examining the pathways for the target years 2030 and 2040, a consistent selection of capacities for key components such as biogas heating, biomass cogeneration, and wood boilers was noticed. These pathways exhibit similarity in their approach to meet industrial heat requirements during these years. However, the divergence becomes evident in 2050 when there is a significant increase in heat demand. In the HighRE80 pathway, a dynamic strategy was employed to address this increased demand. Here, a combination of industrial boilers and H2 boilers was selected to effectively cover the additional heat demand.

Conversely, the FullRE100 scenario adheres to a stringent sustainability approach. With a strict prohibition on unsustainable biomass usage and a commitment to exclusively utilize renewable resources, this pathway opts for reduced wood boiler capacities. To meet the additional heat demand in 2050, the FullRE100 scenario relies on H2 boilers, aligning with its sustainability principles.

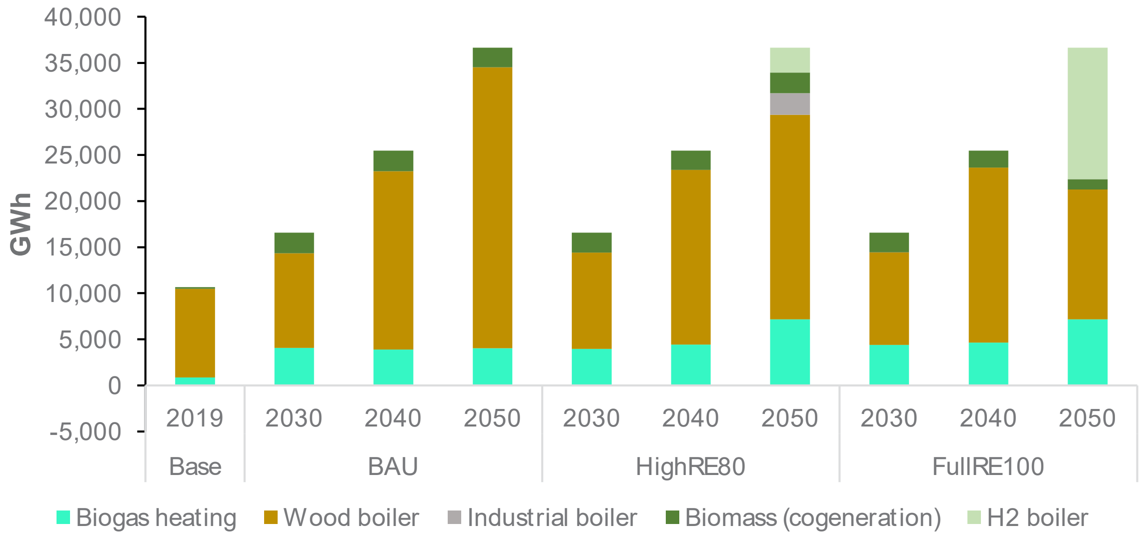


Figure 5-5: Energy consumption by industrial heat supply devices in the demand pathways and target Years

5.1.3. Cooking devices

Figure 5-6 shows the development of the cooking sector in the specific pathways and target years. Across all pathways, a consistent trend emerges – the replacement of unimproved cooking stoves with improved cooking stoves and electric stoves. This transition serves two primary objectives: cost reduction and improved efficiency of cooking appliances.

In the BAU scenario, biomass cooking remains dominant, particularly within improved stoves, supplemented by modest proportions of LPG and electric stoves. LPG stoves serve as transitional solutions in 2030 and 2040 for both the HighRE80 and FullRE100 pathways. By 2050, the HighRE80 scenario relies only on LPG and electric stoves. In the FullRE100 scenario, however, only electric stoves are chosen due to the sustainability limitations on unsustainable biomass usage and restrictions of LPG usage.

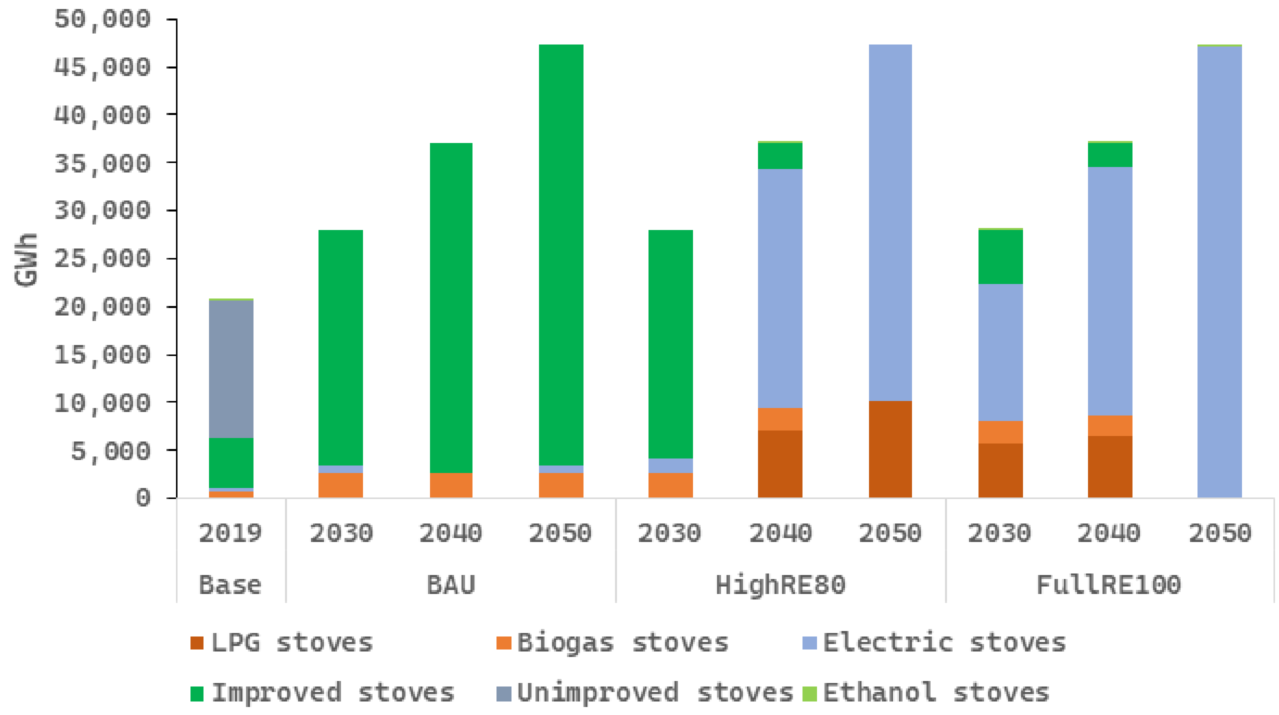


Figure 5-6: Energy consumption by cooking devices in the defined pathways and target years

5.1.4. Transport fleet

Figure 5-7 shows the distinct trends exhibited by the transport fleet for the defined pathways and target years. All pathways transition from combustion engine vehicles to electric vehicles in 2030 due to high fuel oil prices. While biofuel vehicles are deployed until 2040 in BAU, and until 2030 in HighRE due to their relatively low cost, they are also introduced in the FullRE100 2050 scenario to cost-efficiently meet the full renewable energy goals. In the BAU and FullRE100 pathways, there is a shift from kerosene aircrafts to green H2 aircrafts in 2050, attributed to high kerosene prices and the availability of low-cost green H2 resulting from excess, reliable nuclear energy (BAU) or the 100% renewable goal (FullRE100), respectively. However, the HighRE80 pathway continues to use kerosene, as green H2 production prices remain relatively high due to less reliable electricity sources.

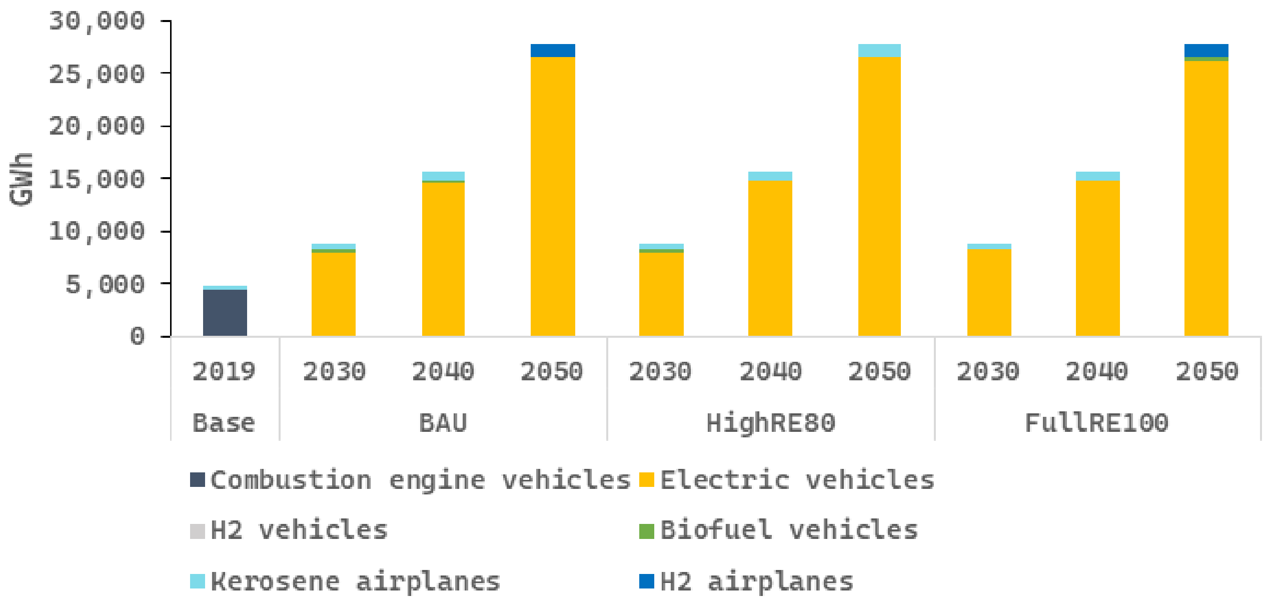


Figure 5-7: Energy consumption of transport fleet in the defined pathways and target years

5.1.5. Renewable share of overall energy system

After considering large parts of current biomass usage as unsustainable and thus non-renewable, the renewable share of the total energy system in 2019 is 36%. In BAU, the renewable share rises until 2030, largely attributed to the affordability of PV panels and a relative reduction of biomass consumption due to the adoption of improved stoves. However, the BAU scenario witnesses a decline in renewables shares by 2040 and 2050 (Figure 5-8), primarily due to the introduction of nuclear energy and the ongoing unrestricted use of unsustainable biomass. HighRE80 and FulLRE100 increase their renewable share according to the defined trajectory. This increase is achieved through the deployment of large PV and storage capacities, as well as using electricity and green H2 to replace unsustainable biomass use and fossil fuels in the transport, heat, and cooking sector.

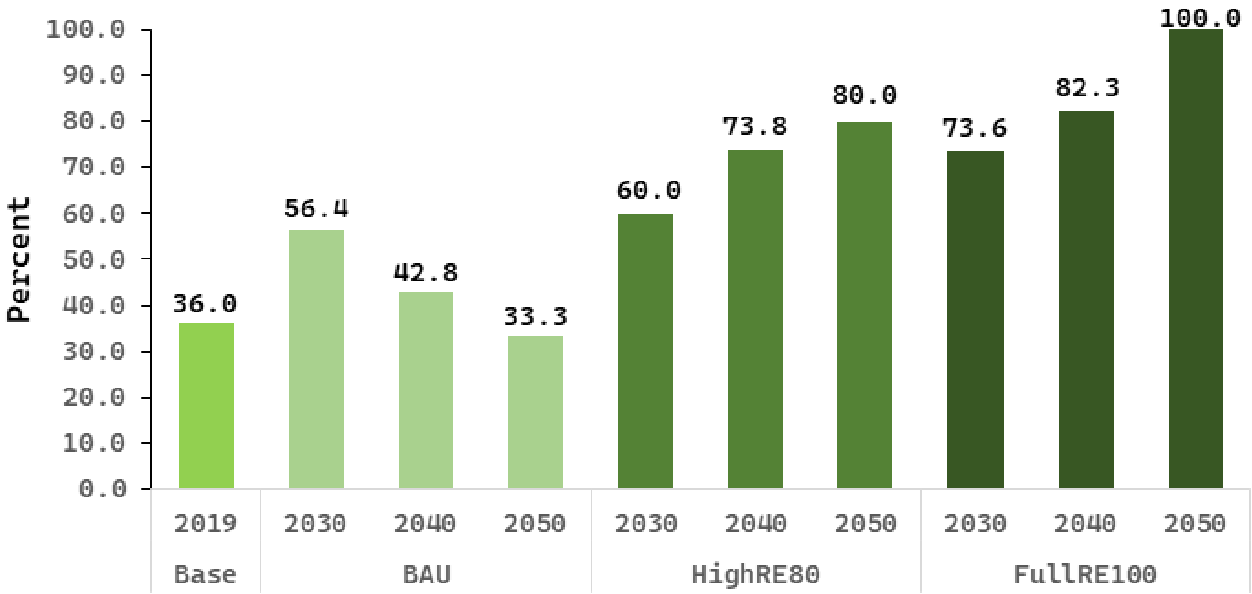


Figure 5- 8: Renewable share of energy generation for the defined pathways and target years

5.1.6 Investment Cost of Renewable Energy Scenarios

Figure 5-9 shows the additional upfront investment costs required for each target year of each defined pathway. In 2030, the BAU and HighRE80 scenarios demand upfront investments of around 16 billion USD, while the FullRE100 scenario requires 47 billion USD due to larger PV and storage infrastructure. In 2040, the upfront investment costs are substantially lower for the BAU scenario at 33 billion USD compared to 94-97 billion USD for the renewable pathways. A 100% renewable transition by 2050 necessitates an extra 249 billion USD, while an 80% transition requires 136 billion USD. The BAU case calls for 84 billion USD in additional investments. The transition to a high or full renewable energy system requires total upfront investment costs over the target years, ranging from 245 to 393 billion USD, in contrast to 132 billion USD in the BAU scenario. Despite the high upfront investment requirements for a renewable transition, they still make sense from a cost perspective due to reduced fuel costs. This can be seen in the LCOE comparison in Figure 5 4, where potential cost savings of up to 80% can be achieved.

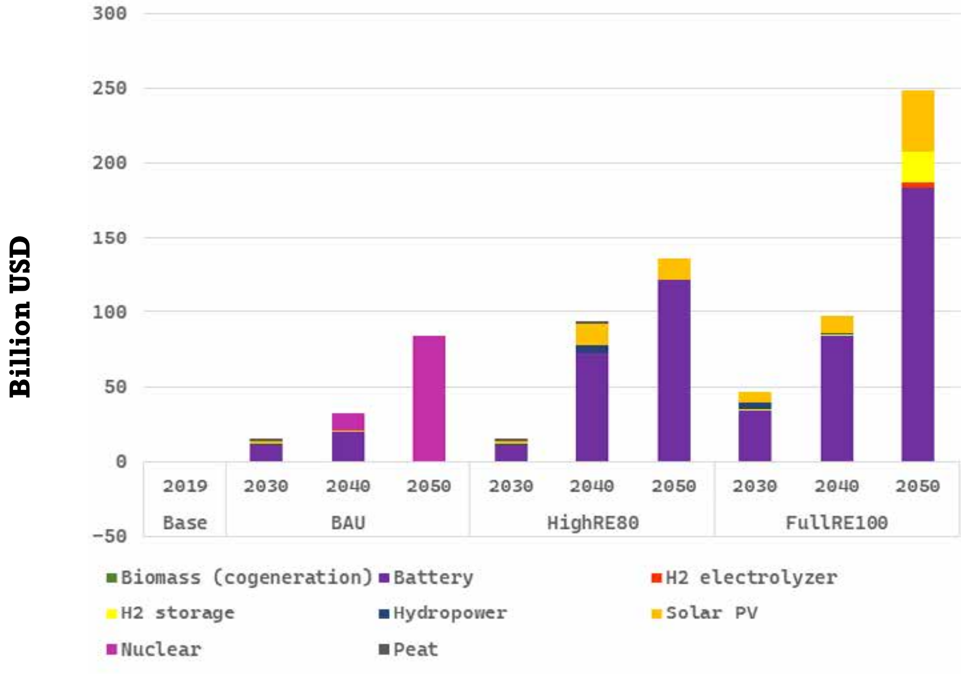


Figure 5-9: Upfront investment costs for the defined pathways and target years

5.2. Sensitivity analysis

To evaluate the robustness of the oemof model results and explore key parameter sensitivities, a sensitivity analysis was conducted. Specifically, the focus was on two critical parameters: the equivalent annual costs associated with PV and battery storage. From 2030 onwards, a noteworthy 46.4% reduction in PV equivalent annual costs, based on insights from the African Energy Outlook 2022 (IEA, 2023a) was assumed. However, it was important to acknowledge the dynamic nature of technology costs, and as such, scenarios where the equivalent annual costs for PV and battery storage range from 50% below the predicted prices to 100% above the predicted prices were considered. By conducting the sensitivity analysis, the aim was to gain an understanding of how changes in these costs impact the energy system model. The interest was assessing the effects on key variables such as newly invested capacities or LCOE.

The target year 2050 was selected to demonstrate the effects of changing PV and battery costs across defined pathways on installed power capacities (Figure 5-10), installed storages (Figure 5 -11) and LCOE (Table 5 1). In the BAU 2050 scenario, the energy system remains unaffected by changes in PV and battery storage costs. This is because even at predicted prices, there are no additional investments in PV or battery storage. Instead, the energy system heavily relies on other sources, with substantial investments in nuclear energy amounting to 15,600 MW. The LCOE experiences a moderate 5% increase across the range of cost scenarios.

In the HighRE80 scenario, increasing equivalent annual costs led to a reduction in PV and battery investments. Specifically, there was a 12% decrease in PV investments and a 7% decrease in battery storage capacity when comparing the least expensive and most expensive scenarios. However, the LCOE showed a significant 185% increase. The choice of transportation options varies based on equivalent annual costs. In the most cost-effective scenario, green H2-powered airplanes become a competitive choice compared to traditional kerosene-powered aircraft due to lower electricity costs for green H2 production. Conversely, at current predicted costs, kerosene remains the preferred option. In the most expensive scenario, biofuel vehicles gain prominence due to reduced investments in PV and battery storage.

The FullRE100 pathway exhibited significant variations in response to changing equivalent annual costs for PV and battery storage. Notably, PV and battery storage investments experienced a reduction of 30% and 12%, respectively, when comparing the most affordable and most expensive scenarios. However, the LCOE depicted a substantial increase of 205%. One noteworthy shift was observed in the transportation sector. As equivalent annual costs rise above predicted levels, green H2 production and storage become competitive alternatives to PV and battery storage for electric vehicles. This shift in competitiveness prompts the need for larger green H2 storage capacities to compensate for reduced PV capacities. These storages play a crucial role in ensuring a consistent supply of green H2 to meet the demands of the transportation sector.

Notably, the full and high RE pathways have a lower LCOE than BAU, even at the extreme assumption of 200 percent higher prices of PV panels and battery storages as they predicted prices (HighRE80: 0.111 USD/kWh. FullRE100: 0.143 USD/kWh, BAU: 0.196 USD/kWh, Table 5 1). This underpins the strong economic advantages of an RE -based transition in comparison to the development of nuclear energy in BAU.

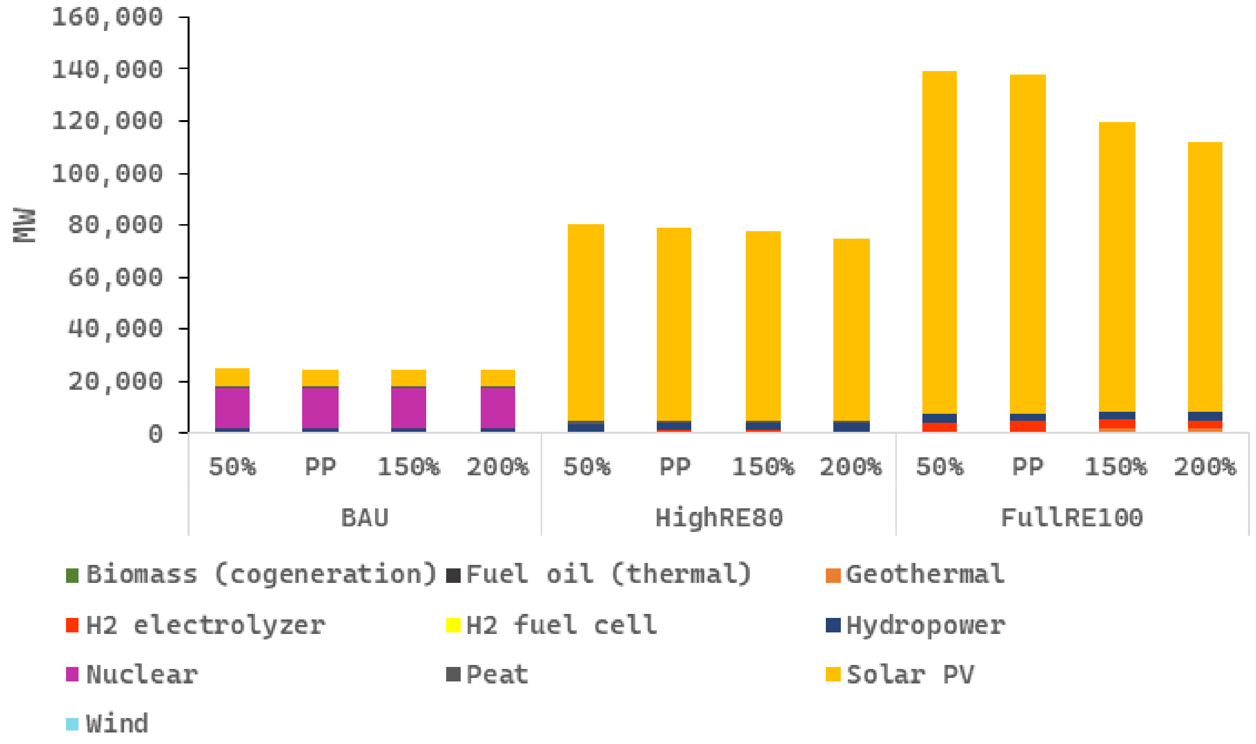


Figure 5-10: Installed capacities for sensitivity analysis analysis on pv and battery storage equivalent annual costs

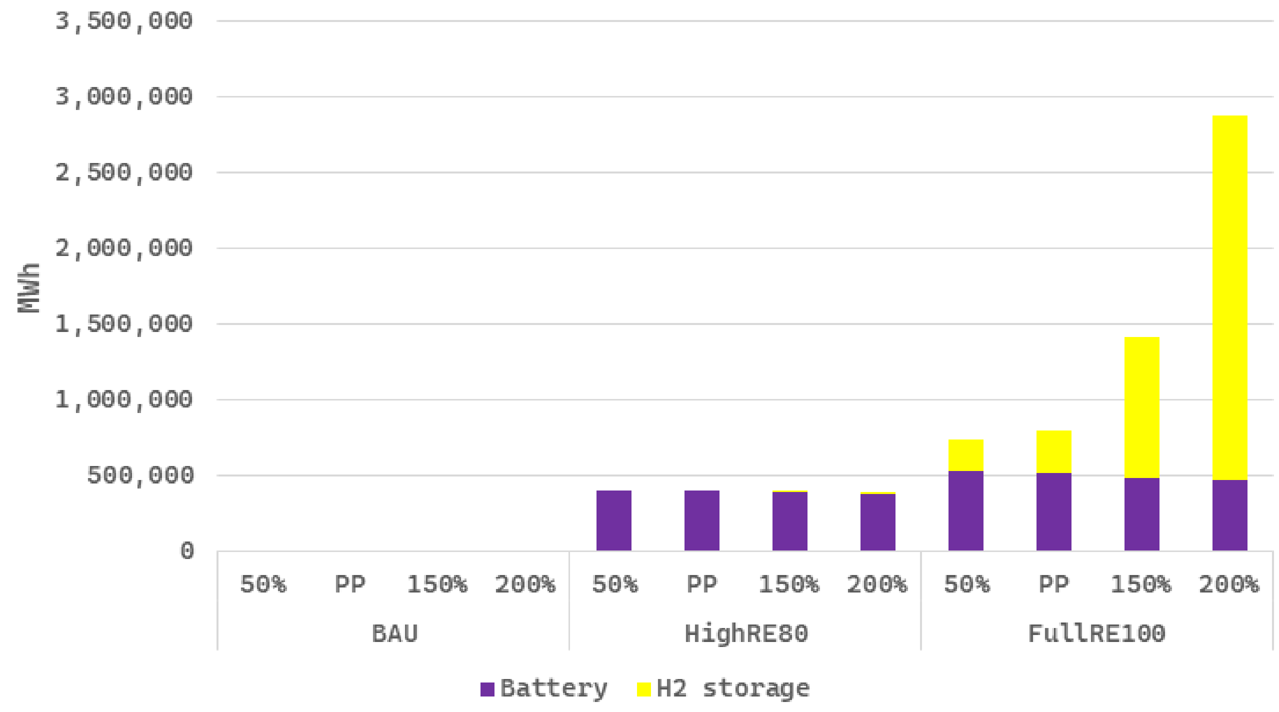


Figure 5-11: Installed storage capacities for sensitivity analysis on PV and battery storage equivalent annual costs

Table 5 -1: Key performance indicators (KPIs) for sensitivity analysis on PV and battery storage equivalent annual costs

Scenarios	PV and battery storage equivalent annual costs	LCOE (USD/ kWh)	RE share (%)	Investments in PV (GW)	Investments in battery storage (GWh)
BAU 2050	**50% of PP**	0.187	30	0	0
	PP (predicted price)	0.190	30	0	0
	150% of PP	0.193	30	0	0
	200% of PP	0.196	30	0	0
High RE 80% 2050	**50% of PP**	0.039	80	42.3	40.6
	PP (predicted price)	0.063	80	40.8	40.4
	150% of PP	0.088	80	39.6	38.6
	200% of PP	0.111	80	37.1	37.9
FullRE100% 2050	**50% of PP**	0.047	100	93.1	53.5
	PP (predicted price)	0.085	100	91.2	52.5
	150% of PP	0.118	100	72.1	48.7
	200% of PP	0.14	100	64.9	47.1

5.3. CO_2 emissions reduction potential

The expected annual direct CO2 emissions for each pathway were calculated by accounting for specific CO2 emissions of various fuels per used resource using data from Quaschning and Siegel (2022). The total expected annual emissions for the baseline year 2019 were 38 million tonnes of CO2 equivalent. Unsustainable biomass and fuel oil were the largest contributors to the total emissions of the energy system, despite hydropower being the largest installed capacity (1,070 MW). The direct annual emissions for each technology for the considered pathways are illustrated in Figure 5-12. In this context, unsustainable biofuels and unsustainable biomass signify biofuel and biomass usage that exceeds the sustainable limits outlined in Table 3-1. For reference, the installed capacities of each technology for the considered pathways are illustrated in Figure 5-1.

After a short dip in 2030 due to the switch from unimproved to improved stoves, the emissions in BAU rise due to ongoing and unrestricted biomass and peat usage. With increasing renewable shares along the HighRE80 pathway, emissions switch from being predominantly based on unsustainable biomass (2030) to being based on fossil fuels (LPG, Peat, Fuel oil, Kerosene). The resources in the FullRE100 causing net CO2 emissions in 2030 and 2040 are unsustainable biomass, LPG and kerosene. The FullRE100 pathway reduces direction emissions to 0 in 2050 and indicates the path to CO2 neutrality.

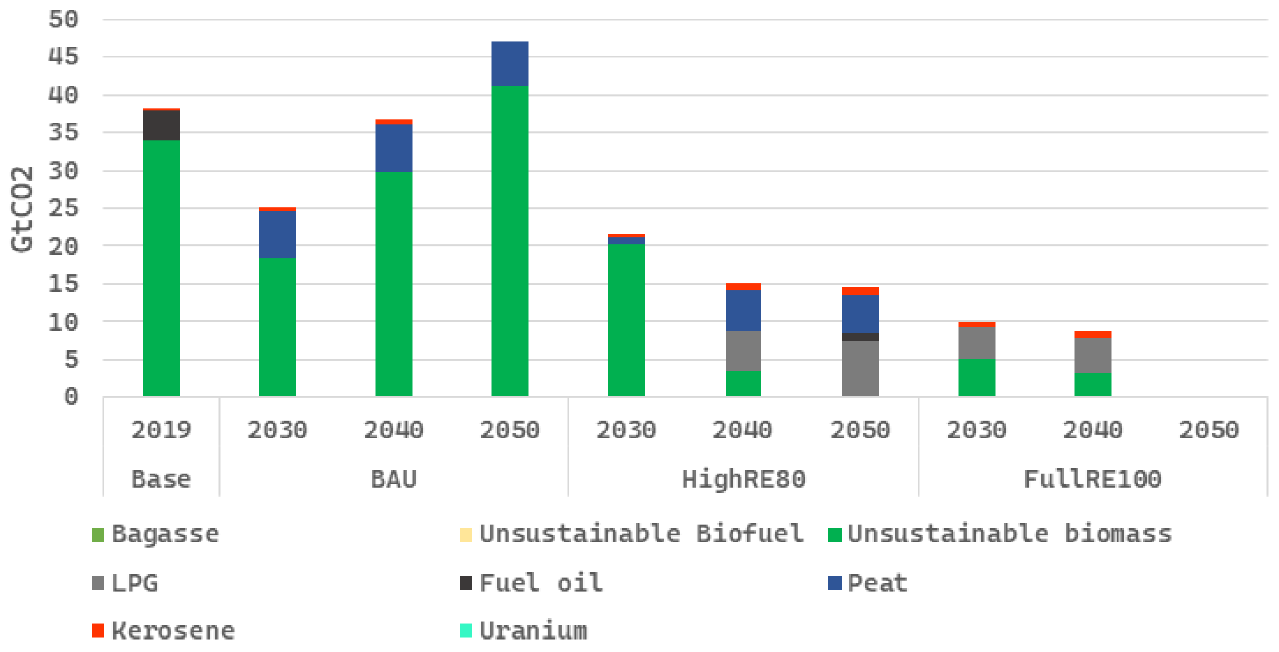


Figure 5-12: Direct CO_2 equivalent emissions for defined pathways

6 DISCUSSION OF THE RESULTS

This chapter provides a discussion for the quantitative results from the study. It is crucial to understand the meaning of the results, and possible advancements that can be made in terms of Uganda's sustainable energy transition. Section 6.1 focuses on the results implications for the four key sectors in Uganda: households, commercial and institutions, industry, and transport. Then the significance of the results, in terms of the financial, environmental and socio-economic impact of a transition towards a high or full RE supply, are presented in section 6.2. The limitations of the study are presented in section 6.3. First, the limitations regarding the methodology of the study are discussed. This includes the limitations with the capabilities of the energy system model, the assumptions used based on literature research and the availability of data. Then the limitations in terms of the resulting implications were discussed, and areas that require further investigation in future studies were identified.

6.1. Implications for the sectors

The pathways for the target years under study showed substantial growth in Uganda's electricity demand and a complete restricting of power production and storage capacities, cooking devices, industrial heat devices, and transport fleet. This transition must be accompanied by a series of measures to make its implementation feasible. The current chapter aims to provide a qualitative discourse on potential measures to support the goals established in the prior quantitative investigation. This discussion focuses on the four key sectors in Uganda: households, commercials and institutions, industry, and transport. Our central inquiry revolves around identifying actionable steps to achieve the objectives outlined in this study. Some of these ideas or recommendations could have already been included in the previous chapters, but it is important to directly address the stakeholders from the different sectors in this chapter so they could translate these results into action.

6.1.1. Households

In households, cooking is the primary driver of energy consumption. At present, this sector accounts for about 56% of Uganda's energy demand where biomass is estimated to be 97% of the total (Figure 6-1), as a large portion of the population primarily relies on firewood or charcoal for their cooking fuels, which are highly inefficient energy sources. Measures to reduce biomass for cooking can be divided into different steps: the procurement, the processing if necessary and the use. According to our information, the procurement of biomass products is currently rather unregulated, which is an uncontrollable factor.

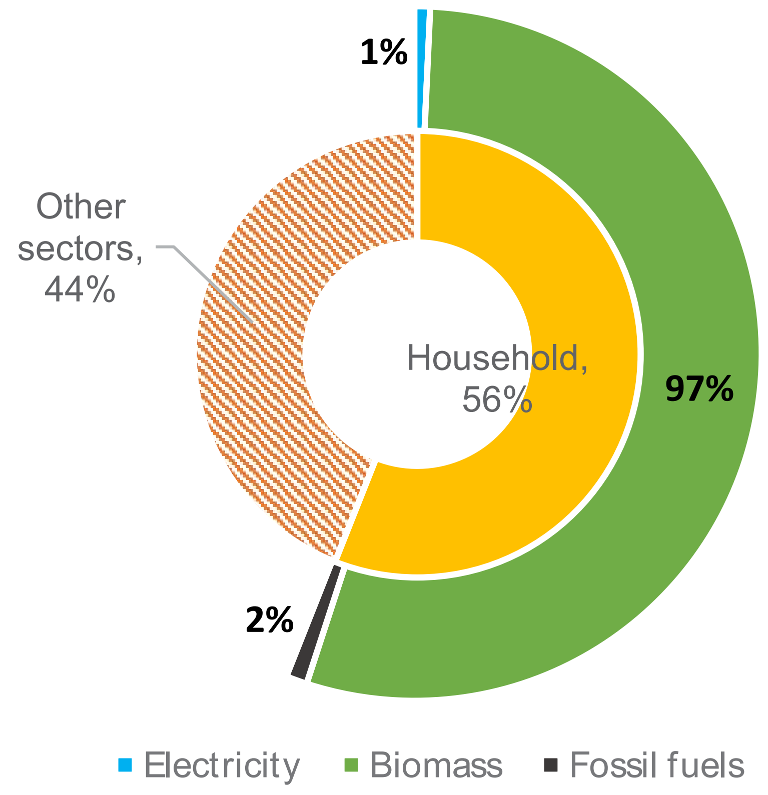


Figure 6-1: Energy demand in household sector. Data source: (WWF,2015) and (ministry of energy and mineral development (MEMD), 2020)

One potential step towards sustainable utilization of biomass resources in terms of procurement is the implementation of a forestry management plan or a controlled deforestation strategy. However, it is important to acknowledge that such a regulatory framework could have unintended consequences for certain populations, particularly in rural areas. Therefore, it is crucial to consider and address the potential drawbacks before implementing such measures.

The main factor for influencing the processing step would be to improve the efficiency of the used kilns for charcoal burning. The current efficiency is stunningly low because most people are using traditional pit kilns, which are inefficient. So one way could be to teach people how to build and use modern kilns, which could reduce the amount of needed firewood significantly or the charcoal production could partly be in authority's hand. Since most of the charcoal is used in urban areas (Figure 6 2) due to already mentioned reasons, one suggestion would be to implement some governmental charcoal production sites in the urban areas and train the people in the rural areas to build and use kilns that are more efficient by themselves.

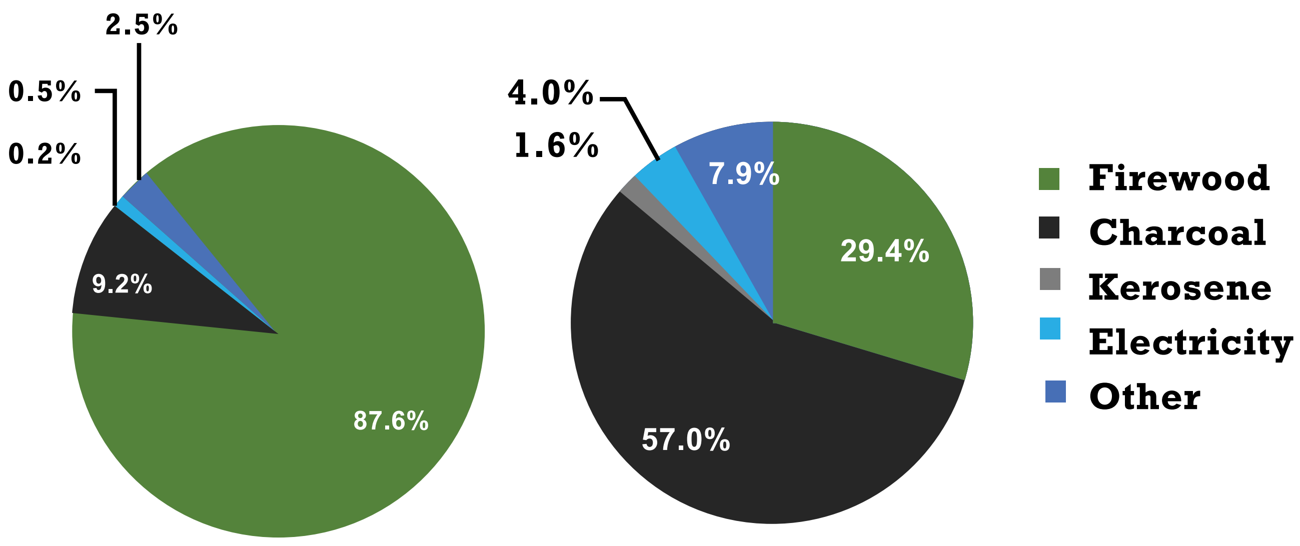


Figure 6-2: Distribution of households by cooking fuel in rural (left) and urban (right) areas data source: (UBOS, 2021)

There are two ways to optimize end-use efficiency. If it is not possible for people to switch to other forms of cooking, such as electric stoves, because of where they live or their financial situation, then the only option is to improve the efficiency of the existing technology. Since in rural areas people still cook with open fires, which is a very inefficient way of cooking, there is a great potential for improvement in this area. However, the reality of life and the acceptance of the people living there must also be taken into account here. The general obstacles to the implementation of the proposed changes will be, on the one hand, the acceptance among the population and, on the other hand, the financing of the respective transformation.

6.1.2. Commercial and institutions

The commercial sector, primarily represented by restaurants and bakeries, and the institutional sector, primarily represented by schools, both have cooking and heating as their primary drivers of energy consumption. Some of the strategies discussed in the previous chapter regarding household energy consumption could be adapted for this sector as well. However, it is important to note that the kitchens in these businesses, such as restaurants or hotels, are typically much larger than those in private homes. Switching to electric stoves or LPG based cooking could result in substantial energy savings in these businesses. Once again, the biggest obstacles will be acceptance and funding.

6.1.3. Industry

The industrial sector also mainly uses biomass as an energy source to meet its energy needs. Part of this consumption will certainly remain in the future, because parts of Uganda's industry are and will remain energy-intensive. These include, for example, brick burning or tea drying - both heat-intensive processes. Here, it is important to examine whether it is possible to implement similar co-generation processes to those used by the sugar cane industry. Otherwise, the only option here is to switch to technology that makes more efficient use of the biomass input.

6.1.4. Transport

Various approaches are needed to make the transport sector emission-free. There are three different approaches, the combination of which will probably lead to the right solution in the end. On the one hand, there is the possibility of retaining parts of the current vehicle fleet and converting them to be powered by green biofuels. This would have the advantage that car owners could keep part of their fleet and the disadvantage that the electricity demand would increase enormously, and this obviously must be produced with renewable technologies. However, for the first years of conversion, this step would probably be feasible because there are already small biofuel productions.

The other two steps involve a complete change in the vehicle fleet by switching to H2 or electricity-powered vehicles. On the part of the government, however, this also means creating sufficient charging infrastructure for this vehicle fleet. Again, implementation in rural areas will be a difficulty. Perhaps using biofuels in very remote areas and switching to H2 and electricity in all other regions will end up being the implementable mix. Either way, this switch needs to be studied in much more detail.

Unlike in the other sectors, much of the funding for the transformation of the transportation sector appears to be required on the governmental side. This requires thoughtful planning and conscientious implementation.

6.2. Significance of the results

The purpose of this chapter is to understand the feasibility of the potential scenarios for Uganda's future energy supply. The financial impacts of the future pathways, in comparison to the current situation as well as between each other are explored to better understand the long term costs, rather than only the initial investments required. Further, the ability for future scenarios to meet Uganda's climate goals is analysed. In order to achieve a sustainable transition, the socio-economic impacts of an expanding energy supply for the Ugandan population must be considered. Factors such as job opportunities and health impacts are noted.

6.2.1. Costs of e transition to 100% renewables including climate and environmental impact

A transition of the energy system towards 100% renewables until 2050 (FullRE100) is economically viable in comparison to the BAU pathway, as the former results in substantially lower LCOE (0.076 USD/KWh vs. 0191 USD/kWh). The abandonment of nuclear energy as a potential alternative option, in contrast to Uganda's Vision 2040 and the BAU pathway, is the more favourable choice in economic terms. This also omits the risks and high costs associated with nuclear material and waste. 100% RE requires significant storage capacities (batteries and H2), which decrease exponentially by allowing for minor shares of flexible power plants (like biomass CHP) and fossil fuel back-up generation. This fact is reflected in the HighRE80 pathway, having the lowest LCOE (0.055 USD/kWh) at a renewable share of 80%.

Uganda has signed the Paris Agreement and commits to reducing its CO2 emissions, e.g. as defined in Uganda's NDCs. Uganda has a vast potential for RE with solar and hydropower being the two most important energy carriers. Uganda also has a large potential in biomass, but since sustainable use is often difficult to achieve, we have set strict biomass limits in our RE pathways (HighRE80, FullRE100). However, reforestation policies and the exploration of additional organic waste potentials could increase the sustainable biomass and biogas deployment required as flexibility options for high-RE system. These measures can further reduce the negative climate and environmental impact of Uganda's future energy system.

6.2.2. Socio-economic development

A well-functioning energy system forms the basis for economic development. The projected increasing demand for electricity in the next decades reflects this: The average per capita demand will increase and people which are currently not or not sufficiently supplied, will be included. Due to the climate crisis, the only way forward is to meet this demand by sustainably sourced electricity, hence, RE.

The modelling results indicate that a massive expansion of generation capacities is required. This results in a need of skilled experts and labour force for planning, construction and operation of the additional generation units. By providing sustainable and affordable access to electricity, productive use thereof is stimulated and can create new business opportunities. Studies underline the positive impact of RE technologies on the labour market and economic development.

Fossil-fuelled electricity generation leads to emissions. Besides CO2 emissions, there are emissions of e.g. particulate matter, which poses severe health risks. Also, the usage of biomass for cooking is often associated with negative health impacts. By increasing the share of RE and transforming to a fully RE systems, these impacts can be reduced through the transformation process towards 100 % RE. The replacement of decentral small diesel generators by RE-technologies also reduces noise emissions and increases the supply quality, which in turn has an overall positive impact as defined in SDG7.

6.3. Limitations of the study and outlook

Pathways are used to map out possible development paths for the demand and supply of an energy system and to identify the key challenges and opportunities associated with increasing the share of RE in the energy mix. They can be used to compare different policy options and to explore the feasibility and implications of transitioning to a low-carbon energy system.

Modelling of pathways has several limitations that should be considered when interpreting and using the results. The methodology used in this study is based on demand forecasting and energy system analysis with linear optimization to minimize system cost. Energy system analysis is commonly used to analyze the possibilities of future energy supply and especially the integration of renewable energies. For country studies it is a proven method because, the individual components of the system can be mapped accurately enough in their characteristics and the level of detail is adapted to the consideration of the entire country. In addition, open-source software was used for modelling and simulating the pathways. The advantages of open-source tools lie in its transparency and in its robustness: the existing code and the simulation tool has already been used in many scenario analyses and are open and reproducible for other energy modelers, institutions and follow-up projects.

The results of this study provide a profound overview of the types and sizes of technologies Uganda should begin investing in to achieve a transition to a RE system in the face of increasing demand, and scopes the respective costs and emissions. As scenarios are always based on assumptions about and constraints to future economic, technological, and policy developments, the data used can have significant impact on the results. Hence, it is critical to understand the assumptions and data that underlie each scenario when interpreting the results. In future studies, sensitivity analysis can be extended to other factors like energy prices and costs of further technology investments in order to reinforce the results and to learn about important influencing factors, which can, for example, be costs or regional division of resources. Further, scenarios are only as good as the data that is available. The data used to create the scenarios may not be accurate or up to date. This may also have an impact on the findings, and future research may concentrate on scenario modifications using more recent available data.

7 | APPENDIX

Table 7- 1: : Techno-economic parameters

Parameter	Value	References
Biomass Cogeneration (CHP), sugar cane (bagasse) heat to process industry, power to grid/other devices		
Investment cost ($/kW)	2,500	(Allington *et al.*, 2022)
Fixed O&M cost ($/kW/yr)	75	(Allington et al., 2022)
Variable O&M cost ($/kWh/yr)	0.005	(IRENA, 2021)
Electric efficiency (%)	35	(Allington et al., 2022)
Thermal efficiency (%)	35	(U.S. Department of Energy, 2017)
Operational lifetime (yrs)	30	(Allington et al., 2022)
Geothermal Power Plant		
Investment cost ($/kW)	4,000	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	120	(Allington et al., 2022)
Variable O&M cost ($/kWh)	0.03	(Office of energy efficiency & renewable energy, no date) (Allington et al., 2022)
Electric efficiency (%)	80	(Allington et al., 2022)
Operational lifetime (yrs)	25	(IPCC *et al.*, 2014)
Nuclear Power Plant		
Investment cost ($/kW)	6,137	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	184	(Allington et al., 2022)
Variable O&M cost ($/kWh)	0.013	(IPCC et al., 2014)
Electric efficiency (%)	33	(Allington et al., 2022)
Operational lifetime (yrs)	50	(Allington et al., 2022)
Peat Power Plant		
Investment cost ($/kW)	2,613	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	50	Assumption
Variable O&M cost ($/kWh)	0.0068	(IPCC et al., 2014)
Electric efficiency (%)	40	(Allington et al., 2022)
Thermal efficiency (%)	40	(Bimenyimana, Asemota and Li, 2018)
Operational lifetime (yrs)	25	(Allington et al., 2022)
Fuel Oil Power Plant		
Investment cost ($/kW)	1,200	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	35	(Allington et al., 2022)
Variable O&M cost ($/kWh)	0.0034	(ZBW *et al.*, 2013)
Efficiency (%)	35-40	(Allington et al., 2022), (Nierop and Humperdinck, 2018)
Operational lifetime (yrs)	25	(Allington et al., 2022)
Large Hydro Power Plant		
Investment cost ($/kW)	3,000	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	90	(Allington et al., 2022)
Variable O&M cost ($/kWh)	0.003	(IRENA, 2021)
Electric efficiency (%)	100	(Allington et al., 2022)
Operational lifetime (yrs)	50	(Allington et al., 2022)
Solar PV (utility)		
Investment cost ($/kW)	1,378	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	18	(Allington et al., 2022)
Electric efficiency (%) (tCO$_2$e/MWh)	100	(Allington et al., 2022)
Operational lifetime (yrs)	24	(Allington et al., 2022)
Wind (onshore)		
Investment cost ($/kW)	1,489	(Allington et al., 2022)
Fixed O&M cost ($/kW/yr)	60	(Allington et al., 2022)
Electric efficiency (%)	100	(Allington et al., 2022)
Operational lifetime (yrs)	25	(Allington et al., 2022)
Electrolyzer		
Investment cost ($/kW)	750	(IRENA, 2021)
Fixed O&M cost ($/kW/yr)	11.25	Assumption
Electric efficiency (%)	66.5	(Danish Energy Agency and Energinet, 2017)
Operational lifetime (yrs)	25	(Danish Energy Agency and Energinet, 2017)
Fuel Cell		
Investment cost ($/kW)	700	(IRENA, 2021)
Fixed O&M cost ($/kW/yr)	35	Assumption
Electric efficiency (%)	60	(Danish Energy Agency and Energinet, 2017)
Operational lifetime (yrs)	20	(Danish Energy Agency and Energinet, 2017)
H$_2$ Storage		
Investment cost ($/kWh)	40-80	(IEA, 2019)
Electric efficiency (%)	88	(Sadaghiani and Mehrpooya, 2017)
Operational lifetime (yrs)	30-50	(IEA, 2019)
Energy content (KWh/kg H$_2$)	33.3	(Ludwig-Bölkow-Systemtechnik, no date)
Battery storage		
Investment cost ($/kWh)	350	(Ralon *et al.*, 2017)
Fixed O&M cost ($/kWh/yr)	3.59	Assumption
Electric efficiency (%)	86	(National Renewable Energy Laboratory, 2022)
Operational lifetime (yrs)	15	(Ralon et al., 2017)
Airplane (Kerosene)		
Investment cost ($/kW)	12,375	Assumption
Fixed O&M cost ($/kW/yr)	1	Assumption
Variable O&M cost ($/kWh)	0.12	(Sandhills Global, 2023)
Efficiency (%)	30	(Eller, 2013)
Operational lifetime (yrs)	30	(Airbus, 2023)

Parameter	Value	References
Airplane (H_2)		
Investment cost ($/kW)	23,000	Assumption
Fixed O&M cost ($/kW/yr)	1	Assumption
Variable O&M cost ($/kWh)	0.18	Assumption
Efficiency (%)	30	Assumption
Operational lifetime (yrs)	30	Assumption
Combustion Engine Vehicle		
Investment cost ($/kW)	50 -100	(Najib, 2020)
Fixed O&M cost ($/kW/yr)	10	Assumption
Variable O&M cost ($/kWh)	0.08 -0.1	Uganda partners
Thermal efficiency (%)	20-40	(Isaac, 2021)
Operational lifetime (yrs)	8-15	(CASCADE, 2020)
Electric Vehicle		
Investment cost ($/kWh)	150-250	(Conzade *et al.*, 2022)
Fixed O&M cost ($/kW/yr)	10	Assumption
Variable O&M cost ($/kWh)	0.15	(Borlaug *et al.*, 2020)
Electric efficiency (%)	70	(U.S. Department of Energy, no date)
Operational lifetime (yrs)	10-20	(Chakraborty *et al.*, 2021)
H_2 Vehicle		
Investment cost ($/kW)	150	(Hydrogen Council, 2021)
Fixed O&M cost ($/kW/yr)	10	Assumption
Variable O&M cost ($/kWh)	0.24	(Hydrogen Council,)
Efficiency (%)	30	Assumption
Operational lifetime (yrs)	10-20	(Hydrogen Council, 2021)
Unimproved Stove (Wood), 3 stones		
Investment cost ($/kW)	1	(Jeuland and Pattanayak, 2012)
Fixed O&M cost ($/kW/yr)	0	(Toman and Bluffstone, 2017)
Thermal efficiency (%)	10-17	(Price, 2017)
Operational lifetime (yrs)	3-10	(O'Kelly, 2020)
Improved Stove (Wood)		
Investment cost ($/kW)	5	(Jeuland and Pattanayak, 2012)
Fixed O&M cost ($/kW/yr)	0	(Toman and Bluffstone, 2017)
Thermal efficiency (%)	25-40	(Jeuland and Pattanayak, 2012)
Operational lifetime (yrs)	3-5	(Jeuland and Pattanayak, 2012)
Gas Stove (LPG)		
Investment cost ($/kW)	12	(Jeuland and Pattanayak, 2012); (Borutsky, 2019)
Fixed O&M cost ($/kW/yr)	0.67	(Jeuland and Pattanayak, 2012)
Thermal efficiency (%)	25-40	Assumption
Operational lifetime (yrs)	5-15	(Jeuland and Pattanayak, 2012)
Ethanol Cooker		
Investment cost ($/kW)	10	Assumption
Fixed O&M cost ($/kW/yr)	0.67	Assumption
Thermal efficiency (%)	45	Assumption
Operational lifetime (yrs)	5-10	Assumption
Biogas Cooker		
Investment cost ($/kW)	10	(Figueroa *et al.*, 2017)
Fixed O&M cost ($/kW/yr)	0.2	(Figueroa et al., 2017)
Thermal efficiency (%)	50	(Khandelwal and Gupta, 2009)
Operational lifetime (yrs)	5-10	(Figueroa et al., 2017)
Electric Cooker		
Investment cost ($/kW)	12	(JUMIA, 2023)
Fixed O&M cost ($/kW/yr)	0.2	(Atepo, Mashoo and Butegwa, 2022)
Thermal efficiency (%)	80	(Ayub and Ambusso, 2021)
Operational lifetime (yrs)	10-15	(Jeuland and Pattanayak, 2012)
Biogas Digester (input animal and human waste)		
Investment cost ($/kW)	75	(IEA, 2020)
Fixed O&M cost ($/kW/yr)	0.5	(IEA, 2020)
Thermal efficiency (%)	40-70	(IEA, 2020)
Operational lifetime (yrs)	10-20	(IEA, 2020)
Biogas Heating System (chick breeding)		
Investment cost ($/kW)	51.6	(Zhao *et al.*, 2019)
Fixed O&M cost ($/kW/yr)	0.5	Assumption
Thermal efficiency (%)	50-70	(Clarke Energy, 2013)
Operational lifetime (yrs)	20	(Sistema.bio, no date)
Woody Biomass Boiler		
Investment cost ($/kW)	67	Assumption
Fixed O&M cost ($/kW/yr)	0.5	Assumption
Thermal efficiency (%)	50	Assumption
Operational lifetime (yrs)	25	(IEA ETSAP, 2010)
Industrial Boiler		
Investment cost ($/kW)	200	(Gurr, 2020)
Fixed O&M cost ($/kW/yr)	0.5	Assumption
Thermal efficiency (%)	50-90	(Spirax Sarco, 2023)
Operational lifetime (yrs)	20	(Industrial Boilers America, 2022)

Table 7- 2: Energy Prices

Parameter	Value	References
Energy Prices [$/MWh]		
Fuel Oil	88.9	(GlobalPetrolPrices.com, 2023)
Biofuels	64.1	(IEA, 2023b)
Kerosene	99.8	(GlobalPetrolPrices.com, 2023)
Bagasse	6.5	Premier Distilleries Limited, Uganda

LPG	25.46	(GlobalPetrolPrices.com, 2023)
Woody biomass	7.2	(Ito *et al.*, 2019)
Peat	2.78	(Indexbox, 2023)
Uranium	3.4	(PyPSA meets Earth, no date)

Table 7- 3: Emission Factors

Parameter	Value	References
CO_2 emission factors (tCO_2e/MWh)		
Bagasse	0	Assumption
Unsustainable biofuel	0.255	(IPCC, 2006)
Unsustainable biomass	0.368	(Quaschning and Siegel, 2022)
LPG	0.239	(Quaschning and Siegel, 2022)
Fuel oil	0.267	(Quaschning and Siegel, 2022)
Peat	0.367	(Quaschning and Siegel, 2022)
Kerosene	0.264	(Quaschning and Siegel, 2022)
Uranium	0	(IPCC et al., 2014)

8 LITERATURE

Airbus (2023) Operating life - From delivery to service retirement, www.airbus.com. Available at: https://www.airbus.com/en/products-services/commercial-aircraft/the-life-cycle-of-an-aircraft/operating-life (Accessed: 17 August 2023).

Allington, L. et al. (2022) 'Selected "Starter kit" energy system modelling data for selected countries in Africa, East Asia, and South America (#CCG, 2021)', Data in Brief, 42, p. 108021. Available at: https://doi.org/10.1016/j.dib.2022.108021.

Atepo, S., Mashoo, E. and Butegwa, V. (2022) 'How Electric Pressure Cookers (EPC) solve household cooking dilemmas', Nilepost, 22 September. Available at: https://nilepost.co.ug/2022/09/22/how-electric-pressure-cookers-epc-solve-household-cooking-dilemmas/ (Accessed: 17 August 2023).

Ayub, H.R. and Ambusso, W.J. (2021) 'A Review of Cooking Systems and Energy Efficiencies', American Journal of Energy Engineering, 9(1), pp. 1–7. Available at: https://doi.org/10.11648/j.ajee.20210901.11.

Bahati, G. and Natukunda, J.F. (2020) 'Geothermal Energy Exploration in Uganda, Country Update', in. Available at: https://publications.mygeoenergynow.org/grc/1034213.pdf.

Bimenyimana, S., Asemota, G.N.O. and Li, L. (2018) 'The State of the Power Sector in Rwanda', frontiers in Energy Research, 6(68), p. 14. Available at: https://doi.org/10.3389/fenrg.2018.00068.

Biofuels Act, 2020 (2020). Available at: https://ulii.org/akn/ug/act/2020/14/eng@2020-08-28 (Accessed: 23 September 2023).

Bongomin, O. and Nziu, P. (2022) 'A Critical Review on the Development and Utilization of Energy Systems in Uganda', The Scientific World Journal, 2022, p. e2599467. Available at: https://doi.org/10.1155/2022/2599467.

Borlaug, B. et al. (2020) 'Levelized Cost of Charging Electric Vehicles in the United States', Joule, 4(7), pp. 1470–1485. Available at: https://doi.org/10.1016/j.joule.2020.05.013.

CASCADE (2020) What's the Average Life of a Car?, cascadecollision.com. Available at: https://cascadecollision.com/what-is-the-average-life-of-a-car/.

Chakraborty, S. et al. (2021) ‘Real-Life Mission Profile Oriented Lifetime Estimation of a SiC Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains’, IEEE Journal of Emerging and Selected Topics in Power Electronics [Preprint]. Available at: https://doi.org/10.1109/JESTPE.2021.3083198.

Clarke Energy (2013) CHP efficiency for biogas. Available at: https://www.clarke-energy.com/2013/chp-cogen-efficiency-biogas/ (Accessed: 29 September 2023).

Conzade, J. et al. (2022) ‘Power to move: Accelerating the electric transport transition in sub-Saharan Africa’, ;cKinsey, 23 February. Available at: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/power-to-move-accelerating-the-electric-transport-transition-in-sub-saharan-africa#/ (Accessed: 15 August 2023).

Copernicus Global and Land service (2022) ‘Uganda forest cover’. Available at: https://land.copernicus.eu/global/products/lc.

Danish Energy Agency and Energinet (2017) Technology Data – Renewable fuels, p. 335. Available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

Dunks, C. et al. (2023) ‘Uganda oemof tabular’. Available at: https://github.com/ciaradunks/uganda-oemof-tabular (Accessed: 27 September 2023).

Electricity Regulatory Authority - ERA (2022) Data & Statistics. Installed Capacities. Available at: https://www.era.go.ug/index.php/stats (Accessed: 19 January 2023).

Electricity Regulatory Authority (ERA) (2022) Notice of Intended Application for a Generation and sale of Electricity License for the Development of the Proposed Hybrid 33 MW Peat Fired and 80 MW Solar PV Power Project in Rubanda District - ERA - Electricity Regulatory Authority. Available at: https://www.era.go.ug/index.php/decisions-notices/notices/689-notice-of-intended-application-for-a-generation-and-sale-of-electricity-license-for-the-development-of-the-proposed-hybrid-33-mw-peat-fired-and-80-mw-solar-pv-power-project-in-rubanda-district (Accessed: 17 February 2023).

Eller, A. (2013) Energy and Power of Flying. Stanford University. Available at: http://large.stanford.edu/courses/2013/ph240/eller1/ (Accessed: 17 August 2023).

Esri (2022) ‘World Topographic Map’. Available at: https://www.arcgis.com/home/item.html?id=30e5fe3149c34df1ba922e6f5bbf808f,.

Figueroa, A. et al. (2017) Biogas for Domestic Cooking: Technology brief. Abu Dhab: International Renewable Energy Agency. Available at: https://www.irena.org/publications/2017/Dec/Biogas-for-domestic-cooking-Technology-brief (Accessed: 17 August 2023).

GADM (2022) ‘boundaries GADM’. Available at: https://gadm.org/.

Gelaro, R. et al. (2017) ‘The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)’, Journal of Climate, 30(14), pp. 5419–5454. Available at: https://doi.org/10.1175/JCLI-D-16-0758.1.

globalforestwatch.org (no date) Uganda Deforestation Rates & Statistics | GFW. Available at:https://www.globalforestwatch.org/dashboards/country/UGA?category=undefined (Accessed: 26 September 2023).

Global Petrol Prices.com (2023) Uganda Gasoline prices, www.GlobalPetrolPrices.com. Available at: https://www.globalpetrolprices.com/Uganda/gasoline_prices/ (Accessed: 15 August 2023).

Gurr, C. (2020) ‘How Much Does a Commercial Boiler Cost to Replace’, Cowley Group, 7 October. Available at: https://www.cowleygroup.co.uk/how-much-does-a-commercial-boiler-cost-to-replace/#:~:text=This%20said%20if%2C%20for%20a%20very%20straightforward%20single,you%20would%20be%20looking%20between%20%C2%A37%2C200%20and%20%C2%A312%2C000. (Accessed: 17 August 2023).

Hilpert, S. et al. (2018) ‘The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling’, Energy Strategy Reviews, 22, pp. 16–25. Available at: https://doi.org/10.1016/j.esr.2018.07.001.

Hörsch, J. and Chloe, L. (2019) hydropowerlib. Available at: https://github.com/hydro-python/hydropowerlib.

Hydrogen Council (2021) Hydrogen Insights Report 2021. Hydrogen Council, McKinsey & Company. Available at: https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf (Accessed: 15 August 2023).

IATA (2022) Global Outlook for Air Transport. Time of Turbulence. Available at: https://www.iata.org/en/iata-repository/publications/economic-reports/airline-industry-economic-performance---june-2022---report/ (Accessed: 23 September 2023).

IEA (2019) IEA G20 Hydrogen report: Assumptions. Paris: International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf (Accessed: 15 August 2023).

IEA (2020) Outlook for biogas and biomethane - Prospects for organic growth. World Energy Outlook Special Report. International Energy Agency. Available at: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf (Accessed: 17 August 2023).

IEA (2023a) Africa Energy Outlook 2022 – Analysis. Available at: https://www.iea.org/reports/africa-energy-outlook-2022 (Accessed: 23 September 2023).

IEA (2023b) Biodiesel and diesel prices, 2019 to April 2022 – Charts – Data & Statistics, IEA. Available at: https://www.iea.org/data-and-statistics/charts/biodiesel-and-diesel-prices-2019-to-april-2022 (Accessed: 29 September 2023).

IEA ETSAP (2010) Industrial Combustion Boilers. Available at: https://iea-etsap.org/E-TechDS/PDF/I01-ind_boilers-GS-AD-gct.pdf (Accessed: 29 September 2023).

Indexbox (2023) Uganda: Articles Of Peat Market 2023, indexbox.io. Available at: https://www.indexbox.io/store/uganda-articles-of-peat-market-analysis-forecast-size-trends-and-insights/ (Accessed: 17 August 2023).

International Energy Agency (2022) Uganda - Countries & Regions, IEA. Available at: https://www.iea.org/countries/uganda (Accessed: 15 February 2023).

International Food Policy Research Institute (IFPRI) (2019) ‘Global Spatially-Disaggregated Crop Production Statistics’. Available at: https://doi.org/10.7910/DVN/PRFF8V.

IPCC (2006) Guidelines for National Greenhouse Gas Inventories. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf (Accessed: 29 September 2023).

IPCC et al. (2014) Technology-specific Cost and Performance Parameters IPCC Annex-iii, p. 28. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf.

IRENA (2021) IRENA Power Generation Cost 2020, p. 180. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf.

Isaac (2021) Thermal efficiency: what is it, diesel vs. gasoline and how much does your engine have, actualidadmotor.com. Available at: https://www.actualidadmotor.com/en/thermal-efficiency-motor-thermal-efficiency/ (Accessed: 15 August 2023).

Ito, T. et al. (2019) Solid biomass supply for heat and power: Technology brief. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_Solid_biomass_supply_2019.pdf (Accessed: 17 August 2023).

Jeuland, M.A. and Pattanayak, S.K. (2012) ‘Benefits and Costs of Improved Cookstoves: Assessing the Implications of Variability in Health, Forest and Climate Impacts’, PLoS ONE [Preprint]. Available at: https://doi.org/10.1371/journal.pone.0030338.

JUMIA (2023) Double Solid Electric Hotplate, www.jumia.ug. Available at: https://www.jumia.ug/generic-double-solid-electric-hotplate-black-97026758.html (Accessed: 17 August 2023).

Kamese, G. (2004) Renewable Energy Technologies in Uganda: The potential for Geothermal Energy. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=7d007661645e9a28a19a93126f33e863f376239b.document?repid=rep1&type=pdf&doi=7d007661645e9a28a19a93126f33e863f376239b.

Katutsi, V. et al. (2021) Overview of hydropower resources and development in Uganda, p. 1310. Available at: http://www.aimspress.com/article/doi/10.3934/energy.2021060.

Katutsi, V., Dickson, T. and Migisha, A.G. (2020) ‘Drivers of Fuel Choice for Cooking among Uganda’s Households’, Open Journal of Energy Efficiency, 09(03), pp. 111–129. Available at: https://doi.org/10.4236/ojee.2020.93008.

Keita, J.D. (1984) Small-scale forest enterprises - Wood or charcoal - which is better? Available at: https://www.fao.org/3/s4550e/s4550e09.htm (Accessed: 28 September 2023).

Khandelwal, K.C. and Gupta, V.K. (2009) Popular Summary of the Test Reports on Biogas Stoves and Lamps prepared by testing institutes in China, India and the Netherlands. The Hague: SNV Netherlands Development Organisation. Available at: https://bibalex.org/baifa/Attachment/Documents/171754.pdf (Accessed: 17 August 2023).

Lombardi, F. et al. (2019) 'Enabling combined access to electricity and clean cooking with PV-microgrids: new evidences from a high-resolution model of cooking loads', Energy for Sustainable Development, 49, pp. 78–88. Available at: https://doi.org/10.1016/j.esd.2019.01.005.

Ludwig-Bölkow-Systemtechnik (no date) H2data.de - Hydrogen fact sheet. Available at: http://www.h2data.de/ (Accessed: 29 September 2023).

MAAIF (2021) Statistical Abstract 2019/20. Ministry of Agriculture, Animal Industry and Fisheries, p. 7,8,14,35. Available at: https://nfass.agriculture.go.ug/MnE/MnEDocuments/DownloadMnEDocuments/1011.

MEMD (2015) Biomass energy strategy (BEST) Uganda. Available at: https://www.undp.org/uganda/publications/biomass-energy-strategy-best-uganda-0.

Ministry of Energy and Mineral Development (MEMD) (2020) Statistical Abstract 2020, pp. 53–54. Available at: https://energyandminerals.go.ug/wp-content/uploads/2020/07/2020-Statistical-Abstract.pdf.

Ministry of Water and Environment (2021) National Resources, Environment, Climate Change, Lands and Water Management Programme Report 2021. Available at: https://www.mwe.go.ug/library/nrecclwm-programme-perfomamce-report-2021 (Accessed: 19 January 2023).

Mitchell, D.O. (2011) Biofuels in Africa: opportunities, prospects, and challenges, World Bank, Washington D.C. Available at: https://openknowledge.worldbank.org/server/api/core/bitstreams/4de83c62-2fb4-5aa1-9d09-413418ac12ab/content.

Mutumba, G., Echegu, S. and Adaramola, M. (2021) 'Prospects and Challenges of Geothermal Energy in Uganda', Journal of Energy Research and Reviews, pp. 47–58. Available at: https://doi.org/10.9734/jenrr/2021/v9i230230.

Nagler, A. and Gerace, S. (2020) First and second generation Biofuels. Available at: https://waferx.montana.edu/documents/fact_sheets/B-1360-3-switchgrass-biofuels-web.pdf.

Najib, M. (2020) Top 12 most fuel efficient cars in Uganda and their prices in bonds. Available at: https://www.watchdoguganda.com/entertainment/lifestyle/20210104/107140/top-12-most-fuel-efficient-cars-in-uganda-and-their-prices-in-bonds-2.html (Accessed: 15 August 2023).

National Planning Authority (2013) Uganda Vision 2040. Available at: https://www.greengrowthknowledge.org/sites/default/files/downloads/policy-database/UGANDA%29%20Vision%202040.pdf.

National Renewable Energy Laboratory (2022) Annual Technology Baseline, nrel.gov. Available at: https://atb.nrel.gov/electricity/2022/residential_battery_storage (Accessed: 15 August 2023).

Nhede, N. (2023) 'Uganda to Build Two Nuclear Power Stations with Russia and South Korea', 16 August. Available at: https://energycapitalpower.com/uganda-nuclear-power-russia-south-korea/ (Accessed: 23 September 2023).

Nierop, S. and Humperdinck, S. (2018) nternational comparison of fossil power efficiency and CO2 intensity. Final Report 205329. Ecofys, p. 90. Available at: https://guidehouse.com/-/media/www/site/downloads/energy/2018/intl-comparison-of-fossil-power-efficiency--co2-in.pdf (Accessed: 15 August 2023).

Nile Basin (2016) 'Nile Basin Water Resources Atlas – Synthesized Information, Identifying and Devising Mitigation Measures'. Available at: http://atlas.nilebasin.org/ (Accessed: 15 February 2023).

oemof documentation (no date). Available at: https://oemof.readthedocs.io/en/latest/ (Accessed: 23 September 2023).

Office of energy efficiency & renewable energy (no date) Geothermal FAQs. Available at: https://www.energy.gov/eere/geothermal/geothermal-faqs.

O'Kelly, J. (2020) 'How Long Does A Wood Burning Stove Last?', Fireplace Universe, 1 October. Available at: https://fireplaceuniverse.com/how-long-wood-stove-lasts/ (Accessed: 15 August 2023).

Pfenninger, S. and Staffell, I. (2016) 'Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data', Energy, 114, pp. 1251–1265. Available at: https://doi.org/10.1016/j.energy.2016.08.060.

Price, R. (2017) "Clean" Cooking Energy in Uganda– technologies, impacts, and key barriers and enablers to market acceleration. Helpdesk Report. Institute of Development Studies. Available at: https://assets.publishing.service.gov.uk/media/5bae05abe5274a3e019d86ae/191_Clean_cooking_energy_Uganda.pdf (Accessed: 15 August 202AD).

Prina, M.G. et al. (2020) 'Multi-Objective Optimization Model EPLANopt for Energy Transition Analysis and Comparison with Climate-Change Scenarios', Energies, 13(12), p. 3255. Available at: https://doi.org/10.3390/en13123255.

PyPSA meets Earth (no date) PyPSA meets Earth. Available at: https://pypsa-meets-earth.github.io/.

Quaschning, V. and Siegel, B. (2022) Specific Carbon Dioxide Emissions of Various Fuels, volker-quaschning.de. Available at: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php (Accessed: 15 August 2023).

Ralon, P. et al. (2017) Electricity Storage and Renewables: Costs and Markets to 2030. Abu Dhabi: International Renewable Energy Agency. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf?rev=a264707cb8034a52b6f6123d5f1b1148 (Accessed: 15 August 2023).

Sadaghiani, M.S. and Mehrpooya, M. (2017) 'Introducing and energy analysis of a novel cryogenic hydrogen liquefaction process configuration', International Journal of Hydrogen Energy, 42(9), pp. 6033–6050. Available at: https://doi.org/10.1016/j.ijhydene.2017.01.136.

Sandhills Global (2023) BOEING 737-700 Price and Operating Costs, Aircraft Cost Calculator. Available at: https://www.aircraftcostcalculator.com/AircraftOperatingCosts/377/Boeing+737-701 (Accessed: 15 August 2023).

Scarlat, N. and Dallemand, J.-F. (2011) 'Recent developments of biofuels/bioenergy sustainability certification: A global overview', Energy Policy, 39(3), pp. 1630–1646. Available at: https://doi.org/10.1016/j.enpol.2010.12.039.

Sistema.bio (no date). Available at: https://sistema.bio/faq/ (Accessed: 29 September 2023).

pirax Sarco (2023) The Boiler Hose, www.spiraxsarco.com. Available at: https://www.spiraxsarco.com/learn-about-steam/the-boiler-house/boiler-efficiency-and-combustion (Accessed: 17 August 2023).

Staffell, I. and Pfenninger, S. (2016) 'Using bias-corrected reanalysis to simulate current and future wind power output', Energy, 114, pp. 1224–1239. Available at: https://doi.org/10.1016/j.energy.2016.08.068.

Stefan Pfenninger and Iain Staffell (n.d.) Renewables.ninja. Available at: https://www.renewables.ninja/ (Accessed: 15 February 2023).

Tesfamichael, M. et al. (2022) 'Barriers to the institutionalization of industrial energy efficiency in Africa: A case study from Uganda', WIREs Energy and Environment, 11(3). Available at: https://doi.org/10.1002/wene.427.

The Global Runoff Data Centre (no date) GRDC Data Portal. Available at: https://portal.grdc.bafg.de/applications/public.html?publicuser=PublicUser#dataDownload/Home.

The UN Refugee Agency - UNHCR (2023) Refugees Operational Data Portal, The UN Refugee Agency. Available at: https://data.unhcr.org/en/country/uga (Accessed: 15 February 2023).

The World Bank (2021) Uganda | Data. Available at: https://data.worldbank.org/country/uganda?view=chart (Accessed: 15 February 2023).

The World Bank (2022a) Population estimates and projections. Available at: https://databank.worldbank.org/source/population-estimates-and-projections (Accessed: 15 February 2023).

The World Bank (2022b) 'Poverty & Equity Brief - Africa Eastern & Southern - Uganda'. Available at: https://databankfiles.worldbank.org/public/ddpext_download/poverty/987B9C90-CB9F-4D93-AE8C-750588BF00QA/current/Global_POVEQ_UGA.pdf.

The World Bank (2023) World Bank Country and Lending Groups. Available at: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

Toman, M. and Bluffstone, R. (2017) 'Challenges in Assessing the Costs of Household Cooking Energy in Lower-Income Countries', Policy Research Working Paper, 8008. Available at: https://openknowledge.worldbank.org/server/api/core/bitstreams/5475b301-c1fc-5cad-9186-3f7015e9e674/content (Accessed: 15 August 2023).

Tumwesigye, S. et al. (2021) 'Spatial patterns of urbanisation in Sub-Saharan Africa: A case study of Uganda', Development Southern Africa, 40(1), pp. 1–21. Available at: https://doi.org/10.1080/0376835X.2021.1932426.

UBOS (2020) Statistical Abstract 2019. Uganda Bureau of Statistics, p. 384. Available at: https://www.ubos.org/wp-content/uploads/publications/01_20202019_Statistical_Abstract_-Final.pdf (Accessed: 23 September 2023).

UBOS (2021) 'The Uganda National Household Survey (UNHS) 2019/2020'. Available at: https://www.ubos.org/wp-content/uploads/publications/09_2021Uganda-National-Survey-Report-2019-2020.pdf.

UBOS (2022a) Revised Annual Gross Domestic Product 2021/2022, Uganda Bureau of Statistics. Available at: https://www.ubos.org/wp-content/uploads/publications/11_2022AGDP_October_2022_Release.pdf (Accessed: 15 February 2023).

UBOS (2022b) Statistical Abstract 2021. Uganda Bureau of Statistics, p. 81. Available at: https://www.ubos.org/wp-content/uploads/publications/01_20222021_Statistical_Abstract.pdf.

Uganda Electricity Transmission Company Limited (UETCL) (2022) 'Generation sites, Transmission and Distribution Lines and Industrial Parks'. Available at: https://uetcl.go.ug/.

Uganda Energy Policy, 2023. Available at: https://nrep.ug/wp-content/uploads/2023/09/Energy-Policy-for-Uganda-2023.pdf (Accessed: 21st October 2023).

Uganda Investment Authority (no date) Opportunities in Energy. Available at: https://www.ugandainvest.go.ug/why-uganda/opportunities/energy/ (Accessed: 17 February 2023).

UIA (2022) Bankable Projects. Viable Investment Opportunities in Uganda 2022-2023. Uganda Investment Authority, p. 67. Available at: https://www.ugandainvest.go.ug/wp-content/uploads/2022/08/Bankable-Projects-V8-compressed.pdf (Accessed: 23 September 2023).

University of Maryland (no date). Available at: http://flood.umd.edu/.

U.S. Department of Energy (2017) Overview of CHP Technologies. Available at: https://www.energy.gov/sites/prod/files/2017/12/f46/CHP%20Overview-120817_compliant_0.pdf#:~:text=While%20eficien-%20cies%20vary%20for%20CHP%20installations%20based,typically%20operate%20with%20an%20overall%20eficiency%20of%2065%E2%80%9385%25.

U.S. Department of Energy (no date) Where the Energy Goes: Electric Cars. Available at: https://fueleconomy.gov/feg/atv-ev.shtml (Accessed: 29 September 2023).

Vestas (n.d.) V90-2.0 MW technical specifications. Available at: https://www.vestas.com/en/pages/backup-2-mw-platform/V90-2-0-MW (Accessed: 17 February 2023).

Wabukala, B.M. et al. (2021) 'Assessing wind energy development in Uganda: Opportunities and challenges', Wind Engineering, 45(6), pp. 1714–1732. Available at: https://doi.org/10.1177/0309524X20985768.

'waterbodies - OpenStreetMap' (2022). Available at: https://www.openstreetmap.org.

World Bank (2019) Ugandan Government Steps Up Efforts to Mitigate and Adapt to Climate Change, World Bank. Available at: https://www.worldbank.org/en/news/feature/2019/05/31/ugandan-government-steps-up-efforts-to-mitigate-and-adapt-to-climate-change (Accessed: 27 September 2023).

World Bank Group (2022a) 'Global Solar Atlas'. Available at: https://globalsolaratlas.info/.

World Bank Group (2022b) 'Global Wind Atlas'. Available at: https://globalwindatlas.info/en.

World Economic Forum (2019) The Global Competitiveness Report 2019. Available at: https://www3.weforum.org/docs/WEF_TheGlobalCompetitivenessReport2019.pdf.

World Health Organization (2022) Proportion of population with primary reliance on clean fuels and technologies for cooking. Available at: https://www.who.int/data/gho/data/themes/air-pollution/household-air-pollution (Accessed: 15 February 2023).

WWF (2015) Energy Report for Uganda. A 100% Renewable Energy Future by 2050. Available at: https://wwfint.awsassets.panda.org/downloads/energy_report_for_uganda_2015.pdf.

ZBW et al. (2013) Current and prospective costs of electricity generation until 2050 - DIW Berlin. Available at: https://www.econstor.eu/bitstream/10419/80348/1/757528015.pdf.

Zhao, S. et al. (2019) 'Construction of a biogas heat storage greenhouse ecosystem under the context of water pollution resulting from livestock breeding', Environmental Engineering and Management Journal, 18(3), pp. 757–764.

Why we are here.
To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

panda.org/uganda

WWF Uganda Country Office
Plot 2 Sturrock Road, Kololo
P.O. Box 8758, Kampala
Tel: +256-200510800
Email: kampala@wwfuganda.org

Visit: 100re-map.net **Write** info@100re-map.net **Tweet** @100reMap