Delft University of Technology

Department of Water Management

Faculty of Civil Engineering and Geosciences

Investigating the potential role of pumped hydro storage in the Ethiopian energy system using OSeMOSYS

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by

D.H.X. de Vries

Committee:

Chair	Dr. Ir.	E. Abraham	TU Delft
Second Supervisor	Prof. Dr. Ir.	R. Uijlenhoet	TU Delft
Member	Prof. Dr. Ir.	N.C. van de Giesen	TU Delft
Member	Ir.	F.O. Annor	TU Delft
External Member	Prof. Dr. Ir.	V. Martin	KTH Stockholm

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TU Delft Delft University of Technology

Acknowledgements

The first moment I became interested in water resource management in the context of social and economic welfare was when I took the course on integrated water management, supervised by Edo Abraham, during the first year of my MSc program. The course was engaging and intellectually stimulating. I reached out to Edo in December 2021 to discuss potential thesis research opportunities, and through our discussions and with his guidance, I was presented with the opportunity to collaborate with the KTH Royal Institute of Technology in Sweden on a project investigating energy modelling for Ethiopia. This was a topic I would not have considered directly as a water management student. Nevertheless, it aligns with my sincere and intrinsic interest in complex problems on a large scale that integrate multiple subjects such as financial viability, societal development and global issues such as the energy transition. This project allowed me to delve into these subjects in a single research project. Throughout the process, I have learned a lot, both academically and personally. Academic research has to provoke, challenge and entice questions, and I think I have been able to achieve this. I want to thank the following people for enabling me to do this.

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Abstract

Ethiopia's energy demand is expected to increase sevenfold in the coming 30 years, resulting in increased variable renewable electricity (VRE) production by solar PV and wind. Energy storage acts as a buffer that mitigates the effects of over- or under-capacity in production by VRE. With 97% of global bulk energy storage, pumped hydro storage is the most widely used and mature energy storage method. With its long operational life, high round-trip efficiency (80%) and stable cost trajectory, it is a beneficial option for many energy systems. However, drawbacks of pumped storage include heavy technical, site-specific restrictions, long construction times and high initial capital investment requirements.

This study investigates if Ethiopia's energy pathways benefit from adding pumped storage, where to build it, and if storage increases system resilience. The long-term energy planning tool OSeMOSYS is used, which allows for detailed investigation into system dynamics whilst parallelly minimising costs. OSeMOSYS enables the investigation into Ethiopia by looking at an extensive host of techno-economic specifications and supply and demand dynamics from the electrification of transport and integration of variable renewables to residential cooking demands.

This report discusses thirteen scenarios which are separated into three main categories: *Base Case* (3), *Emission Penalty (EMI)* (6) and *Varying Wind Capacity and Seasonality (WND)* (6). The base case introduces pumped storage to the energy pathways. The EMI scenario characterises three pathways for carbon pricing. In the WND scenario, wind power's capacity factor and seasonality are altered to investigate the potential effects of using more accurate local data or prioritising some supply zones on the energy system configuration. Additionally, the most favourable locations for solar PV and wind are combined with potential PHS locations to find optimal sites for storage construction.

The results of the research show that pumped hydro storage is adopted into the energy system in all scenarios, following both a diurnal and seasonal (dis)charge pattern. Variable renewable integration increases by an average of 10% from the addition of storage (78 GWh). The emission penalty increases the electrification of residential cooking demand and boosts VRE penetration but does not integrate storage integration further than the base case due to reaching the upper limit of the storage capacity set in the planning experiments. Lastly, the changes in capacity factor and seasonality have a marginal effect on the energy pathways.

Pumped hydro storage increases the energy system's resilience to climate-driven seasonal uncertainties and prices due to fossil fuel and carbon price uncertainties by making it less dependent on fossil fuels, decreasing vulnerability for potential emission penalties and seasonal capacity fluctuations. The introduction of PHS does not increase overall system costs, making it a prime candidate for large-scale energy storage in Ethiopia, combined with the stable levelised cost of storage and high maturity.

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Acronyms

GERD	Grand Ethiopia Renaissance Dam. 18
GHG	greenhouse gases. 21
MoO	Mode of Operation. 32
PHS	Pumped Hydro Storage. vi, 3, 6, 7, 11, 13, 16, 32
RES	Reference Energy System. vi, 26, 30–32, 37
SSA	Sub-Saharan Africa. 17

1 Introduction

Energy systems worldwide are undergoing a transition which involves the decarbonisation of energy technologies, increased energy demand and electrification, a growing role of variable renewable energy sources, policies that aim at mitigating the effects of climate change and reducing greenhouse gas emissions, and a focus on improving energy security. Global policies are seeing these changes as well. Sustainable Development Goal 7 by the United Nations is to ”ensure access to affordable, reliable, sustainable and modern energy for all” (United Nations, 2022). As a result of this transition, intermittent renewable energy sources like solar and wind power are expected to play a larger role in energy production. Following the more extensive integration of intermittent renewables, clean storage technologies, such as pumped hydro storage, are projected to play an increasing role in global energy systems.

Pumped hydro storage is a mature storage technology with long operational life, a stable levelised cost of storage, no emissions after construction, low ramp-up times and high round-trip efficiency. Energy is stored by pumping up water when there is overcapacity in electricity production and releasing it when there is under capacity. This technology is ideal for storing high quantities of energy, i.e. more than 100 MWh. However, the primary drawbacks are long construction times, site-specific restrictions and high initial capital costs.

Ethiopia is chosen as a case study for this research because of four drivers. Firstly, its energy demand is expected to increase sevenfold between 2015 and 2050. Secondly, the integration of variable renewable energy sources is expected to increase over the coming decades. Thirdly, Ethiopia is adopting policies focused on decreasing the effects of climate change. Lastly, data availability and quality in Ethiopia for energy modelling are improving, which allows better analysis of the energy pathways for this quickly changing country.

Pumped hydro storage could potentially fit into the energy pathways of Ethiopia. Therefore, the objective of this research is to explore the introduction of PHS in Ethiopia's energy pathways, and understand whether and under what scenarios/conditions it could:

1. increase energy system resilience and flexibility,
2. reduce fossil fuel dependence,
3. be financially viable,
4. accelerate (variable) renewable energy integration.

To explore these pathways, the report describes a contextual analysis of Ethiopia and its drivers concerning the energy transition. For energy planning, the OSeMOSYS modelling tool is used. It is a free, bottom-up, long-term tool that optimises for an energy system discounted costs while adhering to an array of end-use demand criteria. It is deterministic and applies linear optimisation based on algebraic statements to calculate the objective function, which minimises the net present costs of the energy system. The results from the modelling phase of the research are linked to the Global Pumped Hydro Atlas, which utilises a GIS algorithm to locate potential PHS locations worldwide.

The report is structured as follows. **Chapter 2** provides the **theoretical background** of the research. First, Section 2.1 discusses the drivers of the global transition to decarbonised energy systems. Secondly, the motivation for studying pumped hydro storage is given in Section 2.2. Then, the case is made for Ethiopia as a target country for this thesis research in Section 2.3. Subsequently, resilience and flexibility in the context of energy pathways are discussed in Section 2.4. To conclude, Section 2.5 defines the objective of the study and research questions.

Chapter 3 elaborates on **the research methodology**, starting with an overview of the methodological approach in Section 3.1. Secondly, Section 3.2 motivates the choice of OSeMOSYS as a modelling tool for long-term energy planning. Section 3.3 provides information on using a Reference Energy System (RES) in the schematic representation of the Ethiopian energy system. The construction of the baseline scenario is discussed in Section 3.4, which transitions into the specific scenario decisions in Section 3.5. Then, Section 3.6 elaborates on the validation of the pathways. Lastly, Section 3.7 introduces the Global Pumped Hydro Atlas, which gives insight into potential pumped hydro storage locations in Ethiopia.

Chapter 4 examines **the results of the study**, starting with the common outcomes of all scenarios in Section 4.1. Results from individual pathways are split into three sections. First, the base case is reviewed in Section 4.2, after which, in Section 4.3. the WND scenario is discussed. Then, in Section 4.4, the results of the EMI pathway that dives into carbon pricing are debated. The last section of the chapter, Section 4.5, discusses the potential locations in Ethiopia where pumped hydro storage can be constructed.

Chapter 5 describes **the discussion** of the results. Firstly, Section 5.1 focuses on the discussion points for the research questions. Section 5.2 elaborates on the methodology of the study.

Chapter 6 presents **the conclusions** of the report. Finally, **Chapter 7** makes **recommendations for future work**.

2 Theoretical Framework

This chapter first gives an overview of the global drivers of the energy transition. Secondly, it elaborates on the choice for pumped hydro storage (PHS) and explains the functioning of PHS and its primary advantages and limitations. It then discusses the capital and levelised costs of pumped storage, followed by a discussion of the benefits of PHS in combination with intermittent energy sources. Thirdly, the choice of Ethiopia as a case study for this research is motivated, and resilience measures of an energy system are defined. Lastly, the last section elaborates on the objective of this research and subsequent research questions.

2.1 Global drivers of the energy transition

Figure 1 portrays the drivers and trends that constitute the global energy transition and includes motivation for clean storage as a part of this energy transition. Here, *clean* refers to storage with low or no emissions. In comparison, *non-clean* storage methods could include batteries that need minerals that require mining operations of scarce resources, thus incorporating carbon emissions and other environmental impacts.

In the outer layer of the figure, drivers of the energy transition are found. Subsequently, these are connected to global trends within the energy transition, and these trends are further elaborated on below. Lastly, these trends converge to the motivation for clean energy storage in energy systems to respond to these global trends.

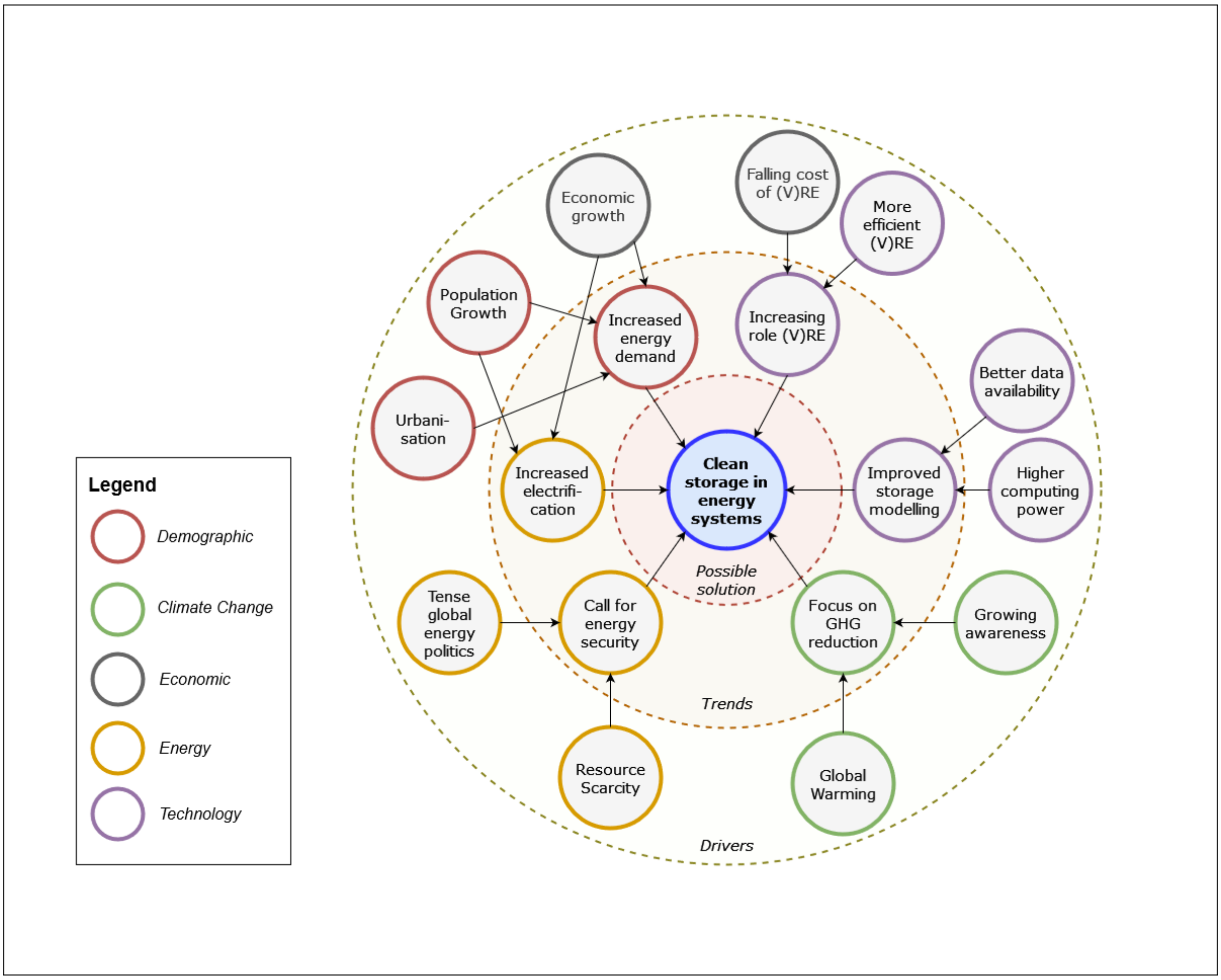


Figure 1: A schematic overview of drivers and trends of the global energy transition with a focus on clean storage in energy systems as a solution. The groups to which elements belong are indicated by the colour of the circle's outline. Drivers are connected to the trends that they prompt by arrows. A possible solution in the space of the trends is placed in the centre of the figure.

In the sections below, the connection between the trends of global energy transition and (clean) storage methods is elaborated.

2.1.1 Energy security

Energy security is a key trend in the global energy transition that partially originates from resource scarcity and the geopolitics of energy. Amongst other reasons, this is because global energy consumption is expected to continue to rise, driven by population growth and economic growth. At the same time, the availability of resources, such as fossil fuels, becomes more limited.

Resource scarcity is a critical driver in the global energy transition. The availability of traditional fossil fuels, such as oil, natural gas, and coal, is decreasing due to both rising demand and the depletion of finite resources. This is causing prices to rise, making energy security increasingly important. Additionally, the increasing severity of climate change has led to an increased focus on renewable energy generation, such as wind and solar power. As a result, the need for increased energy security is even more critical.

Global politics are also driving the global energy transition. As economies such as China and India increase their energy demand, there is a rising need to secure reliable energy sources. This has resulted in a heavier focus on energy security and developing cleaner, more sustainable energy resources. Additionally, geopolitical tensions, such as the war in Ukraine, have led to increased concern about energy security. As a result, global energy politics is a critical driver in the energy transition towards renewable sources.

These factors mentioned above lay the basis for improving large-scale energy storage methods in energy systems. Storage facilities such as batteries, hydrogen or pumped hydro storage provide energy security and independence from energy imports.

2.1.2 Focus on greenhouse gas reduction

Global warming and the effects of climate change are widely recognised drivers of the energy transition. Parallelly, the general public is becoming increasingly aware of the potential consequences of climate change. These drivers resulted in globally agreed energy targets for global greenhouse gas reductions.

Also, the growing recognition of the need to reduce global carbon emissions has further increased the focus on energy security, which is linked to the previous trend. Governments and businesses are increasingly looking to reduce their reliance on fossil fuels and to invest in renewable sources, such as wind and solar.

For these reasons, energy storage with low or no emissions could be more prominent in energy pathways to adhere to global climate policies and reduce carbon emissions.

2.1.3 Improved storage modelling

High-power computing solutions such as the Dutch national supercomputer Snellius are becoming increasingly available to researchers worldwide. Alongside this drive for faster computing, data quality and availability are improving globally. An example is the Model Supply Regions (MSR) (Sterl et al., 2022), which are elaborated on in section 2.3.5. In these MSRs and in Renewables.ninja, data on hundreds of high-potential solar and wind locations in Ethiopia has been made publicly available for this research. In addition, resources such as the Global Pumped Hydro Atlas (Blakers et al., n.d.), a result of a GIS algorithm identifying possible PHS locations, and Renewables.ninja make modelling energy pathways, including storage modelling, more easily accessible to energy researchers and practitioners.

The advancements in storage modelling also increase the understanding of storage capabilities to make widespread adoption easier. Furthermore, it helps energy storage investors and developers assess the economic viability of storage projects and identify which technologies are the most cost-effective when placed in a specific situation. In addition, improved storage modelling allows system performance evaluation for different energy supply scenarios, such as load-following and peak-shaving, to help optimise grid stability and resource utilisation.

All these drivers allow for improved research into pathways incorporating clean storage into energy systems.

2.1.4 Rising energy demand and increasing role of (variable) renewables

Global energy demand is expected to grow by 4% in 2022, with the majority of the growth (56%) covered by renewables, 40% by fossil fuels, i.e. gas and coal and the last part by nuclear power (International Energy Agency, 2021). For the large part, the contribution of renewable will be filled by solar PV and wind power. Parallel to this, the levelised cost of electricity for solar has dropped 88% for utility-scale PV from 2010 to 2021, with the onshore wind dropping 68% in the same period (International Renewable Energy Agency, 2022). Also, the efficiencies of solar and wind have grown by 3.4% and 12% in the same period. These factors forecast a more significant role for these variable renewables in the global energy transition.

With the boost in intermittent sources of electricity generation, the necessity for energy storage grows. Energy storage dampens the need to construct significant overcapacity of solar and wind to accommodate for days with low capacity. Storage contributes to peak shaving and boosts the resilience and flexibility of national energy systems.

2.1.5 Increasing electrification

Between 1990 and 2015, global access to electricity rose by 15%, from 71% to 86%, a trend expected to continue for the coming years. Primary drivers of this trend include higher global economic prosperity, a global movement from rural areas to cities and population growth.

The rising global electrification reduces emissions from power generation and paves the way for the generation of energy by renewable resources. Furthermore, increased electrification contributes to the worldwide energy transition by augmenting energy access. Higher electrification results in a higher renewable energy integration, e.g. by boosting the integration of electric vehicles, allowing for the heating and cooling of buildings or increasing the use of electric appliances in households. By generating electricity from clean energy sources and deploying decentralised energy systems and services, many countries are expanding access to electricity services in rural and remote areas.

2.2 Pumped Hydro Storage

Pumped hydroelectric storage (PHS) is a mature and highly used method of energy storage. The majority share of global energy storage, over 97%, is in pumped hydro facilities (Azzuni & Breyer, 2018). This chapter discusses the workings of pumped storage, the different types, its primary advantages and drawbacks and its place in an energy system with high variable renewable energy penetration.

2.2.1 PHS, how does it work?

Pumped hydro storage utilises gravity to store energy in the form of potential energy between two reservoirs. It mitigates fluctuations in energy supply and demand by storing energy during overproduction and releasing it during underproduction. PHS generally consist of an upper and a lower reservoir. The reservoirs do not necessarily have to be constructed from scratch, as existing infrastructure, such as dams, lakes or even old mines, can function as a reservoir. A generic overview of a system setup is presented in figure 2.

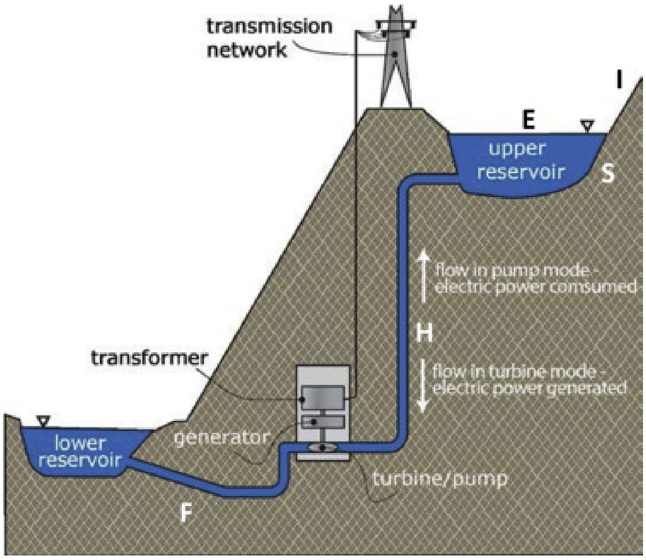


Figure 2: A generic pumped hydro storage system setup (Viadero et al., 2017)

During peak production hours or when the price of electricity is low, overcapacity is used to drive a turbine to pump water from the lower reservoir to a secondary reservoir located at a higher elevation. Subsequently, in a period of under-capacity or higher-priced electricity, the volume of water is discharged to power the generator by converting potential to electrical energy. The system is connected to a transmission network to supply and dispose of energy. The dynamics of storing and releasing energy in this way are called arbitrage.

The cycle of pumping and releasing the water can have an efficiency of 70-80% (Alnaqbi et al., 2022), going up to 87% in certain estimates (Rehman et al., 2015), which is relatively high compared to other methods. Solar and wind power have estimated conversion efficiencies of 20% and 40% respectively (Blakers et al., 2021).

Even though the concept of pumped storage is relatively simple, the construction of pumped hydro storage is subject to various requirements. Alnaqbi et al. (2022) elaborate on the technical requirements that are imperative to the construction site for PHS reservoirs. These are:

1. Geographical qualities that enable a minimal head between the two storage reservoirs ;
2. Absence of landslides or similar movement of the ground ;
3. Water resources are accessible and suffice in quantity ;
4. Infrastructure for electricity transmission and distribution is in place ;

Firstly, PHS requires both a substantial head and sufficient water supply. A bigger head results in increased gravitational energy potential. Because of the higher potential, it is possible to construct a smaller reservoir, potentially leading to lower construction costs. Furthermore, the ratio between the length of the waterway between the two reservoirs (L) and the head (H), expressed in L/H, is preferentially kept between 2 and 10 where a lower ratio is preferred (Kucukali, 2014). Foremost, this is because a shorter connection between the reservoir lowers construction expenses and hydraulic losses.

Secondly, the reservoirs must be filled through water resources such as nearby rivers or precipitation. PHS setups with a lower reservoir connected on a river or other waterway can utilise this incoming water directly. Once off-river pumped storage reservoirs are filled, there are generally low losses, as water can move between the two reservoirs without discharging downstream. A PHS reservoir that gets additional supply from precipitation or nearby water resources such as rivers could offset losses due to evaporation.

Lastly, the pumped storage needs to be connected to transmission and distribution networks to facilitate the input and discharging of electricity. The connection of the powerhouse to the grid is crucial. As discussed in section 2.2.3, lacking transmission or distribution infrastructure arises as one of the primary barriers to the implementation of pumped storage.

2.2.2 What types of pumped storage exist?

Three types of pumped storage exist: open-loop, closed-loop or off-river, and pump-back pumped hydro storage. This subsection discusses each of these methods one by one. The types of pumped storage discussed here do not cover all configurations, as site-specific properties allow construction to be adapted to a local situation.

Conventional pumped hydro storage is constructed in an open-loop configuration in which the lower reservoir is built on a waterway, e.g. river, and the upper reservoir is located off-river above it. Figure 3 details an example of such a configuration. The pump is placed beneath the lower reservoir to ensure complete filling of the connection and prevent cavitation.

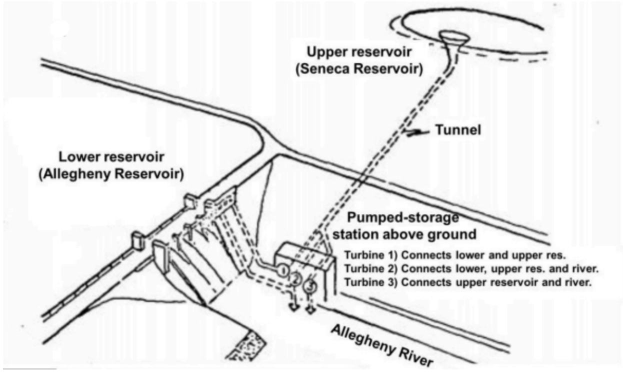


Figure 3: PHS: An open loop configuration (Kerr, 1977)

Globally, the vast majority of pumped hydro storage is considered open-loop. For example, the United States has 23 GW of pumped hydro capacity, which makes up 94 % of its bulk storage (National Hydropower Association (NHA), 2021). These pumped storage configurations are considered open-loop. A principal advantage of this setup is that it can be added to existing hydroelectric infrastructure or reservoirs, often reducing costs and construction time. Nevertheless, a potential risk with open-loop systems is that they interfere with the downstream water supply for ecosystems, communities and industry.

Closed-loop pumped hydro reservoirs consist of an upper and lower reservoir located outside of a waterway. This setup has less interference with the river course compared to open-loop PHS, thus reducing the environmental and ecological impact of operation and construction. Furthermore, off-river configurations have fewer geographical restrictions as they can be constructed multiple kilometres from rivers. Figure 4 shows a basic schematic overview of a closed-loop PHS setup. Closed-loop pumped hydro is expected to take a more prominent role in the future than open-loop setups. In the United States, all current PHS is open-loop. However, a significant share of the 67 planned PHS projects, with an expected added capacity of 50 GW, is made up of off-river systems (National Hydropower Association (NHA), 2021).

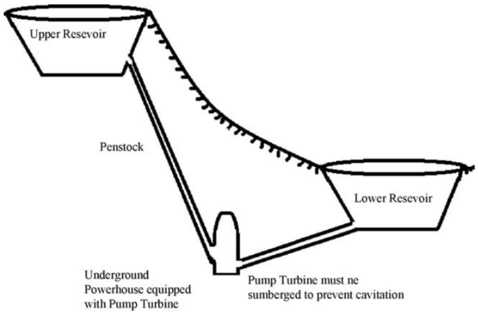


Figure 4: PHS: A closed-loop configuration (Deane et al., 2010)

Energy storage in off-river configurations is generally lower than when hydroelectric dams with a comparable power output are utilised but remains higher than other storage options. Blakers et al. (2021) illustrates this by providing an example of a hypothetical off-river configuration with two reservoirs, a 600-meter head, a 200-hectare area and a 20-meter depth. The assumed round-trip efficiency is 80%, and 90% of the water is available for use. This system can deliver 24 GWh at a power output of 1 GW. For context, the Hornsdale power reserve, one of the largest global lithium-ion battery storage facilities, only stores 0.129 GWh (*The Hornsdale Power Reserve*, n.d.). This shows that pumped hydro storage is still one of the most straightforward methods of storing large quantities of energy.

The Snowy 2.0 project in Australia is an example of an off-river system which improves renewable energy penetration into an energy system and reduces emissions, thus decreasing fossil fuel dependency. Two large reservoirs are connected by nearly 30 kilometres of underground networks. The system has a projected capacity of over 2 GW, 350 GWh (Snowy Hydro, n.d.). The modelled impact of Snowy 2.0 is increased variable renewable energy penetration compared to a baseline scenario without the facility. The construction decreases emissions by removing the need to construct additional coal power and decommissioning of current coal infrastructure. A crucial effect of Snowy 2.0 is that the storage enables 3,000 MW of additional variable renewable energy production and a reduction of 2,000 MW of gas-powered energy generation. This is illustrated in Figure 5. Snowy 2.0 portrays the capability of pumped storage to enable higher penetration of intermittent renewables.

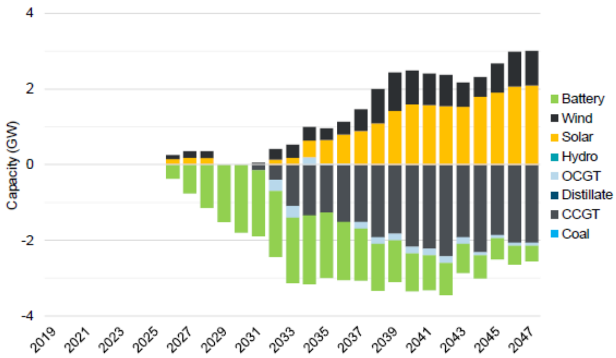


Figure 5: Change in Australia's National Electricity Markets' installed capacity due to Snowy 2.0 (Marsden Jacob, 2018)

Pump-back pumped hydro storage consists of connecting two hydropower dams on the same waterway already built to minimise construction costs and influence the river course. Here, the primary advantage is that it provides adaptability in that powerhouses can be used both for conventional hydroelectricity generation and storage (Hunt et al., 2022). Furthermore, a benefit of this system configuration is that it strengthens the water resources as downstream water, e.g. rain, can be pumped back upstream instead of flowing downstream.

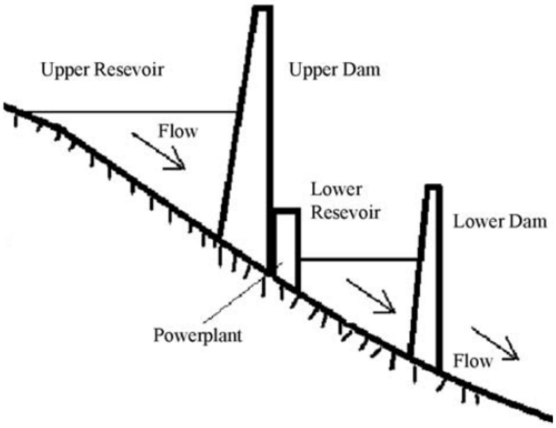


Figure 6: PHS: A pump-back configuration (Deane et al., 2010)

2.2.3 Advantages and limitations of pumped hydro storage

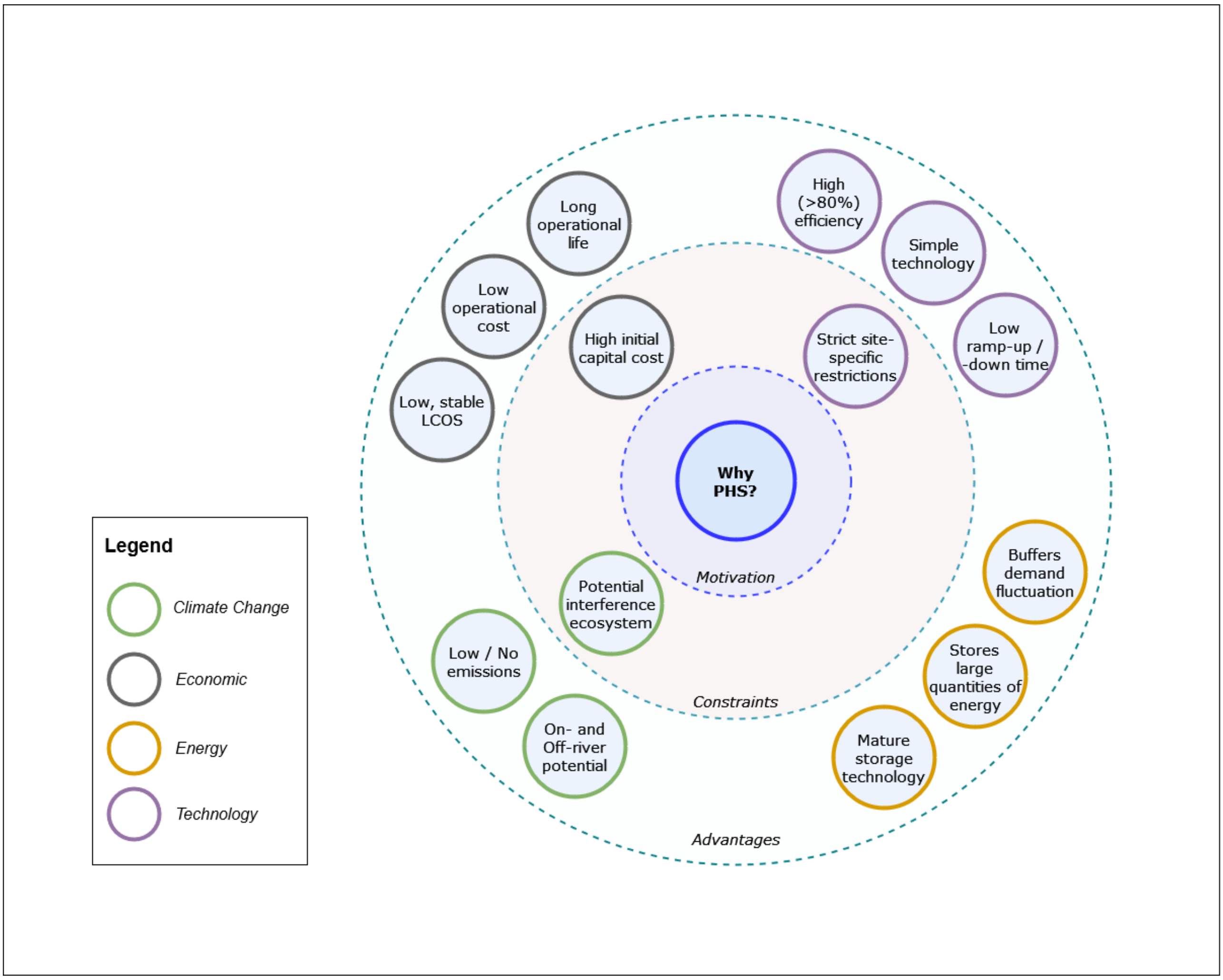


Figure 7: A schematic overview of the advantages, shown in the outer layer, and constraints, shown in the middle layer, of pumped hydro storage (PHS). These elements motivate the choice of PHS in the middle of the figure as a possible storage technology in energy pathways. The colour of the circle's outline indicates the groups to which elements belong.

Pumped hydro storage provides many benefits within an energy system, including large-scale energy storage, low ramp-up time and stable integration with variable renewable energy sources. An overview of the benefits and drawbacks of pumped hydro systems is found in figure 7.

Firstly, economic aspects favouring pumped hydro storage are a relatively low and stable levelised cost of storage (LCOS), low operational costs and a long operational life, generally over 50 years. Additional information on the (levelised) costs of pumped hydro storage is found in Section 2.2.5. Pumped hydro storage is a mature technology, with low operational and maintenance costs after construction. However, the primary drawback of pumped storage is the high initial capital costs. The high project investment is also the primary socio-economic barrier to pumped hydro storage, as found in a literature study by Ali et al. (2021).

Operationally, pumped hydro storage is a simple technology with a high round-trip efficiency of 80% or higher. Additionally, it has a low ramp-up time of seconds to minutes. This low ramp-up time enables it to respond quickly to fluctuations in energy supply and demand. Despite the simplicity of pumped storage, there are generally high site-specific restrictions that need to be adhered to construct a complete PHS system. Landscape topology is the second most reported inhibitor of PHS integration by (Ali et al., 2021).

Pumped storage reservoirs can store large quantities of energy in absolute terms and relative to other storage technologies.

Lastly, the environmental benefits of pumped storage facilities are that after construction, there are low to no emissions after the construction of the reservoirs. Also, construction can be done both on- and off-river. Primarily, on-river pumped hydro storage still risks high interference with the surrounding ecosystem.

In addition, to Figure 7, Ali et al. (2021) present a systemic literature review of the drivers and barriers of implementing PHS. The main driver of pumped hydro storage is increased resilience, elaborated in section 2.4.1. The most frequently occurring barrier was insufficient infrastructure, especially if transport and transmission were not present. Transmission is pivotal to the (dis)charging of energy between the reservoirs and the energy system.

2.2.4 Why choose PHS over conventional hydropower?

Conventional hydropower is a centralised, grid-connected solution to an energy storage problem. Consequently, reservoirs for traditional hydropower are large, resulting in significant investment costs and long construction times. Even though construction times are also long for PHS, a characteristic of PHS facilities is that they are cost and energy efficient at a smaller scale and thus can be placed more in a more decentralised fashion.

Secondly, on-river hydropower plants often heavily interfere with the river course, as they are an integral part of it. Generally, this interferes with the surrounding ecosystem and can have a major social impact, e.g. relocation of communities, change in the flow regime and affect the ecosystem (Kuriqi et al., 2021). Primarily off-river pumped storage allows reservoirs to be located away from waterways so as not to obstruct the flow directly. Off-river PHS can operate mostly autonomously as water is recycled between two storages. Consequently, this prevents or decreases the chance of ecological and ecosystem damage or relocation of communities around a river.

Lastly, the choice is not necessarily an either-or one, as pumped storage can be built as an addition to existing hydropower facilities if the geographic and hydrological situation allows it. This reduced capital cost and construction time.

2.2.5 The construction cost of pumped hydro storage

The cost of pumped hydro projects is a major factor in building PHS as a storage technology. High initial capital costs are one of the primary barriers to pumped hydro storage. The cost of building pumped hydro storage differs greatly from project to project. It is one of the most difficult metrics to homogenise for this research due to the variance in geographical, climatic and other site-specific properties. In addition to this, the accessibility of the site, existing transmission and distribution and country-specific policies and subsidies add to the complexity of determining a single cost value.

The financial expenses for pumped storage are divided into costs for power ($/kW) and energy ($/kWh). Firstly, the power costs are determined by the desired power output of the system. Here, the primary influence on the costs is the connection between the two reservoirs, generally in the form of a high-pressure pipe or tunnel. The energy generated by the system is described by Kucukali (2014) in equation 1:

$$P = \rho * g * Q * (H - \Delta H) * \eta \tag{1}$$

Where:

P = Generation Capacity [kW]
ρ = Density of water [kg/m^3]
g = Gravitational acceleration [m/s^2]
H = Head [m]
ΔH = Hydraulic head loss [m]
Q = Discharge [m^3/s]
η = Full-cycle efficiency of the system [-]

Here, the displaced volume of water per unit of time and the head between the reservoirs determine the system's power production. For example, if the needed output has to be doubled, twice the volume of water has to be displaced per unit of time, or the head has to be doubled. The power costs do not grow proportionally to this increase in power (Blakers et al., 2021), which makes it advantageous to construct larger tunnels to increase power. Additionally, the length of the pipe determines the system's power, as the longer the connection, the more power is needed to transfer the water from the lower to the upper reservoir.

Secondly, the stored energy in the system is depicted in equation 2 (Hunt et al., 2022):

$$E = H_{\text{av}} * S * g * e \tag{2}$$

Where:

E = Energy Storage [J]
H_{av} = Head [m]
S = Mass of water [kg]
g = Gravitational acceleration [m/s^2]
e = Full-cycle efficiency of the system [-]

The amount of energy stored in the system directly influences energy costs. Energy storage costs are also halved if the head is doubled or halved. Furthermore, the water-to-rock ratio, or the volume of water stored in the reservoir, affects the energy cost. More water storage means the power plant can operate for a longer period, thus decreasing the cost. For this reason, it is advantageous to construct larger reservoirs.

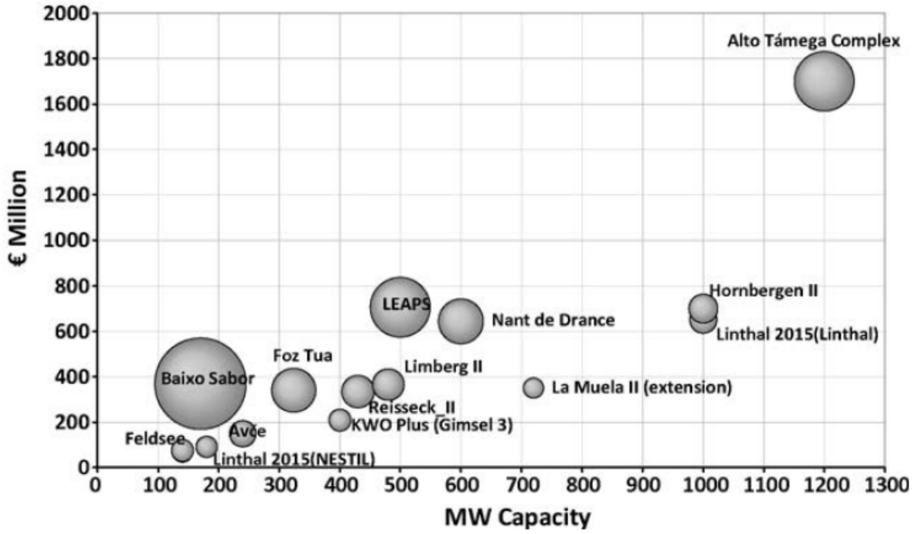


Figure 8: Cost [USD million] vs capacity [MW] for PHS in Europe. Y-axis is the full CapEx cost. The size of the bubble indicates the relative cost per MW. Plants in Switzerland and the US were converted to euros using the following exchange rates. (1 CHF = 0.6515€, 1 USD = 0.70715€). (Deane et al., 2010)

Figure 8 by Deane et al. (2010) illustrates the differences in capital cost between existing facilities in Europe against their respective capacities. The bubble size represents the relative cost per MW of installed generation capacity. The spread of facilities conveys that project costs are difficult to express in a singular value per unit of power ($/kW) or energy ($/kWh).

In addition to the power cost, project costs differ due to the varying construction requirements per project, e.g. in some instances, completely new reservoirs have to be constructed. In contrast, only the connection and turbine between two existing reservoirs are necessary in other cases. All of these aforementioned elements make it difficult to define a single cost per kW or kWh for constructing pumped hydro reservoirs for energy planning.

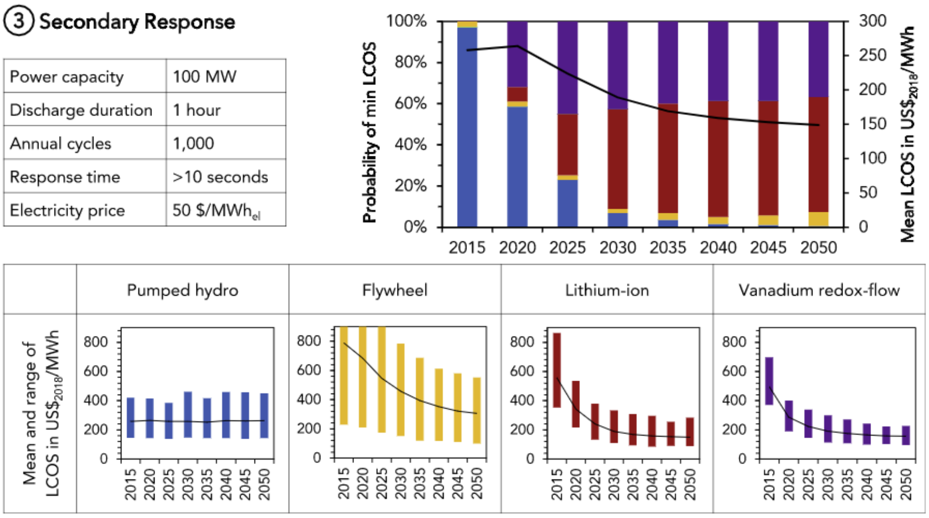
Nevertheless, estimations for the capital cost of pumped hydro storage systems exist. For this study, storage costs are applied per power unit (kW). Roberto et al. (2012) gives a range for the capital cost between 600 and 3000 \$/kW, depending on the project's power capacity and reservoir size. National Hydropower Association (NHA) (2021) indicates that projects around 500 MW have a CAPEX of about \$ 2500 per kW, and larger projects over 1,000 MW are associated with costs below \$ 2000 per kW. Two of the biggest global PHS reservoirs, Fengning in China and Bath County in the USA, have a respective cost per kW of \$ 519 and \$ 1342 per kW. However, this could also relate to differences in factors like the local cost of labour. This study uses a value of 2000\$ per kW to characterise PHS between small and large projects.

Energy arbitrage plays a pivotal role in the attractiveness of PHS to energy companies. Charging the reservoir in off-peak moments against a low price and selling it during peak time can be a robust way of trading energy. Storage can buffer off-peak overproduction of electricity to release during peak hours. However, electricity cannot be stored as is; it has to be converted to another medium, in this case, water. If electricity is needed, it has to be converted back from the storage medium to electricity, introducing round-trip energy losses. Despite energetic losses, this process can be financially beneficial under two conditions. Firstly, the price difference between peak and off-peak electricity has to be sufficient. Secondly, round-trip losses have to be relatively low (Crampes & Moreaux, 2010). If these requirements are met, pumped storage can be a cost-effective storage infrastructure.

2.2.6 Levelised cost of storage

In contrast to the high initial capital cost of pumped storage, the levelised cost of storage for PHS is one of the lowest for large-scale energy storage technologies. Levelised cost of storage is an expression of the financial aspects of storage, i.e. initial investment, operational and maintenance, charging and end-of-life cost relative to the produced energy. LCOS is therefore reported in costs per MWh.

Figure 9 (Schmidt et al., 2019) shows the projected mean LCOS for four major storage technologies between 2015 and 2050, accompanied by a range in which this LCOS can fall based on 500 Monte Carlo simulations. This study states that pumped storage is and will remain one of the cheapest forms of storage, ranging between $150 and $400 per MWh. After 2030, when PHS is expected not to be the cheapest option anymore, the price remains comparable to competitive technologies such as lithium-ion and redox-flow batteries. This is especially true for high volume and long-term energy storage, as pumped hydro stands above the rest in terms of operational life and stored energy.



Power capacity	100 MW
Discharge duration	1 hour
Annual cycles	1,000
Response time	>10 seconds
Electricity price	50 $/MWh$_{el}$

Figure 9: Application requirements (top left), probability of exhibiting lowest LCOS (top right), and explicit LCOS projections for four most competitive technologies, including uncertainty ranges based on Monte-Carlo simulation of LCOS calculation (bottom). Monte-Carlo simulation conducts 500 LCOS calculations per technology and year with random technology input parameter values from an 80% confidence interval of the parameter's attributed normal distribution, corresponding to 1.285 standard deviations from the mean. The top-right chart includes the mean LCOS of technology with the highest probability of being the most cost-efficient (black line). Probability reflects the frequency with which each technology offers the minimum LCOS accounting for the uncertainty ranges. Schmidt et al. (2019)

It should be noted that in Figure 9, the discharge duration is 1 hour, with a power capacity of 1 MW, giving it an energy storage capacity of 100 MWh. Looking back at figure 9, it is clear that this is on the low end for many pumped hydro reservoirs, whereas this is on the high end of the spectrum for lithium-ion batteries and flywheels. As mentioned previously, the Hornsdale Power Reserve is one of the largest lithium-ion battery facilities at 129 MWh storage capacity. In contrast, the largest pumped storage reservoir, the Bath County reservoir, stores 24,000 MWh.

Furthermore, the price stability of the LCOS for the coming 30 years makes investments in these systems more predictable. Additionally, pumped hydro storage is simple and requires only water as the primary energy transmitter. The other storage methods named in the article are limited by factors such as higher operational complexity, not being mature technologies, and relying on the mining of scarce materials. These drawbacks make pumped hydro storage an ideal option for countries that are projected to increase their variable renewable energy production and thus benefit from and require large-scale, long-term energy storage.

2.2.7 Pumped hydro storage combined with intermittent energy sources

Solar and wind energy are intermittent renewable energy sources, meaning that their availability fluctuates in time. Solar energy potential adheres to a relatively predictable pattern compared to wind energy, as it is always unavailable at night and fluctuates during the day. The result of their intermittency is that both these energy sources might not be available for energy production ath their full capacity during peak demand hours. For this reason, mature electric energy storage, such as pumped storage, is a solid addition to a system in which these variable sources constitute a large proportion of the energy system. This storage facilitates flexibility, enabling operations to be maintained at a required minimal output. When the system's electricity production exceeds the necessary demand, storage is charged, and it discharges when the demand exceeds production. Apt implementation of storage with wind and solar power reduces costs, enables a consistent energy output and increases flexibility. In turn, these factors may drive the faster penetration of renewable energy sources.

Wind power is set to increase rapidly in the following decades. For example, in Ethiopia, the case study for this research, the generation capacity for wind power is expected to increase 6.5 times over the coming 20 years. Bueno & Carta (2006) show that a combined wind-PHS system can reduce the waste of energy from a wind farm by up to 10% compared to a situation without storage. Canales et al. (2015) conclude that while initial capital costs are 33% higher for a wind-PHS system compared to a similar system with conventional hydropower, the net present costs after 20 years are only 47% compared to a traditional method as a result of reduced fuel consumption and decreased emissions. As such, it is established that the wind-PHS configuration accelerates incorporating variable renewable energy sources into the energy system.

Due to their complementary nature, solar and wind power are increasingly used together for variable renewable energy generation. In contrast with a singular source intermittent source, the system's total storage necessity decreases, resilience and energy security increase and the entire system could decrease in required size. The combination of solar and wind power reduces the required storage to meet demand as they often generate power at different times. When regions are linked, the necessary storage quantity goes down further as weather with high solar radiation or wind speeds can balance underproduction where the weather is less-favourable (Blakers et al., 2021). Figure 10 presents an example of a wind-solar-PHS setup. This figure depicts reservoir and generation technologies close to each other. However, with off-river PHS facilities, these can be located relatively far from each other.

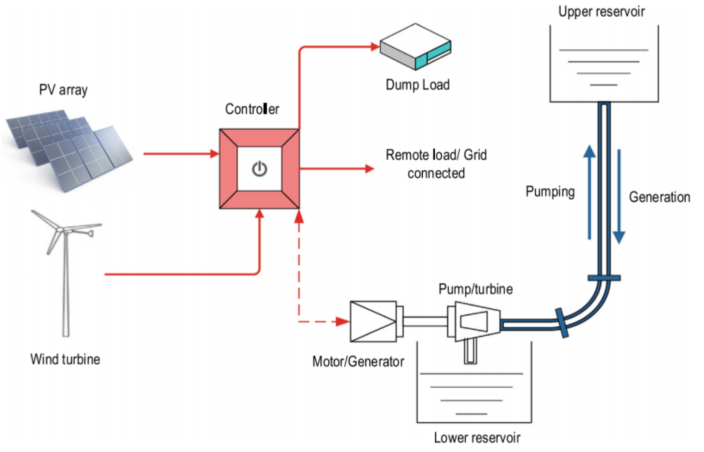


Figure 10: A possible wind-solar-PHS system Javed et al. (2020)

2.3 Ethiopia: A case study

This chapter discusses the motivation to choose Ethiopia as a case study for the implementation of PHS. Ethiopia's rapidly changing demographic, economic, and climatic situation is leading to a dynamic shift in energy demand and supply. Parallelly, intermittent renewable energy sources such as solar power and wind energy are projected to make up a larger share of the energy generation capacity. As discussed in the previous chapter, pumped hydro storage can function as a buffer to these intermittent energy sources, which provides an opportunity to research in the Ethiopian context.

2.3.1 The motivation for considering PHS for Ethiopia: An overview

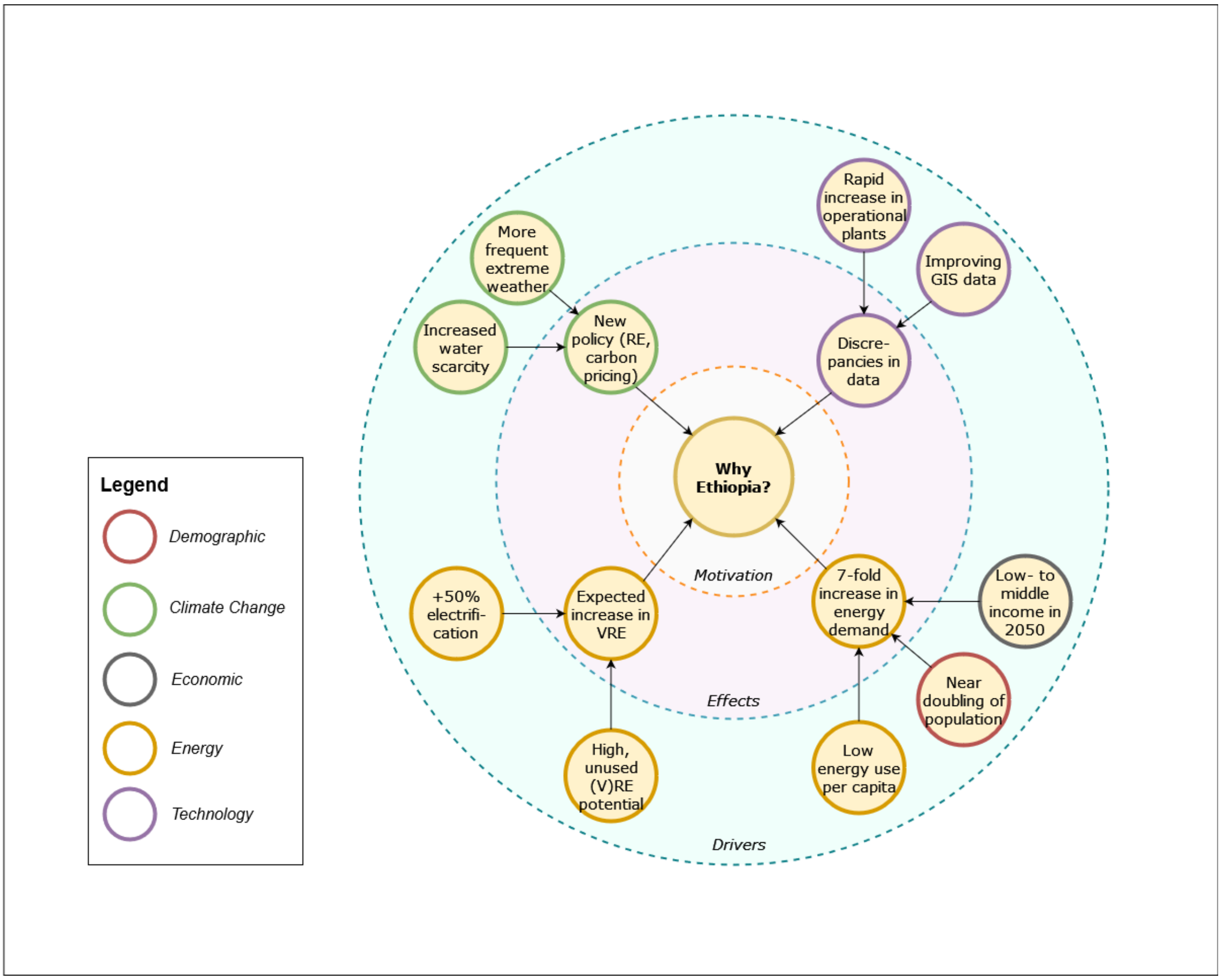


Figure 11: A schematic overview of the drivers and effect of the energy transition specific for Ethiopia. The central question of why Ethiopia is chosen as a case study is located in the centre of the image. The drivers of the energy transition are located in the outer shell. Its subsequent effects are shown in the middle ring, and are linked with driver through the arrows. The groups to which elements belong are indicated by the colour of the outline of the circle.

Figure 11 illustrates the primary drivers and their subsequent effects that constitute the motivation for choosing Ethiopia as a target country for the study. The details of these elements are described in the subsections below. The drivers and effects are categorised into five type: Demographic, Climate Change, Economic, Energy and Technology. The effects shown in the middle ring, namely policy, expansion of (variable) renewables integration, increased energy demand and data discrepancy are discussed in detail in the following sections.

2.3.2 An introduction to Ethiopia

Ethiopia is located in the Horn of Africa, the northeastern part of the continent. Economically, Ethiopia classifies as low-income. It ranks at the bottom for various global economic indicators, such as GDP (95 bln USD, 2019), inflation rate (20.35%, 2021) and per capita income, as well as the human capital index (World Bank, 2014). In contrast, the country consistently ranks amongst the highest in annual GDP growth (9.4%) and population increase (37% between 2010 and 2020). Ethiopia currently has a population of 120 million, which is expected to increase to 200 million by 2050. Lastly, Ethiopia aspires to be a lower-middle-income country by 2030 and progress to a middle- to higher-middle-income country between 2040 and 2050.

Just as in other countries in Sub-Saharan Africa (SSA), climate change is expected to have severe consequences for water, food and energy availability and economic advancements in Ethiopia. Ramifications include, but are not limited to increased potential evaporation, more frequent droughts, higher water demand, also through population increase, a higher frequency of extreme weather events, changes in land use and reduced crop yield. Figure 12 illustrates the dynamics of climate change-induced droughts and how it drives land degradation (Hermans & McLeman, 2021).

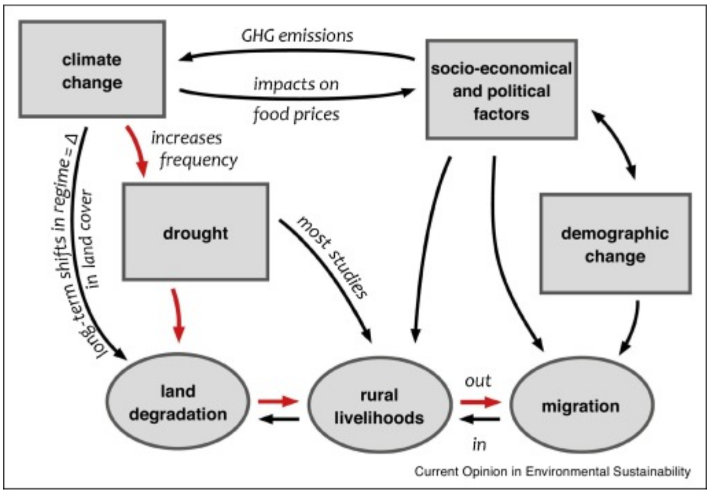


Figure 12: Causal linkages between climate change, drought, land degradation and migration (Hermans & McLeman, 2021)

Ethiopia's agriculture is primarily rain-fed. Therefore, drought frequency is an important parameter. Drought frequency increased from once per decade forty years ago to yearly between 1990 and 2011 (Mekonen et al., 2020). Consequently, in 2050, GDP losses related to agriculture are expected to be 31.1% (Solomon et al., 2021). In addition to drought, Ethiopia is subject to significant demographic changes, as the previously mentioned population and electrification increase. In 2021, 78 per cent of the population lived in rural areas compared to 90 per cent in 1980 (World Bank, 2021c). This number is expected to drop further in the coming years. Lastly, nationally determined targets to reduce GHG emissions try to prevent the worsening effects of climate change.

In 2014, Ethiopia had a per capita electricity consumption of just 69 KWh, compared to 6713 and 1683 KWh for the Netherlands and Egypt, respectively (World Bank, 2021b). There is a large push towards increased electrification of the the country. Country-wide access is lacking. Only 47% of Ethiopians had access to electricity in 2019. This is up from just 12% in 2000 (World Bank, 2021a), indicating a 7.5% annual growth rate. If this trend continues, Ethiopia will have full electricity access by 2030. To add to this, people with access to electricity often utilise unreliable, unsustainable and outdated energy sources (Dingeto Hailu & Kalbessa Kumsa, 2021). In addition to full electrification, Ethiopia strives to expand its position in Eastern Africa as an electricity exporter. Sridharan et al. (2019) project that Ethiopia could export 15% of its annual electricity production. In line with this projection, the government aims to become an export hub for electricity in the East African Power Pool (EAPP). A decrease in water availability in the river flow in the Blue Nile basin is expected due to climate change. This makes a strong case in favour of PHS, which holds water, especially in off-river settings.

As a result of the aforementioned drivers, the water and energy demand of the country rises steeply and there is a call for improved energy security. Gebremeskel et al. (2021) forecast that Ethiopian energy demand rises between 6- and 7-fold between 2020 and 2050, depending on chosen scenario to a maximum of 289 TWh from a current level of around 40 TWh annually. This underscores the importance of a reliable energy supply and the increase of a resilient energy mix.

2.3.3 Etiopia's renewable energy potential

Ethiopia has abundant resources for the generation of renewable energy in the form of geothermal energy, hydro, solar and wind potential. Firstly, Ethiopia has gigantic hydropower potential. The technically and economically exploitable capacities of hydropower in Ethiopia are over 260 and 162 TWh per annum respectively. For reference, in 2040, the complete electricity demand of Ethiopia is expected be 161 TWh (World Energy Council, 2010). Only a fraction of this is currently utilised. In 2019, just over 13.5 TWh was generated by hydropower, which is 5.2% and 8.3% of the technical and economical potential.

Mega-projects such as the construction of the Grand Ethiopia Renaissance Dam (GERD) the last decade, indicate Ethiopia's desire for energy security and increased economic growth. The GERD has a capacity of 6 GW and is expected to produce 54 PJ or 15 TWh of energy annually (Kahsay et al., 2015). Before the construction of the Grand Ethiopian Renaissance Dam, the largest hydropower generation facility was Tana Beles at 460 MW. Tana Beles illustrates the challenges that the region faces in relation to consistent power generation. High climate variability in Ethiopia has as a consequence that optimal power generation only occurs after the rainy season. Because of this, the effective period is less than half a year. When the reservoirs capacity is depleted, Tana Beles is only able to operate at fifty percent of its maximum. Subsequently, when the driest season arrives, the energy demand is at a peak, whilst the plant is not able to meet these demands due to low reservoir levels (Tilahun, 2012). In addition to energy storage, off-river pumped hydro reservoirs are less susceptible to seasonal variation in water availability as water can be cycled between the two reservoirs nearly indefinitely. For this reason, pumped hydro can also increase water security in Ethiopia.

Additionally, the country has a large potential for other renewable energy sources, such as solar (16.5 GW) and wind energy (6.0 GW) (International Renewable Energy Agency (IRENA), 2021). In 2019, installed wind and solar energy capacity were 324 and 11 MW resp. (International Renewable Energy Agency (IRENA), 2020). The projection is that this increases to 2.098 MW (6,5x) for wind and 18.131 MW (1650x) for solar PV in 2040 (International Renewable Energy Agency (IRENA), 2021). Additionally, Ethiopia wants to focus on increasing the grid resilience, increased electrification and move away from fossil fuels.

Currently, Ethiopia relies heavily on biomass for its energy production. In 2018, 88% of total primary energy production came from biomass and waste (Pappis et al., 2021). An issue with biomass use in Ethiopia is that it is inefficient en emits greenhouse gases. Thus, fuel-saving technologies could have benefits that include reduced pressure on resources and higher energy yield (Damte & Koch, 2011).

With Ethiopia's energy and electricity demand expected to rise quickly and steeply, and the penetration of intermittent renewable energy sources poised to increase, the country stands to benefit from large-scale energy storage. In 2020, there was 0 KW installed PHS capacity in Ethiopia and only 3.4 GW in Africa. Front runners in the integration of pumped storage such as the United States and China have 23 and 36 GW respectively. Pumped hydro storage comes with high initial capital costs and long construction times. However, the latter is less relevant for Ethiopia as of right now, as it stands at the beginning of its expected growth period. This moment presents an opportunity because of the unique situation of Ethiopia. Therefore, **the goal of this study is to investigate if the**

incorporation of pumped storage into the energy system of Ethiopia assists in reaching its goals in terms of energy export, electrification, economic growth and resilience. This next section discusses the quantity of pumped storage that is realistic for Ethiopia to achieve in a global context.

2.3.4 Storage capacity: What is realistic?

Ethiopia aims to grow from a low- to a middle-income country, accompanied by complete electrification of its population. For context, the per capita annual electricity use of Australia was around 140 times higher at 9,000 kWh compared to 64 kWh in Ethiopia. Blakers et al. (2021) estimate that for a country similar to Australia around 1 GW or 20 GWh per million inhabitants of storage is necessary to facilitate a 100% penetration of solar and wind into the energy system. However, it is difficult to directly translate this to Ethiopia. Australia is a high-income country with a mature energy market. Therefore, this calculation based on the number of inhabitants does not work for Ethiopia and an estimation based on daily consumption will be used.

Here, the rule of thumb is that an energy system with high levels of intermittent renewables requires a storage capacity of 1 day of energy consumption. This is because it enables a daily demand to be met in case of large fluctuations. For this research, a storage of 10 hours is used as this is generally applied for pumped reservoirs. Table 1 shows the current and planned penetration of pumped hydro storage to support a fully renewable energy system for Ethiopia.

	Year	**Installed PHS**		**Daily Electricity Consumption (DEC)**	**PHS/ DEC**	**VRE Production**	**PHS / VRE**
		GW	*GWh*	*GWh*	*%*	*GWh*	*%*
USA	2022	22.9[1]	229	10,929[3]	2%	1,093	21%[4]
	Planned	75.4[1]	754	14,077[3]	5%	2,815	27%[4]
China	2022	36[5]	360	22,775	2%	2,733	13%
	2025	90	900	22,775	4%	4,555	20%
Japan	2022	27[5]	270	2,591	10%	259	104%
Ethiopia	2015	0	0	25	0%	1	0%
ETH Scenario 1	2050	7.8	78	521	15%	390	20%
ETH Scenario 2	2050	39	390	521	75%	390	100%

Table 1: Penetration of pumped hydro storage in the USA, China, Japan and Ethiopia including two scenarios for Ethiopia in 2050. [1](National Hydropower Association (NHA), 2021) [2](Zhu & Ma, 2019) [3](Office of Energy Analysis, 2022) [4](Congressional Research Service (CRS), 2019) [5] (International Hydropower Association (IHA), 2022)

The results indicate that even the front runners in implementing pumped hydro storage in the context of variable renewable energy production are not expected to reach more than 10 per cent shortly. For this reason, the penetration of pumped hydro storage based on daily consumption is not expected to increase to over 10 per cent. As a result, the applied maximum storage capacity is 7.8 GW for 10 hours or 78 GWh. The following section illustrates the optimal regions to construct solar PV and wind. The importance of evaluating optimal regions for VRE construction is to maximise yield from these resources and identify the ideal locations to build storage to work optimally in tandem with these intermittent energy sources.

2.3.5 Model Supply Regions

Sterl et al. (2022) present IRENA's work on the potential of solar and wind power in Africa. Per country, the top five per cent of suitable locations based on factors including the levelised cost of electricity, resource quality, distance from the grid and land use are provided. These regions are called 'Model Supply Regions (MSR)'. In short, these model supply regions are identified and studied to better understand the availability of solar, wind and other renewable energy resources. The primary reason for establishing model supply regions is that they provide countries with the necessary information to make efficient and useful decisions on renewable energy development. By identifying the best sites for renewable energy installations, countries can focus their energy deployment efforts in those areas, thus ensuring a cost-effective approach to renewable energy.

Figure 13 depicts the location of these regions in Ethiopia. This research uses these MSRs as a basis for future solar PV and wind construction. A description of how the model supply regions are utilised to create scenarios is found in section 3.5.3.

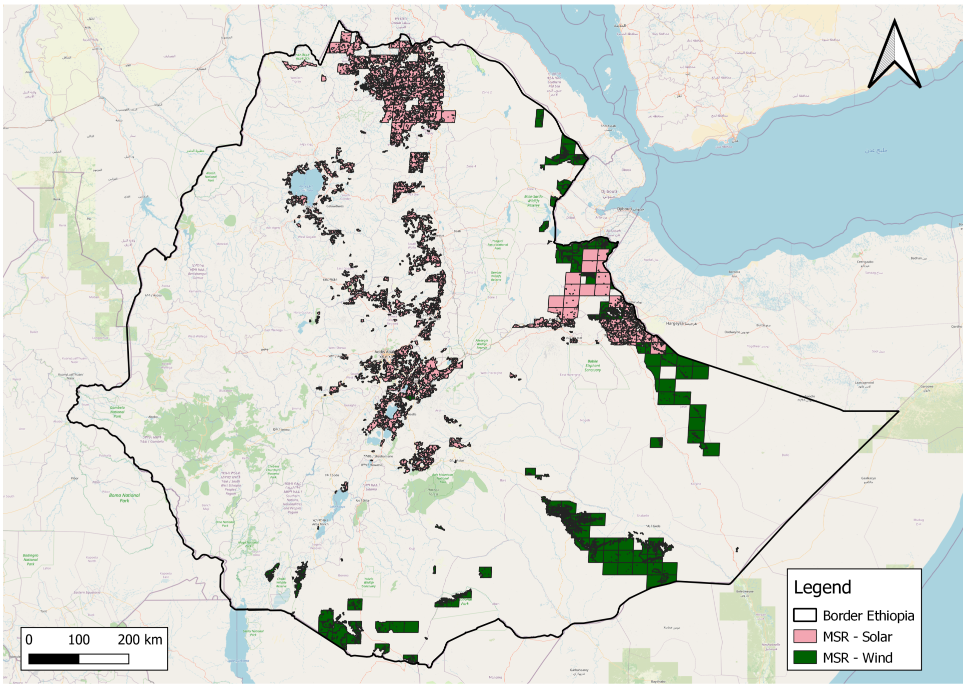


Figure 13: Ethiopia: Model supply regions for solar and wind power. Data adapted from Sterl et al. (2022)

2.4 Qualities of an energy system: Resilience and flexibility

This section elaborates on the interpretation of resilience and flexibility in the context of this research and its applications for pumped hydro storage. The resilience of an energy system is a measure of the adaptability of the system to abrupt, significant disturbances in either the short- or long-term whilst continuing its core operations. In other words, a resilient system can remain operational in a disruptive environment. Flexibility is the ability of the system to adjust to changing demand and supply conditions and match the two in time. In this section, indicators for *resilience* are first evaluated. Indicators for flexibility are outside the sphere of this study. Secondly, resilience in the context of pumped storage is analysed.

2.4.1 An interpretation of resilience and flexibility

Resilience and flexibility are two important qualities of an energy system. Flexibility refers to the ability of the system to adjust to changing demand and supply conditions. This includes adjusting the supply of energy to meet sudden changes in demand or quickly switching from one energy source to another if one becomes unavailable. A flexible energy system can better respond to changing customer needs and market conditions. Resilience refers to the ability of the system to recover quickly from disruption or crisis. For example, if a natural disaster were to occur, an energy system with high resilience would be able to quickly adjust to new conditions and continue to provide energy to large proportions of customers. Other examples of factors that challenge the resilience of a system are:

- Fluctuations in energy prices e.g. the rise of gas and electricity prices as a result of the war in Ukraine and the conflict between European countries and Russia have changed demand and production.
- Consequences of climate change are expected to test global energy system severely. Factors including increased extreme weather events, the temperature changes, variation in weather patterns and more put a strain on conventional energy systems.
- Policy decisions regarding restrictions on the emission of greenhouse gases (GHG) disincentivise fossil fuel investments and call for increased renewable energy capacity. Suppose countries rely substantially on traditional methods of energy generation. In that case, a sudden necessity to steer towards renewables potentially driven by war, price increases or global policy changes can pose a threat to the system and its consumers.
- High reliance on intermittent renewable energy sources such as wind or solar power increases vulnerability to changing weather conditions. If expected wind or solar energy is lower than anticipated, power generation might fail to supply the required demand.
- Countries or systems can be dependent on the import of energy resources from other parties. When the energy supply is disrupted, the recipients of the energy are vulnerable to failing to meet their energy demand.

Resilience is relevant for complex systems that rely on continuous supply and energy availability. Ethiopia is poised to increase the complexity, quantity and quality of its energy output and use. Parallelly, moving towards a higher share of renewable energy sources combined with the doubling of electricity access of the Ethiopian population and general development of demand introduce the necessity for a resilient system.

The interplay between resilience and flexibility is essential for an energy system to work efficiently. Resilience allows the system to quickly recover from unexpected events, while flexibility allows the system to respond to changing supplier and customer needs. The combination of these two qualities enables an energy system to remain reliable and secure and to provide customers with the energy they need.

For this thesis report, indicators of *resilience* are used to qualify the operations of the systems. The flexibility of the system is left out of the scope of this research. From the prior definitions, the question arises of how to make these elements quantifiable. The following indicators of resilience are chosen to be relevant in the context of this research.

Indicator	**Measured by**
Demand satisfaction	Percentage of demand that is met by the system
Renewable energy penetration	Percentage of energy production met by renewable energy
Storage / Daily VRE production	The storage quantity as part of the daily variable renewable electricity production

Table 2: Resilience indicators

These indicators were chosen because they can be quantified in all scenarios. However, these cover only a small part of the spectrum of resilience indicators. Further information on the recommendations for subsequent research on these indicators is found in the chapter 7.1.

2.4.2 Pumped storage in the context of resilience

Energy storage boosts resilience as it assists in the mitigation of demand or supply imbalances. Pumped hydro storage, combined with intermittent sources of energy, add resilience to the grid by smoothing energy output and using the complementary properties of the intermittency of solar and wind power. PHS improves the resilience of the grid by providing a source of backup power. When the production goes down, pumps can reverse and release stored water to generate electricity. This makes pumped storage a key technology in improving energy system resilience.

A systemic literature review by Ali et al. (2021) finds that the benefits of PHS to grid resilience are considered the main driver of its integration into an energy system. The powerhouse of a pumped storage reservoir generally responds to abrupt discrepancies in energy supply or demand, in turn, time-shifting peaks as well as being able to respond within minutes. Also, energy systems that rely heavily on technologies with long ramp-up times for the production of the base load of energy e.g. nuclear energy benefit from the increased flexibility that large energy storage with low ramp-up time i.e. pumped hydro brings. During the night, excess energy production at a low cost is utilised to pump up energy. Additionally, during the day, when demand might exceed base-load production, discharging energy from PHS prevents increased production by the conventional methods, often CO_2 intensive gas-fired thermal production.

As mentioned previously, Ethiopia will heavily increase its share of intermittent renewable energy generation. If the country adapts policies to reduce emissions from fossil fuels, the necessity for storage of excess energy from these renewable sources becomes increasingly relevant. To add to this, the complexity of Ethiopia's energy system will rise as a result of the forecasted seven-fold rise in energy demand (Gebremeskel et al., 2021). Pumped hydro storage provides the possibility to increase the overall resilience of the system by serving as a buffer for intermittent energy sources and providing long-term storage.

2.5 The ambition of the study

This section elaborates on the ambition of this study through the research objective and the subsequent research questions.

2.5.1 The research objective

Section 2.1 presented the primary trends in the global energy transition that are relevant for this research. These trends include:

- rising global energy demand,
- increasing (variable) renewable energy generation,
- improving storage modelling,
- legislation focused on greenhouse gas reduction,
- a need for increased energy security, and
- expanding global electrification of end-users.

In the space of solutions, the incorporation of clean, large-scale energy storage in long-term energy pathways can be part of the answer to the aforementioned dynamics. Storage capacity has the possibility to buffer intermittent renewables, save overproduction for periods of under generation, which in turn increases energy security and could help in meeting rising energy demand. As section 2.2 details, pumped hydro storage fits the requirement for such a storage solution.

Parallel to this, Section 2.3 places the global trends in the energy transition in the context of Ethiopia. Ethiopia is projected to nearly double its population, grow from low- to lower-middle or even middle-income country by 2050 and experience a seven-fold increase in energy demand. All these factors lead to the research objective studied in this MSc. thesis. The results of this work are shown in this report.

The objective of this research is to explore the introduction of PHS in Ethiopia's energy pathways, and understand whether and under what scenarios/conditions it could:

1. increase energy system resilience and flexibility,
2. reduce fossil fuel dependence,
3. be financially viable,
4. accelerate (variable) renewable energy integration.

This objective leads to the research questions discussed in the next section.

2.5.2 The research questions?

1. What are the effects of introducing pumped hydro storage on Ethiopia's energy pathways?
    (a) What is the potential for PHS to increase (variable) renewables penetration towards a fully renewable electricity mix?
    (b) What are the consequences of different CO2 taxation strategies?
    (c) If pumped storage is adopted in the energy pathway, what do the storage dynamics look like?
2. What is the influence of pumped hydro storage on the resilience of the future Ethiopian energy system?
3. Which locations or regions in Ethiopia are suitable to place PHS facilities?
4. What is the influence of discrepancies between operational wind farm and GIS data for wind power on the long-term energy pathways of Ethiopia, and how do these dynamics interact with questions on the viability of PHS?

3 Methodology

In this chapter, the methodology of the thesis research is explained. First, an overview of the working process is provided. Then, the modelling tool OSeMOSYS, its advantages and limitations and the used PuLP version are described. Section 3.3 shows the operations of a reference energy system in OSeMOSYS. Subsequently, section 3.4 elaborates on the creation of a baseline scenario for Ethiopia, which transitions into section 3.5, which demarcates the conditions for all the scenarios. Lastly, section 3.7 describes the incorporation of the pumped hydro atlas into the thesis work.

3.1 Overview of methodological approach

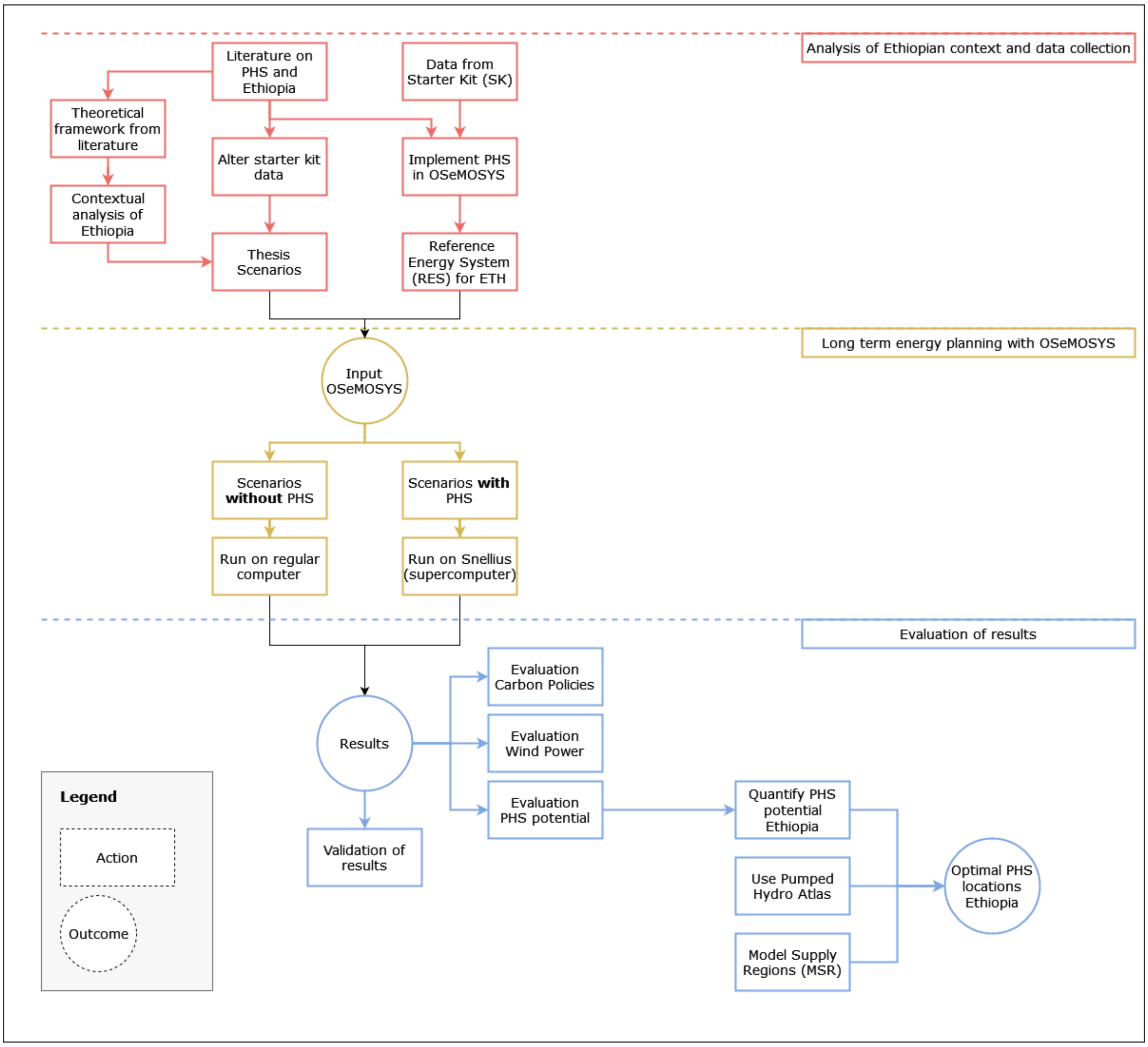


Figure 14: Overview of the methodological approach

Figure 14 illustrates the structure of the thesis work. Firstly, the basis for the data on Ethiopia's energy system was derived from the Starter Kit, which is further elaborated on in section 3.4.1. This dataset was altered with specific data from literature, e.g. electrification of transport or the incorporation of clean cooking in Ethiopia. Also, in this part of the thesis work, a reference energy system for Ethiopia was constructed that included pumped hydro storage, shown in section 3.4.5. The following thesis scenarios are derived from the theoretical framework and the starter kit data. Combined with the reference energy system, this forms the input for the OSeMOSYS modelling tool.

The modelling in OSeMOSYS is down in two ways. Firstly, the scenarios without pumped hydro storage (PHS) are run on a regular computer. Secondly, the pathways in which PHS is incorporated are run on the Dutch national supercomputer, Snellius. The necessity for the supercomputer is elaborated in section 3.2.5.

Lastly, the results from the modelling process are used to answer the three main scenarios, namely the base case that studies pumped hydro potential, a scenario for carbon pricing and a scenario for wind power. The results from the PHS potential are used, together with the Pumped Hydro Atlas and Model Supply Regions, to estimate the optimal pumped hydro locations in Ethiopia.

3.2 Energy system modelling with OSeMOSYS

Various modelling tools for energy planning can be used to study long-term energy planning, such as MARKAL, TIMES and OSeMOSYS. These models are comparable to OSeMOSYS in that they are linear programming software, minimise cost and are based on technologies and commodities flows. OSeMOSYS is chosen for this research because it is freely available and relatively easy to use. This chapter elaborates on the workings of OSeMOSYS, its building blocks, i.e. sets, units and parameters, the representation of time, the use of the Snelius supercomputer and the used version of OSeMOSYS, namely PuLP.

3.2.1 The OSeMOSYS framework

OSeMOSYS, the Open Source Energy Modelling System, is a free, bottom-up, long-term energy planning tool that optimises an energy system's discounted costs while adhering to an array of end-use demand criteria. It is deterministic and applies linear optimisation based on algebraic statements to calculate the objective function. The objective function minimises the net present costs of the energy system and presumes competitive markets and perfect foresight. Additionally, OSeMOSYS strives to make energy planning more readily available to a broader audience as it is open-source and relatively simple to use. In contrast, other modelling tools require high initial investment expenses and/or intricate knowledge of modelling software.

OSeMOSYS was designed to facilitate a plethora of (de)centralised system configurations, that vary in size and time horizon. This enables the investigation into multiple strategies for communities on levels ranging from a local community to a country-wide or even continental scale. Also, it allows for flexibility in its approach to the representation of conversion technologies, e.g. power plants, resources import and mining or energy delivery. An extensive host of techno-economic specifications and restrictions define these technologies, including but not limited to monetary aspects like capital and fixed costs to power generation efficiencies and capacity factors.

Figure 15 illustrates the structure of the OSeMOSYS modelling framework.

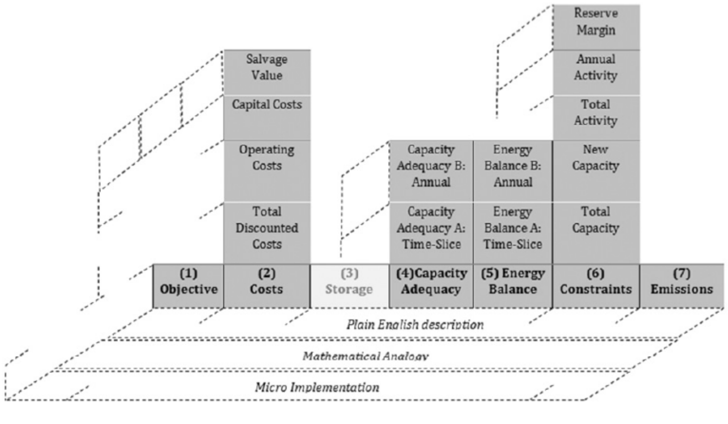


Figure 15: OSeMOSYS: Model structure in blocks and the levels of abstraction

Figure 15 displays seven groups of blocks that structure the operations in OSeMOSYS. Combined, these blocks entail the complete energy system modelling. However, blocks can be added or removed to alter system functionality. Blocks 3, which represents storage, is highlighted in light grey and is an example of a block that was originally not present in OSeMOSYS but was added later. There is storage functionality in OSeMOSYS, but it is currently being expanded. This research strives to be part of that expansion.

Furthermore, the following three degrees define the abstraction of the model elements (Howells et al., 2011).

1. **Plain English Description**
   Documentation used to facilitate clear communication and motivation of choices between the modeller and the user.
2. **Mathematical Analogy**
   The mathematical translation from the explanation in English to the chosen modelling software that depicts used variables, parameters and other system actors.
3. **Micro-Implementation**
   Software or programming language used to implement modelling choices.

In addition to the structure, as mentioned before, the organisation of the technologies and other elements is described in a Reference Energy System (RES). The mechanics of the RES are elaborated on in section 3.3. A comprehensive overview of important sets, parameters and unit is provided in appendix A.

3.2.2 Advantages and drawbacks of working with OSeMOSYS

Advantages
The main benefit of using the OSeMOSYS modelling tool is its comprehensive and detailed assessment of energy systems. It provides an integrated synopsis of a region's energy supply and demand dynamics, including renewable energy sources, energy-consuming sectors, and energy storage systems. The model can also capture the interactions between energy supply and demand and trading and transportation costs. This extensive analysis of a region's energy system can be applied to develop more cost-effective and sustainable energy policies.

Secondly, its ability to model the impact of various energy pathways within a single framework is a major benefit of OSeMOSYS in the context of long-term energy and storage modelling on a national scale. Users can create models to explore the different energy pathways, as well as their costs and environmental impacts, thus allowing for a more comprehensive understanding of national energy systems. Additionally, OSeMOSYS is highly scalable, allowing for the modelling of different sizes of systems from local to international, ensuring that the model is applicable at different scales.

Furthermore, OSeMOSYS provides an open-source framework that allows anyone to access and use the model. This level of accessibility means that researchers, policymakers and activists can use the model to assess potential energy solutions and inform decisions that affect the future of energy supply on a national scale. In addition, OSeMOSYS is highly customizable, leading to better outcomes and more insightful results.

Another significant benefit of OSeMOSYS is its flexibility. It offers a wide range of settings to allow the user to tailor their model to the specific energy system of their region. These settings include selecting energy sources, including renewables, setting up energy markets, and adding storage. This makes the model particularly useful for policymakers and energy planners, as it can be adapted to simulate the impacts of specific energy policies.

Drawbacks
Modelling in OSeMOSYS can be complex and requires a certain level of technical expertise to use. The user must be well versed in the terminology of energy systems, as well as the principles underlying energy modelling. This level of technical knowledge may be out of reach for some users. OSeMOSYS partly provides this information through its Open University course, freely available online.

Secondly, the linear modelling in OSeMOSYS is sub-optimal for representing real-life storage dynamics, as these are generally highly dynamic and non-linear. In the case of pumped storage, only a single charge or discharge can occur during a timeslice. In this research, a timeslice represents 2 days of a year. However, real-life operations of storage dynamics are much more intricate and heterogeneous than can be reasonably modelled in OSeMOSYS.

Another limitation of modelling storage dynamics in OSeMOSYS is that the time resolution has to be drastically expanded to enable a representation of (dis)charging of the reservoir. For this research, the scenarios that included storage had to be expanded from 8 to 360 timeslices in a single year. With this, data handling becomes much more error-prone as this has to be adapted manually for each scenario in Excel. Additionally, a regular computer cannot run the model, which requires supplementary computing power to be purchased in the form of the Dutch national supercomputer.

3.2.3 The PuLP version of OSeMOSYS

This study utilises the PuLP version of OSeMOSYS, which has the benefits of featuring Monte Carlo simulations and being worked and collaborated on by colleagues from the KTH Royal Institute of Technology in Stockholm. With PuLP, the modelling process focuses on the input data-file and not on hard-coding of the model. Widely used solvers such as CPLEX and Gurobi can easily be used to solve optimisation problems with these data sets. This also allows for easy implementation of different data files as input for the model, making it easier to model a range of scenarios.

OSeMOSYS-PuLP introduces the possibility for stochastic elements to influence the model's outcome. In many cases, there is uncertainty in the value of parameters. Examples of this uncertainty are the intensity of solar or wind power on a specific day or the cost development for a particular technology. OSeMOSYS PuLP allows for using Monte Carlo simulations to implement the ranges and probabilities for values of these parameters. We can then evaluate what the different outcomes will be and what influences this random behaviour has on the model's outcome.

3.2.4 The representation of time

An adequate and comprehensive representation of time is crucial to accurately depicting the energy systems dynamics. Factors such as demand, costs and weather patterns change throughout time, ranging from an hourly to multi-annual scale. Therefore, the choice of an apt time scale resolution ensures capturing system dynamics whilst parallelly keeping system complexity and subsequent runtime to a minimum.

Ethiopia experiences four distinct three-month seasons. The input data separate between these seasons to reflect the difference in solar irradiation and wind availability. Furthermore, the days within these seasons are divided into a day and a night. This initially leads to a separation into 8 timeslices per year for the modelled period, which represents four characteristic days in a year. In OSeMOSYS, the *Timeslice* set divides a year into fragments of time. Figure 3 (Allington et al., 2021) shows the ordering of a standard year into 8 timeslices.

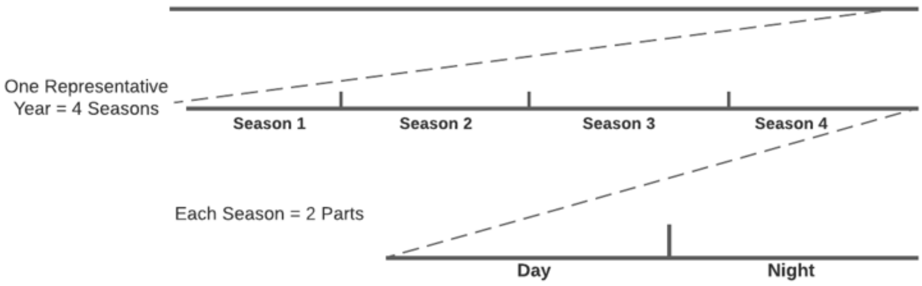


Figure 16: OSeMOSYS: Division of the year into 8 timeslices

This general division into eight distinct day types is maintained in this research. However, the number of timeslices is increased from 8 to 728 to adequately capture storage dynamics, which is elaborated in section .

Furthermore, the modelled period is extended to 2060 instead of ending in 2050 to avoid edge effects. Ramos et al. (2022) indicates that a period of 5 or 10 years suffices to avoid these edge effects.

3.2.5 How to adequately capture storage dynamics?

The dynamics of charging and discharging the storage reservoir are not adequately captured in a system with only eight timeslices in a year. The reason is that within a single timeslice, the storage can either charge or discharge to a certain level *once*. This would mean that if the storage charges during the day and discharges during the night, it can cumulatively only store four times the storage capacity in a single year when eight timeslices are utilised.

The example on the right shows the difference between the storage dynamics for a time resolution of 1 day (2 timeslices) or five days (10 timeslice) per season. Here, It becomes clear that for a coarse resolution i.e. one day, the reservoir is only able to charge and discharge once. For a full year, this extrapolates to four times. For the same system with a higher time resolution, i.e. five days in this example, the same reservoir can go through the same cycle five times. This results in higher cumulative stored energy, a higher required capacity and potentially increased cost-effectiveness due to a lower capital cost per unit of produced energy.

The example mentioned above is why the initial annual time resolution of eight timeslices was translated to a scenario with 360 timeslices, i.e. 180 2-day slices with a day and a night. This time resolution provides the possibility to investigate storage dynamics on a daily level, which increases the potential cumulatively stored amount of energy and better represents storage dynamics in the system. The year lasts 360 days instead of 365 to ensure an equal division of the year into four 90-day seasons.

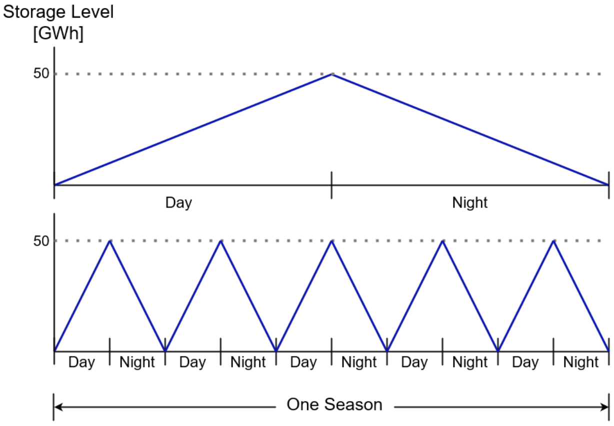


Figure 17: Storage dynamics: 1 day vs 5 days per season

Also, when only two timeslices represent a season, it results in more hours for the (dis)charging of energy per timeslice, leading to a lower required capacity to generate the same energy level. In a run with one day per season and a discharge time of 10 hours for a 50 GWH reservoir, there are 460 available hours per timeslice to discharge. A 50 GWh reservoir, therefore, needs only $\frac{50GWh}{460h} = 0.1GW$ to generate this amount of electricity. This is unrealistic, as pumped hydro storage facilities with such a large storage capacity need a much larger power station in terms of GW. With a finer time resolution of 91 days per season, this cycle can occur each day, leading to a more realistic capacity of $\frac{78GWh}{10h} = 7.8GW$. Therefore the time resolution was increased to 360 timeslices per year, constituting 180 2-day timeslices with both a day and a night. Lastly, a 10-hour discharge period is represented through the $AvailabilityFactor$, which is elaborated in paragraph A.3.

A major drawback of increasing the timeslices is that runtime increases drastically and requires a much larger memory capacity, which excludes regular laptops and desktops from the ability to run a simulation. To run the scenarios for this research, this work used the Dutch national e-infrastructure with the support of the SURF Cooperative using grant no. EINF-3711.

3.3 Working with a Reference Energy System (RES)

OSeMOSYS represents the configuration of the energy system schematically and visually through the Reference Energy System (RES). The RES is a rendition of the real energy system and can be as simple or complex as the creator wishes. A critical requirement for the RES is that it aptly portrays a minimal version of reality to investigate the set hypothesis. Furthermore, the reference energy system is not limited to being a representation of reality but can also be a method of exploring different development pathways and scenarios.

3.3.1 How to construct a Reference Energy System (RES)?

The RES is divided into three major parts: the primary, secondary and final energy systems. The RES is read from left to right, where the arrows indicate the direction of energy flow.

Firstly, the primary energy system displayed in figure 18 depicts raw resources and their treatment, e.g. import and mining of materials. For Ethiopia, elements such as oil imports, coal mining, solar power and wind potential fall into this category. Figure 18 shows a hypothetical configuration of this part of the structure. In a RES, technologies are symbolised by rectangular blocks and fuels are depicted by vertical lines. Energy moves through the RES horizontally from left to right.

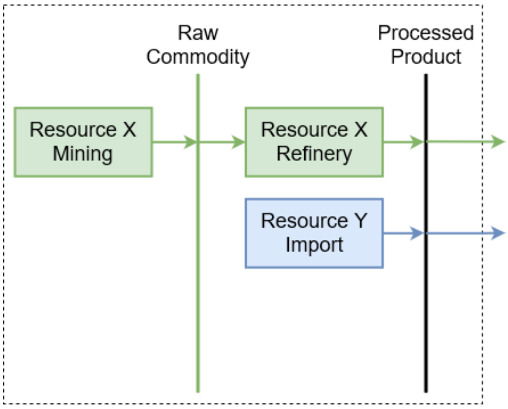


Figure 18: RES: A primary energy system

The secondary energy system consists of technologies used for energy generation, i.e. power plants and energy transport. The conversion from primary goods to secondary products is depicted here, seen in figure 19. Additionally, transmission and distribution facilitate finalised energy commodities to reach the consumer side of the system.

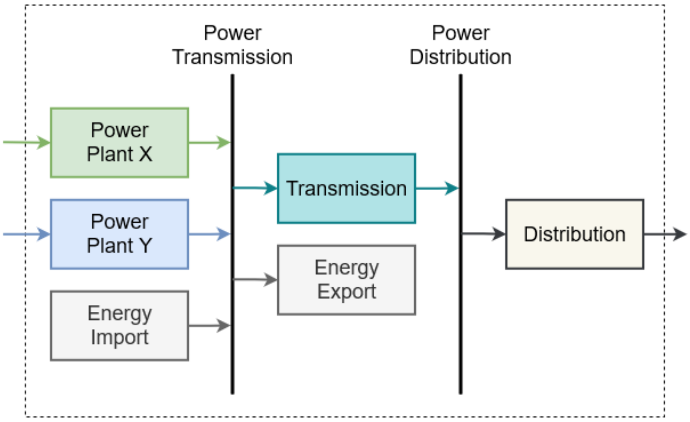


Figure 19: RES: A secondary energy system

The third and last part of the RES consists of finalised energy products. These products do not need to be processed further and can be used instantly by the customer. This is represented by *Energy for*

Use in figure 20. In the Ethiopian context, demand subsisting of industrial, residential, commercial or transport facilities falls into this category. Also, figure 20 shows that demand technologies can meet a singular demand, as shown in yellow for demand A. Also, multiple technologies can contribute to the same demand, e.g. B1 and B2.

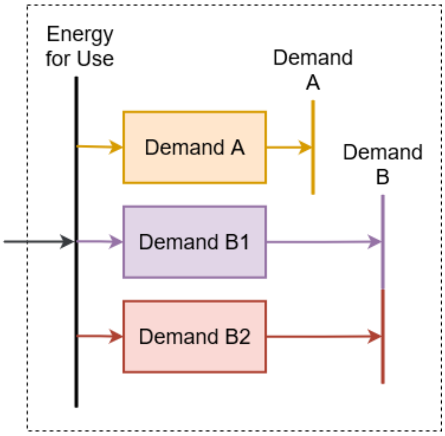


Figure 20: RES: A final energy system

Lastly, an example of a complete RES is presented in figure 21. However, it is crucial to keep in mind that a RES can be drafted in any shape or form relevant to a specific project and depends on the choices of the modeller.

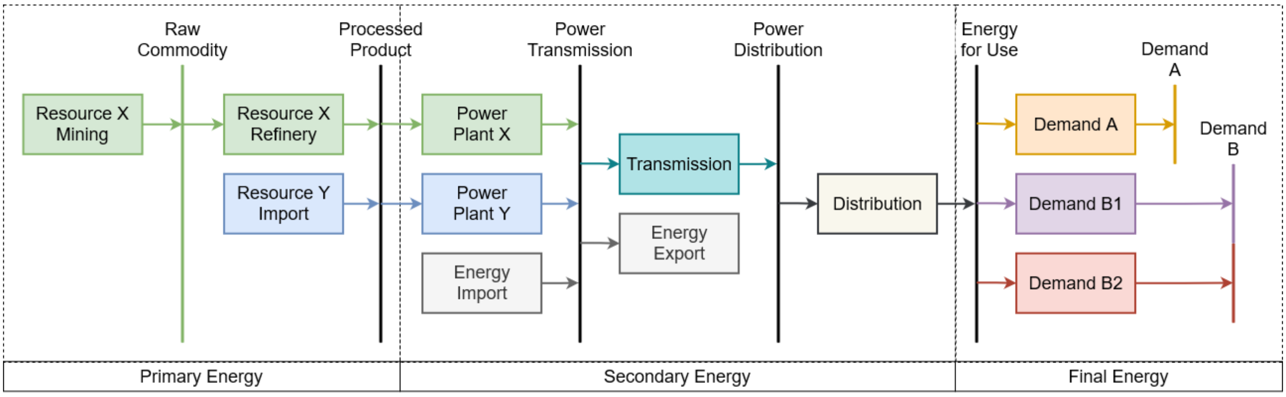


Figure 21: RES: The total energy system

3.3.2 Storage representation in the RES

This section describes the incorporation of pumped hydro storage in the RES for the Ethiopian context. Firstly, a dummy technology for pumped hydro storage has to be implemented. For this project, this technology is called *Power Plant PHS*. Secondly, an element representing the actual storage reservoir is made, namely *Storage Reservoir*. Figure 22 depicts these technologies as part of the RES.

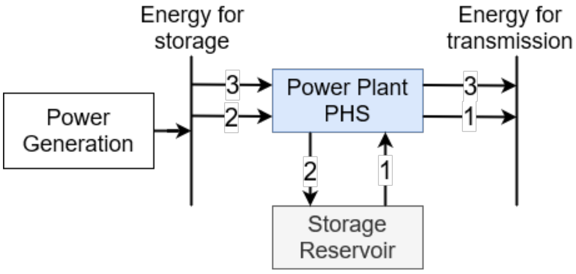


Figure 22: RES: Conceptual implementation of storage

In OSeMOSYS, the function of the dummy technology is that operational parameters for power plants, such as capacity constraints, activity constraints, emissions and other factors, can only be assigned to a technology and not to storage. In contrast, the storage reservoir only represents energy conservation. Consequently, solely elements accounted as storage can be given operational aspects exclusive to storage facilities. These aspects include (dis)charging speed, maximum storage capacity, minimum storage level to be met and other factors.

Technologies are unable to be linked directly to one another. Therefore, a fuel that is utilised exclusively for storage is introduced, shown as *Energy for Storage* in figure 22. Furthermore, one power plant cannot be linked to electricity for transport and storage. For this reason and because the model has to have the option to choose not to adopt storage, a secondary instalment of the same technology is created for the variable renewable energy sources. Operationally, these technologies are identical. However, one is connected directly to electricity for transmission, whereas the other can charge storage.

3.3.3 Modes of Operation

In OSeMOSYS, the set 'Mode of Operation (MoO)' accounts for the methods of energy inputs or outputs. Commonly, energy production technologies such as power plants operate in MoO 1. The implementation of storage into the system introduces the necessity for additional modi. Consequently, figure 23, an part of a RES that includes PHS, shows a scenario with three modes of operation.

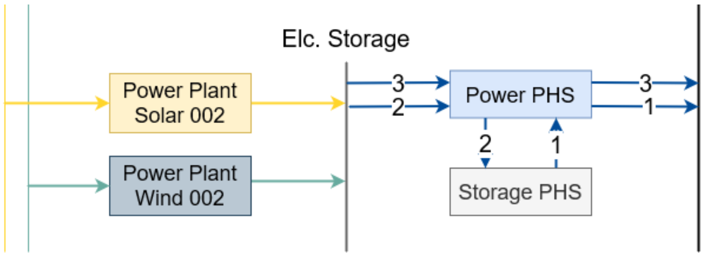


Figure 23: RES: The representation of PHS

The numbers in the blue arrows in figure 23 represent separate modes of operation. Here, MoO 1 stands for regular energy production from a power plant and is the MoO for nearly all technologies apart from storage. Secondly, MoO 2 depicts the path for charging the storage reservoir. The combination of the two lines visualises the energy storage in the reservoir. Operational aspects such as full-cycle efficiency, storage (dis)charge rate and other factors are included in this route.

Mode of operation 3 is put in place to give the model an option to utilise the power plants for solar (002) and wind (002) *without* having to store energy in the reservoir. This occurs when the storage of energy is deemed unfavourable by the model.

3.3.4 The function of the backstop technology

When the energy production from regular technologies is insufficient, backstop technologies are used as a method for energy generation. Backstop technologies have relatively high costs and unfavourable operational properties, making them a last-resort option for the model to choose. In this study of Ethiopia, the backstop does not relate to real-life power generation. Their sole purpose is the indication of inadequacy to meet demand by the suggested technologies.

An example of a system in which a backstop is used is a system without storage that is limited to generation solely by solar power, shown in section B.1. Solar energy is only available during the day. However, if there is demand during the night, a backstop technology is called to meet this remaining demand as opposed to giving an infeasibility error for the model.

3.4 Creating a baseline for Ethiopia

In this section, the elements of constructing a baseline for Ethiopia are discussed. Firstly, Section 3.4.1 describes the OSeMOSYS starter kit used as a basis for this research. Secondly, Section 3.4.2 discusses the implementation of a maximum for solar and wind capacity based on the Model Supply Regions by IRENA (Sterl et al., 2022). Then, Section 3.4.3 elaborates on the dynamics of the cooking demand, after which Section 37 gives information on the transport demand. Lastly, the used Reference Energy System (RES) for Ethiopia is provided in Section 3.4.5.

3.4.1 A starter kit for Ethiopia

The creation of a representative energy system for Ethiopia was done using data from the 'Starter Kit' provided on the OSeMOSYS website (Cannone et al., 2021). The article and its subsequent data aim to provide researchers with a reference point to build their modelling process.

Starter kits in OSeMOSYS were created for over 59 countries, primarily in Africa and Asia. The starter kit consists of information that is freely accessible, e.g. public databases, websites and papers. The underlying goal was to improve the accessibility of these models and smoother continuation of the modelling process directly by the communities through the U4RIA principle. U4RIA constructs a collection of directives for the following concepts (Howells et al., 2021):

- **Ubuntu**
  Ubuntu is a concept that links to the communal aspects of human society and the cooperation that accompanies that relation.
- **Retrievability**
  Data has to be retrievable without difficulty.
- **Reusability**
  The ambition has to be to make the complete modelling process reusable, without the hindrance of licensing constraints.
- **Repeatability**
  The operations must be repeatable by a broader audience than solely energy modelling experts.
- **Reconstructability**
  The construction of the energy system and subsequent choices needs to be understandable, and this is achieved, for example through adequate documentation.
- **Interoperability**
  Interoperability relates to the facilitation of model and scenario testing by other modellers and modelling for management purposes on both a sub-sector and larger scale.
- **Auditability**
  The possibility has to exist to hold those involved in the aforementioned practices accountable to actors providing monetary support and to the general public.

This study builds on these principles by the creators of these starter kits as the repeatability, reusability, and reconstructability are tested. The starter kit data is accompanied by two predetermined scenarios: a fossil fuel scenario and a least-cost scenario. The latter was used as a basis to continue this research. Figure 24 shows the electricity production in this scenario. Appendix C shows the complete results and dynamics from the least-cost scenario from the starter-kit.

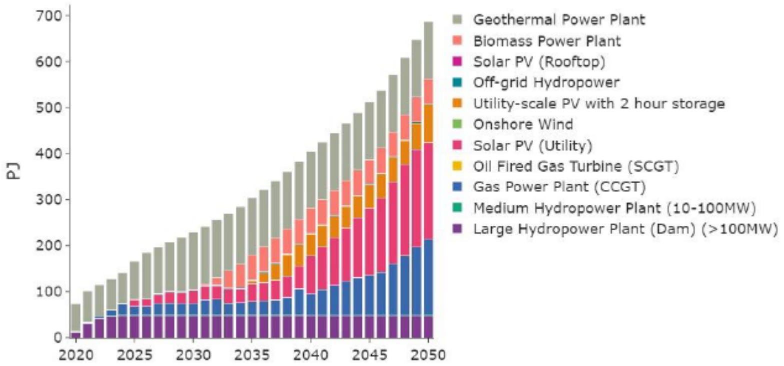


Figure 24: Starter kit: Electricity production [PJ] from 2015 to 2050 for the Least-cost scenario

The primary dynamics from these results are that solar penetration into the energy system increases with its annually decreasing cost, geothermal production is relatively constant throughout the modelled period, and hydropower remains constant after reaching the maximal capacity. This scenario forms the basis of the baseline scenario created for Ethiopia to test a scenario with pumped-hydro storage. Two major constraints define the least-cost scenario. Firstly, nuclear power is unavailable throughout the entire modelled period. Secondly, 5% of the 2050 capacity can be invested each year for runs that have no demand-side investment constraints

Important considerations in the starter kit that are applied in this study consist of the following elements:

- The starter kit separates between regular, medium and high-efficiency technologies per sector, with an output activity ratio of 1, 1.15 and 1.3. This is a path through with the modeller provided the option to invest in higher efficiency generation methods ;
- Energy production from biomass is permitted to supply 30% of electricity demand ;
- Utility-scale PV and onshore-wind are allowed to supply 15% of the demand ;

These elements mentioned above were used in the creation of an energy system baseline scenario for Ethiopia. The data from the starter kit was altered to reflect the dynamics of the Ethiopian energy system more accurately. Most of the removed technologies were so because they were unused or to simplify the energy system to focus on the storage dynamics. Table 3 shows the adjusted data and the subsequent reasons.

3.4.2 Setting a maximum for solar and wind capacity

The solar and wind capacity is set at a maximum of 187 and 166 GW, respectively, based on research into the geographical zones by Sterl et al. (2022) for IRENA that exhibit the most preferential characteristics for each of these technologies. The study based their selection of the location on the optimal levelized cost of electricity, resource quality and distance from the grid. After the initial selection, the top five percent of the regions were adopted in their data, cumulatively amounting to 187 and 166 GW of potential for solar and wind.

Here, the screened optimal locations by Sterl et al. (2022) are used to alter the capacity factor for solar and wind power. The average capacity factor from the top 5% zones with the highest potential for solar power is used. The data by Sterl does not provide seasonality. Here, these locations were used in Renewables.ninja to get a seasonality pattern. The combination of the capacity factors from Sterl and the seasonality from Renewables.ninja is used for the capacity factor of solar power for all scenarios.

Wind power experiences greater variation between the data from Renewables.ninja and the IRENA data. As a base scenario, the capacity factor and seasonality from Renewables.ninja is utilised, but

Action	Change	Reason
Removed	Offshore Wind	Ethiopia is a landlocked country
Removed	Nuclear power	Ethiopia does not have nuclear power nor is it expected to construct any in the future.
Replaced	CSP with storage	The initial "CSP with Storage" was not connected to any storage, thus being storage in name only. It was replaced with CSP that is connected to pumped hydro storage.
Replaced	Wind with Storage	Same as "CSP with Storage"
Replaced	Solar with Storage	Same as "CSP with Storage"
Removed	Electricity Import	Ethiopia does not import electricity
Removed	Residential cooking cooking demand met by oil	Upper limit had already been set to zero. Removed for clarity.
Removed	Industrial high heat demand	Removed for clarity because it was zero.
Altered	Incorporation of energy export	Energy export was not given a demand. Therefore, it did not function as actual export. In section X, the implementation of export is elaborated on.
Removed	Off-grid hydropower	Removed for clarity as it is not used on a significant scale for this study.

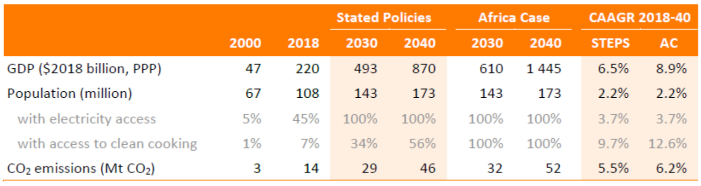
Table 3: Adaptations from the starter kit

additional scenarios are explored with wind capacity based on the IRENA data, with seasonality from the operational wind farm. This is shown in section 3.5.3.

Parallel to this research, a 2021 report by IRENA (International Renewable Energy Agency, 2021) projected that the 2040 capacity of solar and wind would be 18 and 2 GW, respectively. There is a large discrepancy between this forecasted installed capacity and the total potential of the region. For this research, the *potential* of both these variable resources is used to evaluate the pathway for Ethiopia if it were not limited in the construction of these variable renewables.

3.4.3 Projections for cooking demand

Residential cooking demand is the most significant demand in the Ethiopian energy system, making up 55% of total demand in 2030. In the original data, the cooking demand that can be met by electricity was not limited. This is unrealistic because most of Ethiopia's cooking demand is currently supplied by biomass. Nearly 90% of Ethiopia's primary energy demand is met by biomass. Therefore, the current percentage of clean cooking in Ethiopia was taken as a maximum for the penetration of electricity production into the demand for residential cooking. An outlook by the IEA (International Energy Agency (IEA), 2019) for the development of clean cooking is taken as a pathway for the penetration of electricity into the residential cooking demand.



			Stated Policies		Africa Case		CAAGR 2018-40	
	2000	2018	2030	2040	2030	2040	STEPS	AC
GDP ($2018 billion, PPP)	47	220	493	870	610	1 445	6.5%	8.9%
Population (million)	67	108	143	173	143	173	2.2%	2.2%
with electricity access	5%	45%	100%	100%	100%	100%	3.7%	3.7%
with access to clean cooking	1%	7%	34%	56%	100%	100%	9.7%	12.6%
CO_2 emissions (Mt CO_2)	3	14	29	46	32	52	5.5%	6.2%

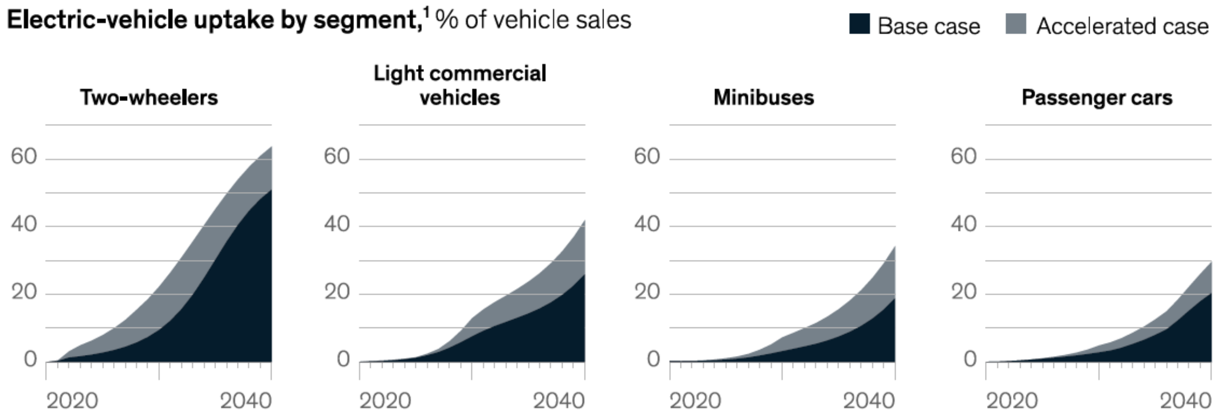
Figure 25: IEA: Percentage of the Ethiopian population with access to clean cooking (International Energy Agency (IEA), 2019)

In figure 25, the predicted pathway for access to clean cooking provided by electricity generation in Ethiopia is laid out. This incremental increase is used as a guideline for the penetration of electricity into the energy supply to meet residential cooking demand. For 2015, the first value is set at 7%, going to 34% in 2030 and reaching 56% in 2040. The access is increased linearly to 2050 to 78% and 100% in 2060. The limitation on maximal investment into electrical residential cooking was removed from the original data set as the clean cooking pathway replaced this. Also, this was done because the investment limit was flat and did not grow with increased electricity access throughout the years.

3.4.4 The evolution of transport demand

The data in the starter kit regarding the penetration of electric vehicles was unrealistic, as electric motorcycle penetration was 100% in 2027 and insufficient, as data after 2050 was not available. The pathway for transport from the starter kit is shown in appendix C in figure 63d. Capital and fixed cost for electric cars was abruptly set to zero after 2050, which is also the end of the modelled period in the starter kit. For this reason, another method of representing the evolution of electric vehicles in Ethiopia was necessary.

A report of McKinsey&Co. on the penetration of electric vehicles into the transport market in Sub-Saharan Africa (Conzade et al., 2022) provides pathways for electric vehicle penetration per type of vehicle. Their projection is shown in figure 26. Ethiopia is one of five countries used as a basis for this projection of Sub-Saharan Africa. These data are used to limit the incorporation of electric vehicles in the Ethiopian market for this research project, as in the starter kit data, this was non-existent. Light commercial vehicles and passenger car data are aggregated under electric cars. The report has data available until 2040. After 2040, the growth rate between 2030 and 2040 is linearly extrapolated to 2060. Naturally, there is great uncertainty in this approach. This research focuses not on the dynamics of transport and electric vehicles in Ethiopia. Lastly, the capital costs of electric cars in 2049 were extended until 2060 to change it from going to zero.



[1] In 5 markets (Ethiopia, Kenya, Nigeria, Rwanda, and Uganda), which make up ~60% of all vehicle sales in sub-Saharan Africa, excluding South Africa.
Source: McKinsey Center for Future Mobility analysis, 2021

Figure 26: Projected EV adoption by segment in Sub-Saharan Africa as a percentage of sold vehicles between 2020 and 2040

3.4.5 The final energy system configuration

Figure 27 shows the full RES for Ethiopia used for this research. The abbreviations for this RES are shown in table 4.

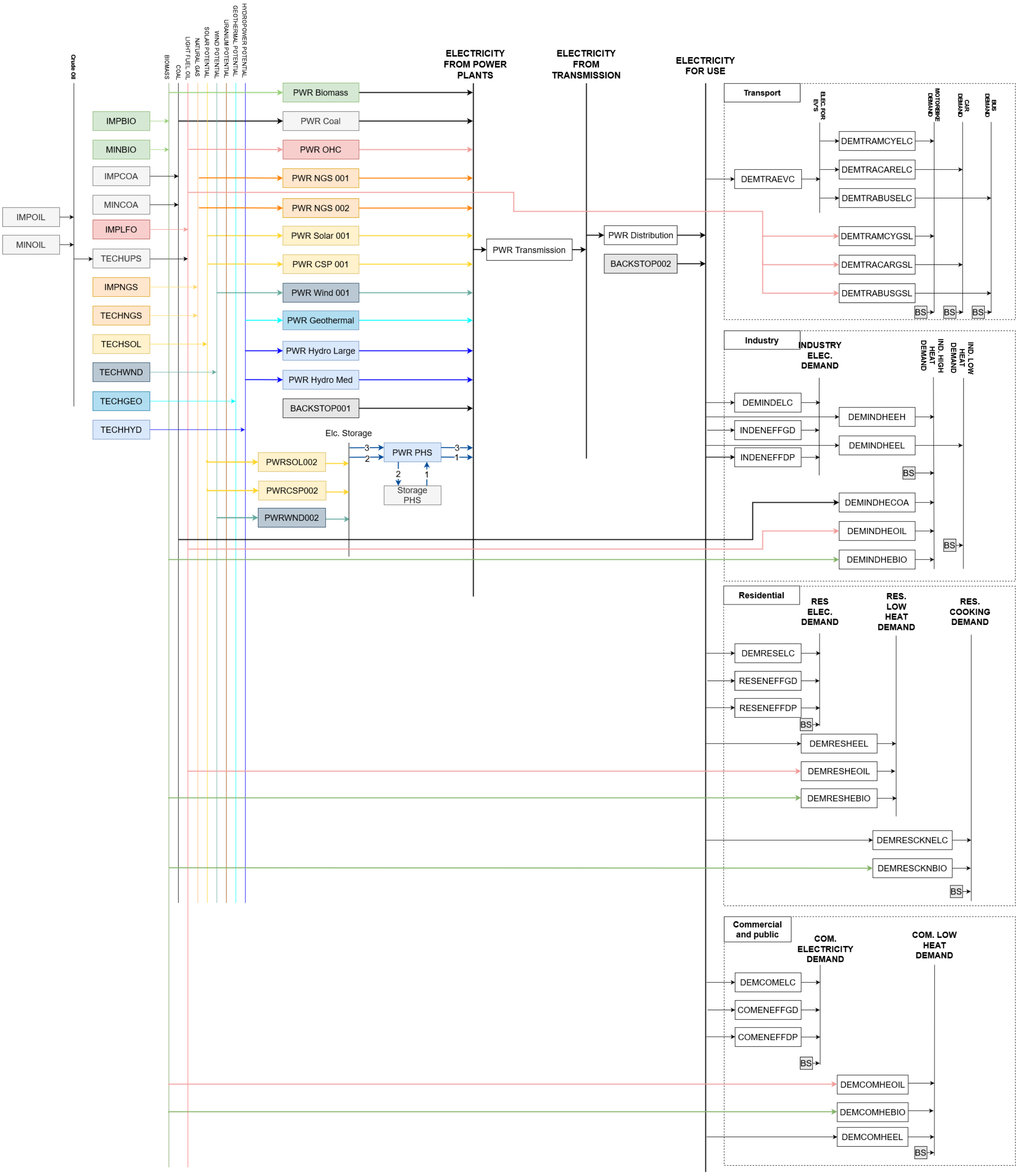


Figure 27: The RES for Ethiopia including pumped hydro storage

Technology Abbreviation	**Full Description**	**Technology Abbreviation**	**Full Description**
COMENEFFDP	Demand Commercial Electric: High Efficiency	INDENEFFDP	Demand Industrial Electric: High efficiency
COMENEFFGD	Demand Commercial Electric: Good Efficiency	INDENEFFGD	Demand Industrial Electric: Good efficiency
DEMCOMELC	Demand Commercial Electric	MINBIO	Mining Biomass
DEMCOMHEBIO	Demand Commercial Heating Biomass	MINNGS	Mining Natural Gas
DEMCOMHEEL	Demand Commercial Heating Electric	PWR Biomass	Power Plant Biomass
DEMCOMHEOIL	Demand Commercial Heating Oil	PWR Coal	Power Plant Coal
DEMINDELC	Demand Industrial Electric	PWRCSP001	Power Plant Concentrated Solar Power 001
DEMINDHEBIO	Demand Industrial Heating Biomass	PWRCSP002	Power Plant Concentrated Solar Power 002
DEMINDHECOA	Demand Industrial Heating Coal	PWR Distribution	Power Distribution
DEMINDHEEH	Demand Industrial Heating Electric High	PWR Geothermal	Power Plant Geothermal
DEMINDHEOIL	Demand Industrial Heating Oil	PWR Hydro Large	Power Plant Hydropower Large
DEMRESCKNBIO	Demand Residential Cooking Biomass	PWR Hydro Medium	Power Plant Hydropower Medium
DEMRESCKNELC	Demand Residential Cooking Electric	PWR NGS 001	Power Plant Natural Gas 001
DEMRESELC	Demand Residential Electric	PWR NGS 002	Power Plant Natural Gas 002
DEMRESHEBIO	Demand Residential Heating Biomass	PWR OHC	Power Plant OHC
DEMRESHEEL	Demand Residential Electric Low	PWR Solar 001	Power Plant Solar 001
DEMRESHEOIL	Demand Residential Heating Oil	PWR Solar 002	Power Plant Solar 002
DEMTRABUSELC	Demand Transport Bus Electric	PWR Transmission	Power Transmission
DEMTRABUSGSL	Demand Transport Bus Gas	PWR Wind 001	Power Plant Wind 001
DEMTRACARELC	Demand Transport Car Electric	PWR Wind 002	Power Plant Wind 002
DEMTRACARGSL	Demand Transport Car Gas	RESENEFFDP	Demand Residential Electric: High Efficiency
DEMTRAEVC	Demand Transport Electric	RESENEFFGD	Demand Residential Electric: Good Efficiency
DEMTRAMCYELC	Demand Transport Motorcycle Electric	TECHGEO	Technology Geothermal Potential
DEMTRAMCYGSL	Demand Transport Motorcycle Gas	TECHHYD	Technology Hydropower Potential
IMPBIO	Import Biomass	TECHOHC	Technology OHC Potential
IMPCOA	Import Coal	TECHSOL	Technology Solar Potential
IMPLFO	Import Light Fuel Oil	TECHUPS	Technology Oil (Combined mining and import)
IMPNGS	Import Natural Gas	TECHWND	Technology Wind Potential
IMPOIL	Import Oil		

Table 4: Abbreviations Ethiopian Reference Energy System

3.5 Scenario Decisions

This chapter elaborates on the decisions for the different scenarios studied in this research. Firstly, a base scenario where just pumped hydro storage is added to the Ethiopia energy system is evaluated with two maximum storage capacities. Secondly, various penalties on CO_2 emissions are investigated. Lastly, the variance in capacity factor and seasonality of wind and solar power is studied.

The scenarios all investigate a period between 2015 and 2050. Table 5 shows the boundary conditions for all scenarios.

Element	Value
Modelled period: Start	2015
Modelled period: End	2050
Modelled period: Years	46
Seasons	4
Days (Annually)	180
Daily Time bracket	2
Timeslices (Annually)	360
# Technologies (No PHS)	68
# Technologies (With PHS)	72
# Fuels (No PHS)	23
# Fuels (With PHS)	24

Table 5: Scenario properties: Parameters that are homogenous through all scenarios

An overview of all scenarios is provided in Table 6.

Scenario	**Name**	**PHS**	**Subname**	**Specification**	**ID**
Base case	Base	No	No storage	Base case	NS
		Yes	Small storage	Add PHS - 78 GWh	SS
		Yes	Large storage	Add PHS - 390 GWh	LS
Varying Wind CF and Seasonality	WND	No	Constant Seasonality	Capacity factor = 0.36, Seasonality = RE.ninja	CS-N
		Yes		Capacity factor = 0.36, Seasonality = RE.ninja	CS-S
		No	Constant Capacity Factor	Capacity factor = 0.44, Seasonality = RE.ninja	CF-N
		Yes		Capacity factor = 0.44, Seasonality = RE.ninja	CF-S
		No	Adama Seasonality	Capacity factor = 0.44, Seasonality = Adama Wind Farm	AD-N
		Yes		Capacity factor = 0.44, Seasonality = Adama Wind Farm	AD-S
Emission Penalty	EMI	No	Slow	$ 25 @ 1% annual growth	SL-N
		Yes		$ 25 @ 1% annual growth	SL-S
		No	Aggressive	$ 50 @ 5% annual growth	AG-N
		Yes		$ 50 @ 5% annual growth	AG-S
		No	Policy	$5in2022increasingto100$ in 2050	POL-N
		Yes		$5in2022increasingto100$ in 2050	POL-S

Table 6: Overview of scenarios

3.5.1 The implementation of pumped hydro storage

The primary goal of this study is to evaluate the potential of pumped hydro storage in the energy system of Ethiopia. This is investigated in this first scenario. Here, a comparison is made to the base case with the only difference being the implementation of pumped storage to the system, which is connected to wind and solar in the form of solar PV and concentrated solar power (CSP). The reference energy system for this scenario is found the previous section 3.4.5 in figure 27. Table 7 shows the characteristics of the two implemented PHS scenarios.

Element	Value	Unit
Capital Cost PHS	2000	$ / kW
Max. Storage Capacity: 1	78	GWh
Max. Storage Capacity: 2	390	GWh
Minimal Storage Capacity	10	%

Table 7: Base case with PHS: Changes to the original data

Firstly, pumped hydro storage is incorporated with a maximum storage capacity similar to China and the United States, measured as part of variable renewable energy production. For China and the US, pumped storage currently makes up between 13 and 27% of their VRE production. This is shown in table 1. Therefore, the first scenario uses 20% of variable renewable production as maximum storage capacity, which translates to 78 GWh for Ethiopia in 2050.

Secondly, Japan has a 100% storage-to-VRE ratio. This 100% is taken as a leap-frog scenario for Ethiopia. In 2050, VRE is expected to make up 75% of electricity production or 390 GWh daily. The second scenario uses 390 GWh as an upper limit for storage capacity.

3.5.2 The implementation of carbon pricing

The goal of evaluating carbon pricing scenarios is to see if the introduction of pumped hydro storage to Ethiopia's energy system incentivises the integration of renewables and increases resilience to price increases due to carbon taxing.

Carbon pricing is becoming a stronger force in decentivising greenhouse gas emissions in the form of CO2. Carbon pricing is relevant for Ethiopia because its energy market is not yet mature, giving it room to anticipate potential pricing scenarios in the development of its energy system. Renewable energy sources like wind and solar power are excluded from this tax as there are no emissions involved after construction, potentially increasing the resilience against price variations for carbon emissions. Theoretically, a subsequent increase in intermittent energy sources results in a greater potential for storage of the surplus in supply when demand is high or vice versa.

At the moment, there are around forty countries that have implemented some form of carbon pricing. This can be either in emission trading schemes (ETS) or a direct carbon tax. The former does not put a price on the emission of CO2 directly but sets an upper limit for the total emissions by the system. Actors with relatively low emissions can trade the allocated emissions they do not utilise to players requiring extra. A carbon tax is a straightforward tax on the emission of CO2. The latter form is used for the creation of the scenarios for this study.

Emissions are taxed per tonne, with the carbon price in the European Union going from 50 EUR per tonne in 2021 to 80 EUR per tonne in September 2022 (EMBER, 2022). The highest price was 98 EUR per tonne CO_2 on August 19 2022. Ethiopia, however, has no emission trading system of a carbon tax in place as of right now but may see an implementation of this in the future. For this reason, 6 scenarios are constructed in this study, 3 carbon pricing scenarios both for a system with and without the possibility of pumped hydro construction.

Firstly, Caron et al. (2018) studied four carbon pricing scenarios for the United States, starting at two different prices and increasing at two separate rates. The choices represent varying levels of aggressiveness in the taxation of carbon and the potential starting price. These scenarios are shown in Figure 28 and are listed below.

I USD 25 per tonne - Growing at 1% annually ;
II USD 25 per tonne - Growing at 5% annually ;
III USD 50 per tonne - Growing at 1% annually ;
IV USD 50 per tonne - Growing at 5% annually ;

Of these four scenarios, scenarios I and IV were utilised in this study. The reason is to investigate a conservative (Slow) and Aggressive strategy for carbon pricing in Ethiopia. As there is no carbon pricing in place at the moment, the carbon pricing scenarios started in 2022.

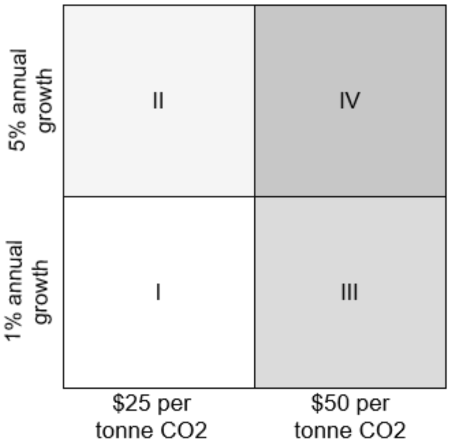


Figure 28: Carbon pricing: Four scenarios

Additionally, Telaye et al. (2019) evaluated carbon pricing pathway specifically for Ethiopia using a computable general equilibrium (CGE) model. They investigated three CO_2 pricing scenarios with the height of the tax as varying parameter. The study was commissioned by the Ethiopian government to inform policy decisions and decrease GHG emissions.

I A low, flat tax rate: USD 5 per tonne of CO_2 ;
II A high, flat tax rate: USD 30 per tonne of CO_2 ;
III An increasing tax rate: USD 5 per tonne at the start of the modelled period, which increases to USD 30 per tonne in 2030 ;

Telaye et al. (2019) utilise only the third scenario, highlighted in bold, under the assumption that the first scenario is too low to meet emission targets in 2030 and the second is too aggressive. Therefore, this third option is used for the scenario for this study. However, the period in this study is shorter, decreasing from 12 years (2018 to 2030) to 8 years (2022 to 2030). After that, the rate increase linearly to the current all time high of 100 USD per tonne CO_2 in 2050.

In OSeMOSYS, the carbon price from the aforementioned scenarios is implemented through the *EmissionsPenalty*. This variable is expressed in million USD per kilotonne of CO_2. All scenarios are studied in an energy system with and without pumped hydro storage. In summary, three pathways for carbon pricing were studied for this research:

1. **Slow**
   USD 25 per tonne - Growing at 1% annually
2. **Aggressive**
   USD 50 per tonne - Growing at 5% annually
3. **Policy**
   USD 5 per tonne at the start of the modelled period, which increases to USD 30 per tonne in 2030. After 2030, it linearly increases to USD 100, the current all time high in the EU, in 2050.

An overview of the pathways is presented in figure 29.

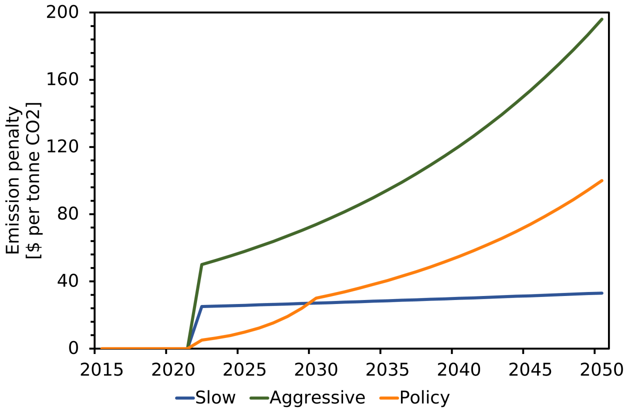


Figure 29: Pathways of the emission penalty [$ per tonne CO_2] per scenario

3.5.3 Varying capacity and seasonality of wind power

Modelling energy pathways relies on both operational and GIS data sources. However, for regions such as Ethiopia, the quality of this data is still improving and can differ greatly between operational and GIS sources. This could have large implications for modelling energy pathways. Therefore, operational data from the Adama wind farm in this scenario is compared to GIS data from Renewable.ninja and the Model Supply Regions by IRENA. Also, the aim is to investigate the sensitivity to fluctuations in changing capacity factors and seasonality of the energy pathways and the subsequent effects on the energy pathways.

OSeMOSYS represents the seasonality of energy sources through an average value for the capacity factor for properties such as wind power and solar irradiation over a long period. However, this is not the case in real-life as these intermittent energy sources can vary heavily both spatially and temporally. The variation in availability is crucial as these define the energy output and therefore level of utilisation of these variable renewable sources. Therefore, in addition to the previous scenarios, four extra scenarios are created in which a combination of low and high values for the capacity factor and seasonality of wind is utilised. These factors are based on the data from IRENA (Sterl et al., 2022) on the optimal supply regions for wind in Ethiopia, data from Renewables.ninja and the ADAMA wind farm in Ethiopia.

The capacity factor and seasonality for solar power are constant in the scenarios that are explored in the research. In contrast, wind power varies.

The high- and low-end for the capacity factor of wind were based on the data from Renewables.ninja and IRENA. Three scenarios are studied regarding the capacity of wind. Firstly, the baseline scenario (base) builds both the capacity factor and seasonality on data from Renewables.ninja. The second scenario (14) uses data from Sterl et al. (2022) for the capacity factor but keeps the seasonality of Renewables.ninja. Thirdly, the data from IRENA is used, but now the seasonality of the operational wind farm Adama II is used. The seasonal and daily pattern of the wind speed from the Adama farm was normalised and applied to the screened IRENA zones. The resulting capacity factors and subsequent seasonalities are shown in figure 30. All of these scenarios are explored in a context with and without pumped hydro storage.

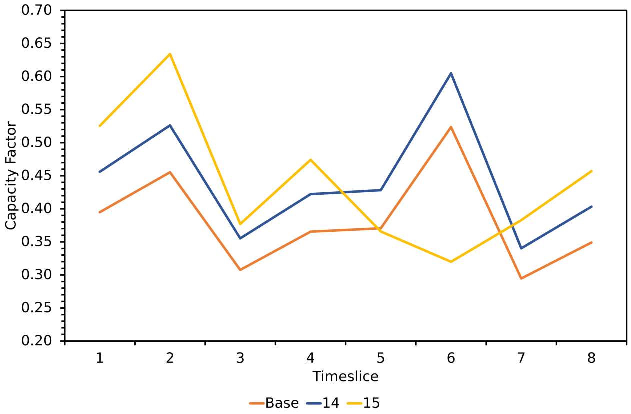


Figure 30: Scenario NS (Base), CF (14) and AD (15): Capacity factors for wind power with varying seasonality

In these scenarios, the year is divided into 4 seasons, which are split into day and night, totalling 8 day types. These day types are subsequently split into 45 timeslices each, but this solely incorporates a higher time resolution and does not alter the seasonality of the capacity factors. The day type that each time slice represents is shown in table 8.

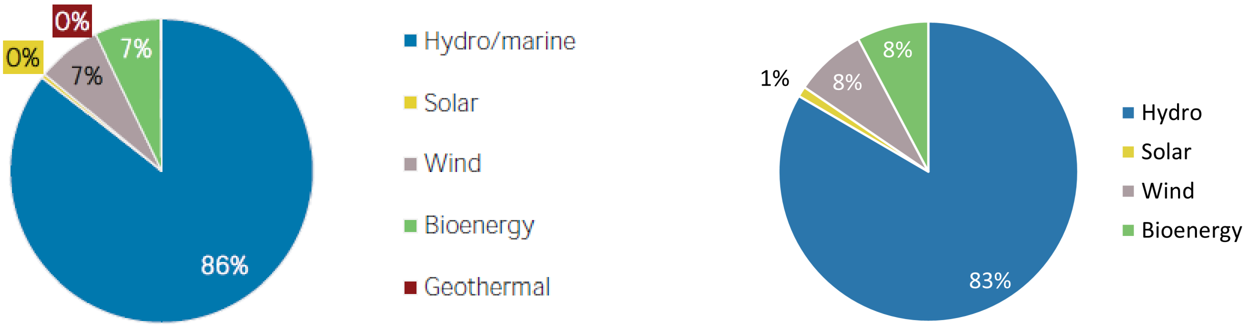
Timeslice	Season	Day / Night
1	Winter	Day
2	Winter	Night
3	Spring	Day
4	Spring	Night
5	Summer	Day
6	Summer	Night
7	Fall	Day
8	Fall	Night

Table 8: Daytypes: The representation of day types through eight timeslices

3.6 Validation of pathways

To validate the pathways, the dynamics in the results from the base case were compared against data on Ethiopia from a country profile by IRENA in 2022 (IRENA, n.d.). The results of this comparison are shown in Figure 31 and Figure 32. The two dynamics shown side by side in this report are the electricity production by renewable energy sources in 2021 and the total energy supply in 2019.

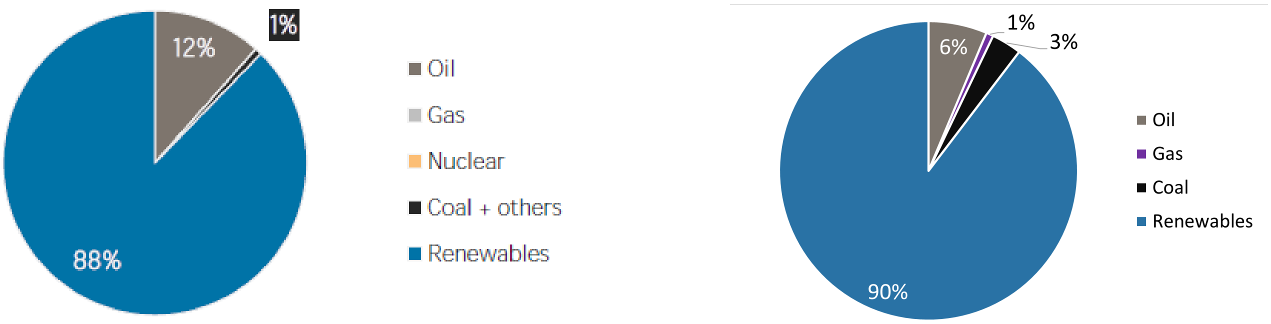
Firstly, Figure 31a presents that IRENA determines that hydropower is the dominant form of renewable electricity production. Secondly, biomass and wind power are the other two sources from the IRENA data. Figure 31b shows that the results from the base case without storage find the same dynamics for 2021. The results are not identical, but these energy pathways have demonstrated from the modelling process to be insensitive to these minor discrepancies. Secondly, the results from the energy pathways should not be interpreted directly but as information on potential policy decisions which have to be validated with further research.



(a) IRENA (b) Base Case NS

Figure 31: Electricity production by renewable energy sources in 2021

Secondly, Figure 32a illustrates that the majority of the total energy supply in Ethiopia in 2019 comes from renewables. Here, biofuels are accounted for as renewables, making up the largest part of this renewable energy supply. The reason is that residential cooking demand is primarily met by biofuels, which comprise the bulk of the total energy supply. From the modelled pathways, the same dynamics emerge, with a slightly smaller role for oil replaced by gas. Again these dynamics are considered similar enough to validate the results for the energy pathways.



(a) IRENA (b) Base Case NS

Figure 32: Total energy supply in 2019

3.7 The global pumped hydro atlas: How to find suitable locations in Ethiopia?

To get a first estimation of potential pumped hydro storage reservoirs in Ethiopia, the global pumped hydro atlas is used (Blakers et al., n.d.). This atlas locates PHS sites by applying GIS algorithms. The elements for every reservoir that are identified are:

- Latitude and longitude
- Elevation
- Volume of water [Gl]
- Dam wall height
- Volume of rock in the dam wall
- Water-to-rock (W/R) ratio
- Head between upper and lower reservoir
- Distance between upper and lower reservoir
- Slope

Reservoirs with a larger W/R are able to store higher quantities of water, making them financially more interesting then those with lower ratios.

The atlas allows for the selection on eight sizes of reservoir capacity.

	2 GWh	5 GWh	15 GWh	50 GWh	150 GWh
6 hours	x	x	x	x	-
18 hours	-	x	x	x	x

Table 9: Global PHS atlas: Types of reservoirs

For the purpose of this study, locations with a power generation capacity between 1 and 3 GW are studied. In practice, this means that 15 GWh at 6 and 18 h, and 50 GWh at 18 h are used as input for potential location. Figure 33 shows the potential locations in Ethiopia for reservoirs with a storage capacity of 50 GWh for 18 hours. These locations will be combined with the model supply regions introduced in section 2.3.5. For the purpose of this study, reservoirs with 15 and 50 GWh of storage, both at 6 and 18 hours of discharge time, are evaluated.

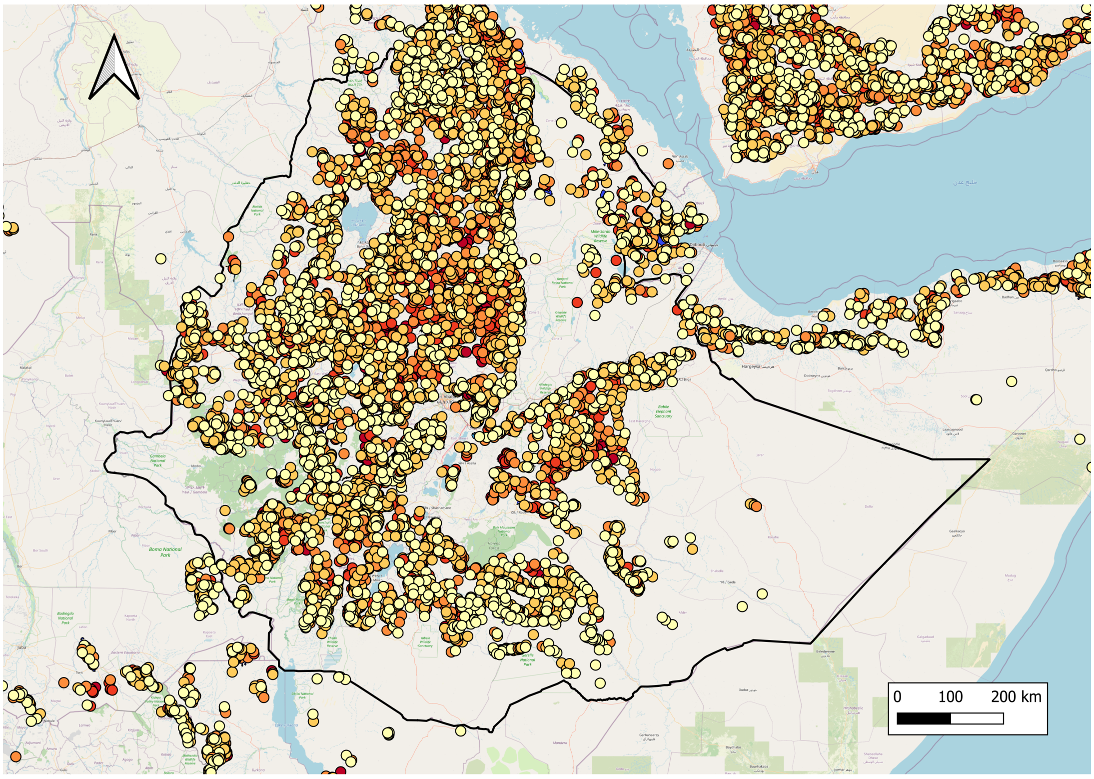


Figure 33: Global PHS Atlas: Location in Ethiopia at 50 GWh for 18 h

4 Results

This chapter discusses the results of the scenarios from Section 3.5. These scenarios contain three baseline scenarios in which pumped hydro storage is introduced into the Ethiopian energy system, six scenarios where an emission penalty is implemented and six, including the base cases, in which the capacity factor of wind is varied based on data from IRENA and the Adama wind farm in Ethiopia. The results of an example case that studies the dynamics of intermittent energy sources with pumped hydro storage are explained in appendix B.

First, the results, which transcend individual scenarios, e.g. the electrification of transport and general storage trends, are discussed in Section 4.1. Then, Section 4.2 examines the results of the base case. Subsequently, Section 4.3 elaborates on the results from the varying capacity factor and seasonality of wind. Lastly, Section 4.4 reviews the results of the carbon pricing scenarios.

The final Section 4.5 gives an overview of the possible pumped hydro storage locations in Ethiopia.

4.1 Common outcomes

In this section, the dynamics that are common throughout all pathways are described. First, the general trend in the projected energy pathway for Ethiopia is given in Subsection 4.1.1. Secondly, the influence on the integration of (variable) renewable electricity production is discussed in Subsection 4.1.2. Then, 4.1.3 reports the generalizable storage dynamics throughout the scenarios. Subsection 4.1.4 reviews the electrification of the transport demand. Subsequently, the total energy supply as an indicator for the resilience of the system is discussed in Subsection 4.1.5. Lastly, the implication of the results are shown in figure 4.1.6.

4.1.1 Expected energy pathways of Ethiopia

Figure 34 illustrates the energy pathway for electricity production in the base case for Ethiopia without the introduction of pumped hydro storage. The trends in this pathway are visible throughout almost all scenarios, and the discrepancies between the scenario outcomes are, except for the carbon pricing scenario, relatively small compared to the overall technology mix and growth of the pathway. The function of the pathways is to provide a first image of the expected energy pathway for Ethiopia between 2015 and 2050 under the constraints considered in this thesis research.

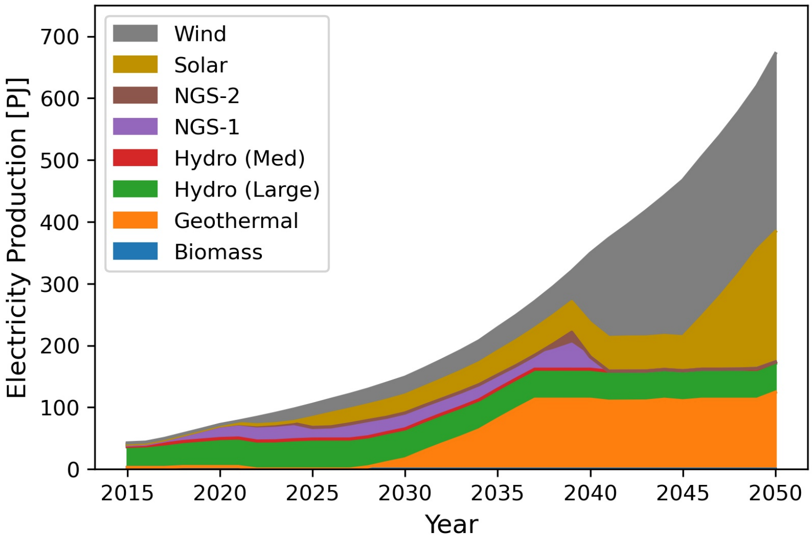


Figure 34: Electricity production per technology for the base case without pumped storage

Firstly, the pathway illustrates that hydropower is and will remain the dominant technology for electricity production until 2025. Between 2015 and 2022, over 80% of renewable electricity production came from hydropower in this pathway.

Secondly, as variable renewable energy sources, i.e. solar and wind power, become cheaper throughout the modelled period, their share of electricity production rises. In 2038, the percentage of electricity produced by variable renewables spikes. The reason for this is two-fold. First, the operational life of other generation technologies, such as natural gas power plants, is between 25 and 35 years. This operational life for most of these technologies, installed at the start of the modelled period, ends between 2040 and 2050. Here, it becomes cheaper to decommission these power plants and build new technologies instead of running the old technologies. Parallel to this, the price of solar and wind decreases throughout the modelled period. With the operational life of other technologies ending, solar and wind have become financially interesting enough to invest in as opposed to the start of the modelled period. The price of solar and wind power decreases by over 60% and 50%, respectively, between 2015 and 2040. These two drivers cause intermittent energy sources to make up a significant portion of the electricity production in the second part of the pathway.

Lastly, across all scenarios, electricity production in 2050 consists of four major sources: Geothermal, Hydropower, Solar, and wind. These are all renewable, emissionless forms of electricity production and contribute to Ethiopia's high renewable energy penetration into the energy system. The next subsection discusses this high renewable energy generation and the connection to pumped hydro storage.

4.1.2 (Variable) renewable electricity production: What is the contribution of pumped hydro storage?

Figure 36 illustrates the average electricity production by renewable (——) and variable renewable (- - - -) energy sources as part of the total electricity production of Ethiopia for all scenarios without (dark blue) and including (orange) pumped hydro storage.

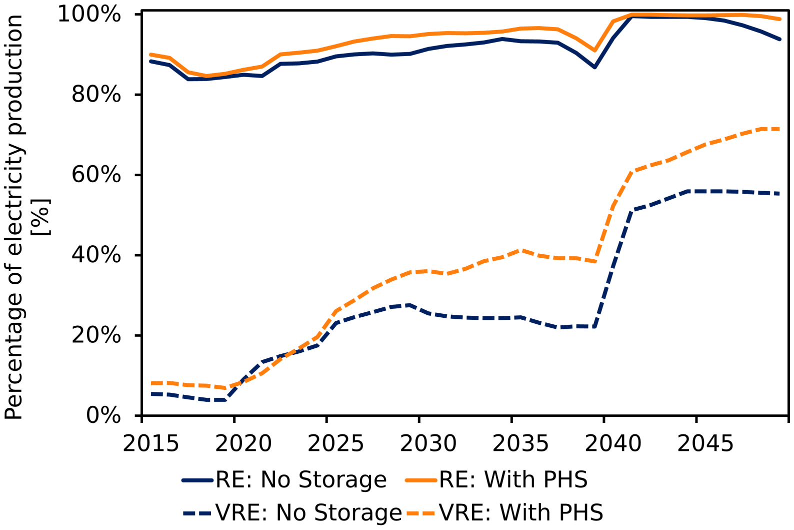


Figure 35: Average renewable energy (RE (——)) and variable renewable energy (VRE (- - - -)) integration as part of total electricity production over all pathways. The dark blue lines indicate the average over scenarios without pumped hydro storage. The orange lines represent the average over scenarios that include storage. VRE production is part of total RE production.

The introduction of pumped hydro storage to the energy pathway makes a relatively small (3% on average) difference in electricity production by renewable energy sources. Renewable electricity production in Ethiopia is already high at over 80% in all cases, regardless of storage. Therefore, the addition of storage has a relatively small impact.

In contrast, the integration of variable renewable methods of energy production is clearly boosted (10% on average) in pathways where pumped hydro storage is part of the pathway. Between 2030 and 2038, scenarios incorporating pumped storage experience an average increase of 15% in variable renewable technologies compared to their counterparts without pumped storage. This is before the spike in VRE production after 2038, indicating that pumped enables earlier adoption of intermittent renewables in energy pathways. For the period between 2045 and 2050, this is 14%. Intermittent renewable energy sources can take up a more prominent role in the energy system whilst also including storage and keeping overall system costs similar to scenarios without storage.

4.1.3 Generalizable storage dynamics

In all scenarios where pumped hydro storage is available, it is adopted into the energy pathway. Here, the upper limit for the storage capacity is reached within 5 years or less. One of the reasons is that the storage reservoirs are relatively small compared to Ethiopia's energy system. For all cases except for one, the storage level is 78 GWh or 0.28 PJ. For reference, the total electricity production of Ethiopia is around 700 PJ or about 20,000 GWh.

Secondly, the average storage level adheres to both a seasonal and daily charging and discharging pattern. Figure 36 displays the average storage level over all scenarios that include pumped hydro storage.

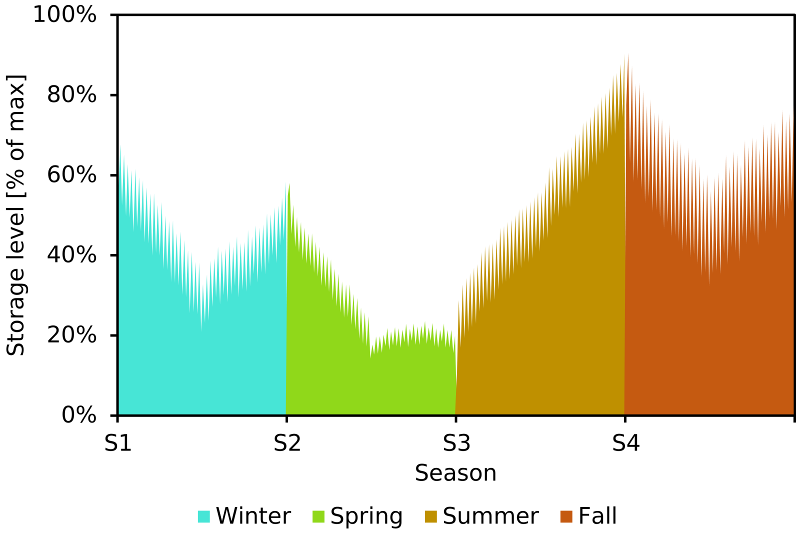


Figure 36: Average storage level [PJ] per timeslice over all scenarios that include pumped hydro storage.

Here, a distinction is made between the four seasons. The Spring season (S1) averages the *lowest* capacity factor for both solar and wind power. For this reason, the storage depletes and is not recharged during Spring. In contrast, the Summer experiences the *highest* average capacity for wind of all four seasons, which explains why the storage primarily charges during this season. Additionally, this can occur because the reservoir is around the minimum level at the beginning of the summer.

Fall and Winter go through more ambiguous patterns, and vary more between scenarios. After the reservoir and capacity factors for wind and solar peak in Summer, the reservoir depletes due to the lower availability of variable renewables in Fall. The detailed, scenario-specific storage patterns are discussed in their respective sections.

In addition to the seasonal storage pattern, a secondary, daily storage pattern is visible. On a timeslice level, the storage charges and discharges, causing fluctuations within seasons. The primary reason for this is that in all scenarios, solar power is incorporated with pumped storage into the energy pathway. The diurnal pattern of solar availability works in tandem with pumped storage and causes these fluctuations on a daily scale. Pumped hydro storage buffers the unavailability of solar power during the night time, resulting in increased flexibility of the energy system.

4.1.4 The electrification of transport

The electrification of transport follows the same trajectory in all scenarios, due to the fact the upper limit of the electrification rate, introduced in section 3.4.4, is already reached in the base scenario. As a consequence, the rate of electric vehicle integration in Ethiopia does not accelerate further under emission penalty scenarios, nor is it influenced by the introduction of pumped storage and variability in wind capacity and seasonality.

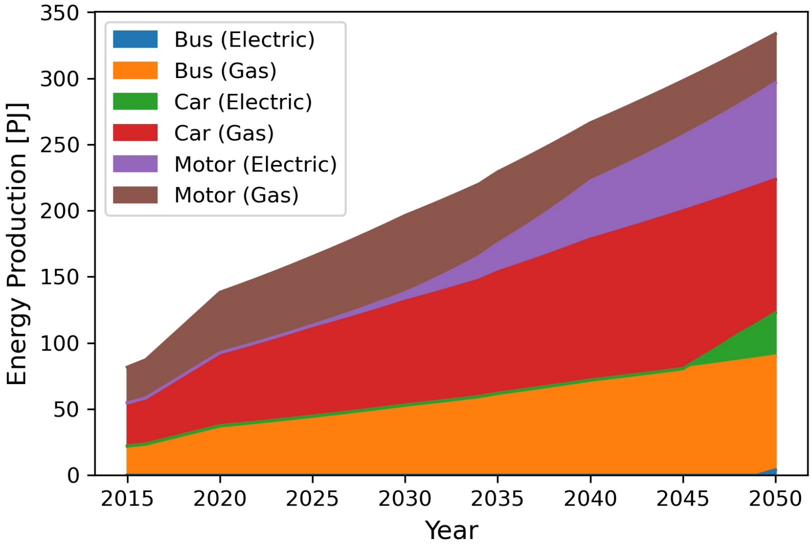


Figure 37: Transport demand [PJ] between 2015 and 2050

The dynamics of incorporation of EVs are that, within the modelled period, both motorcycles and car see gas-powered vehicles being replaced with electric vehicles. In this period, electric buses only begin occurring in the final year. The primary reason for the late replacement of electric buses is due to the high projected costs of these electric vehicles.

4.1.5 Total energy supply

An indicator to quantify the contribution of pumped hydro storage to the resilience of the energy pathway is the percentage of total energy demand met by renewables. Here, like with IRENA, biofuels are accounted as renewables. Table 10 shows the results for the year 2050 for all studied pathways.

Scenario	ID	Renewables	Non-Renewables
Base Case	NS	82%	18%
	SS	82%	18%
	LS	82%	18%
EMI	SL-N	83%	17%
	AG-N	83%	17%
	POL-N	82%	18%
	SL-S	83%	17%
	AG-S	85%	15%
	POL-S	85%	15%
WND	CH-N	82%	18%
	AD-N	82%	18%
	CH-S	82%	18%
	AD-S	82%	18%

Table 10: Percentage of total energy supply met by renewable energy sources

The results of the pathways indicate that the introduction of pumped hydro storage makes a difference to the pathways only in two carbon pricing scenarios. Here, a 2% reduction occurs as a result of the introduction of PHS to the pathway. For the other pathways, this indicators shows no difference between the introduction of PHS or without PHS in terms of renewable energy production. Primarily, the changes to the pathway are seen in the *electricity* production of intermittent sources, but not for the total *energy* production.

4.1.6 Implications of results

A summary of conclusions and subsequent implications of the results are presented in the box shown below, with a detailed explanation provided after the summary.

Implications of results

- **System expenses and financial viability**
  The incorporation of PHS does not raise overall system costs, despite extra capital expenses and additional losses that are introduced.
- **Bridging technology**
  PHS acts as a bridging technology for the early integration of variable renewable energy sources.
- **Small storage, large impact**
  0.28 PJ (78 GWh) of total storage (20% of daily VRE production in 2050) facilitates on average 10% additional solar and wind integration over the modelled period.
- **VRE boost in other countries**
  PHS could accelerate VRE integration even more in countries with a low RE integration for electricity production.
- **Seasonality and diurnal storage pattern**
  0.28 PJ (78 GWh) of storage capacity follows both a seasonal and diurnal storage.
- **Maximal EV adoption**
  The electrification of transport follows the same trend in all pathways, with primarily motorcycles and cars going from gas to electric power.
- **Total renewable energy production**
  Renewable energy as part of total energy production is taken as an indicator of resilience. Total renewable energy production does not increase through the addition of PHS to most of the pathways, which suggest that, looking at this indicator, PHS does not increase the pathway resilience.

A fundamental conclusion from the common outcomes is that all pathways incorporate pumped storage, even with the added capital costs and additional energetic losses to the generation. In all pathways, pumped hydro does not raise system costs. The storage capacity is 20% of expected daily VRE production in 2050 or 78 GWh. This storage capacity will make up just 0.04% of total electricity production in 2050. Nevertheless, it facilitates an average boost in solar and wind generation of 10%. When a 390 GWh storage capacity is implemented in the base case with 100% storage capacity for VRE production, the overall system costs are 11% lower, which is significant as pumped storage only connects to solar and wind that is used for electricity production.

Solar and wind integration will see a spike in 2038 because of the ending operational life for other power plants and decreasing costs of solar and wind power. The result from this study shows that before this point, between 2030 and 2038, the benefits of storage are sufficient to facilitate an earlier boost in the adoption of these technologies by nearly a decade. Globally, countries have to decrease carbon emissions and want to strengthen the resilience and independence of their energy systems. By introducing pumped storage and increasing variable renewable integration, which can replace fossil fuels earlier than systems without storage, these countries could benefit greatly from adopting pumped storage. This is relevant not only for Ethiopia but could translate even better to other countries with low current total renewable integration.

Ethiopia already has a high integration of renewable energy sources for their electricity production. Therefore, the addition of pumped storage does not have a great impact on the total *renewable* electricity production, but only on the *variable renewable* electricity production. For countries that depend more on fossil fuels or other non-renewables than Ethiopia, the added benefit of pumped storage to the system could be even larger. The pathways analysed in this research show that system costs do not rise by adding storage whilst at the same time enabling faster integration of intermittent renewables like solar and wind. Costs do not rise as PHS enables more VRE to be integrated instead of more expensive other technologies. Furthermore, the earlier construction possibility of variable renewables provides countries with a way to more gradually incorporate renewables into the energy pathways.

The storage pattern follows a distinct seasonal and diurnal pattern across all pathways. In this way, pumped storage facilitates water security by holding water in the reservoir for a prolonged period of time whilst providing resilience and flexibility to the energy system on a seasonal and daily scale. The diurnal capacity of solar power is accommodated, as well as the larger temporal fluctuation by wind power.

The electrification of transport follows the same trend in all pathways, in which motorcycles and car are electrified slowly throughout the period. The reason that the rate is that already in the base case without storage, the upper integration limit set in the theoretical framework (section 3.4.4 is reached. Even though the adoption of EVs would be modelled in OSeMOSYS to go quicker without this limit, the restriction is there for a reason. OSeMOSYS determines the rate of electrification based on a cost minimisation. However, the integration of electric vehicles in Ethiopia is limited by many more elements related primarily to infrastructure development and operational facilitation e.g. sufficient charging network. To conclude, the electrification of the Ethiopian transport network follows a static pattern in the results of this research, but it is subject to more dynamics that extend beyond the scope of this research.

4.2 Base Case: Introducing pumped hydro storage

The base case is a comparison between the current energy system of Ethiopia, represented in scenario No Storage (NS), and the same system with the addition of pumped hydro storage, represented in scenarios Small Storage (SS) and Large Storage (LS). The primary differentiator between scenarios SS and LS is the maximum storage level. Table 11 shows an overview of the scenarios that are discussed in this chapter.

Scenario	ID	Specification	PHS	Storage Capacity
Base Case	NS	No storage	No	-
Base Case	SS	Small storage	Yes	78 GWh
Base Case	LS	Large storage	Yes	390 GWh

Table 11: Scenario Specifications: Base Case

This section discusses the three pathways as follows. Firstly, the results for the No Storage (NS) case are discussed in section 4.2.1. Secondly, the findings for the Small Storage (SS) pathway are presented in section 4.2.2. Then, section 4.2.3 shows the results for the Large Storage (LS) pathway. Lastly, the implications of the results are elaborated on in section 4.2.4.

4.2.1 No Storage (NS)

Figure 38 illustrates the electricity production pathway for the base case without storage (scenario NS) between 2015 and 2050. Section 4.1.1 already details the dynamics in this pathway. The primary factors are a high renewable and variable renewable electricity production, continuously increasing production and a spike in solar and wind in 2038.

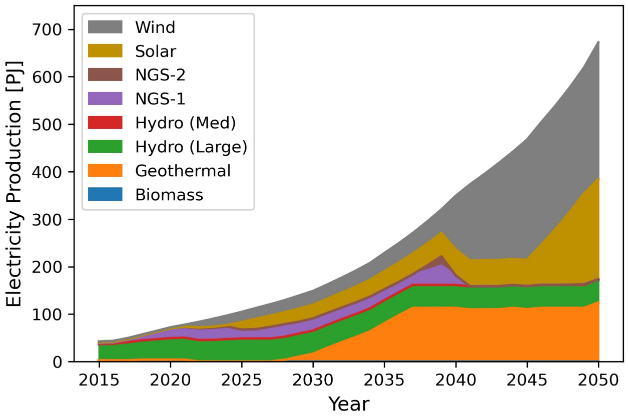


Figure 38: NS: Electricity production [PJ] per technology

4.2.2 Small Storage (SS)

This section presents the results for the incorporation of 0.28 PJ (78 GWh) of storage to the energy pathway, with storage capacity based on 20% of daily variable renewable electricity production in 2050. Firstly, paragraph 4.2.2.1 elaborates on the discrepancies between the electricity production pathways. Then, paragraph 4.2.2.2 discusses the incorporation of pumped storage capacity to the system. Lastly, the storage dynamics are shown in section 4.2.2.3.

4.2.2.1 Electricity production Figure 39 displays the changes to the production of electricity per technology from the pathway with No Storage (NS) to one that includes Small Storage (SS) of 0.28 PJ (78 GWh).

The major change induced by the introduction of pumped storage to the system is that fossil fuels, i.e. natural gas used for electricity production disappears from electricity production. Secondly, from

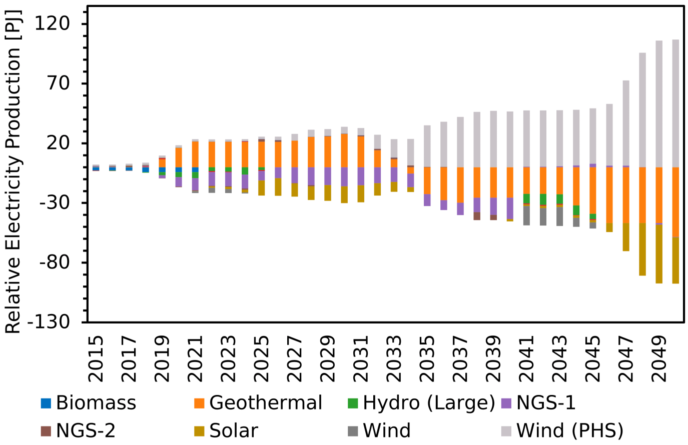


Figure 39: Relative electricity production [PJ] in the Small Storage (SS) vs. No Storage (NS) pathway between 2015 and 2050

2035 primarily solar and wind power without storage and geothermal power are replaced by wind power connected to the pumped storage reservoir. Between 2035 and 2050, cumulatively over 920 PJ of electricity production comes from technologies that are connected to pumped hydro storage i.e. solar and wind power. This translates to 14% of total electricity generation in this 15-year period.

4.2.2.2 Installed pumped storage capacity Figure 40 illustrates the step-wise installation of pumped storage capacity in GW throughout the modelled period. PHS is added to the system in three large steps at 0.4, 3.4 and 7.5 GW of total installed capacity. Firstly, in 2027, 0.4 GW of storage is installed. A decade later, an additional 3 GW of storage has been added to the system. Lastly, the maximum generation capacity of 7.5 GW is reached in 2050.

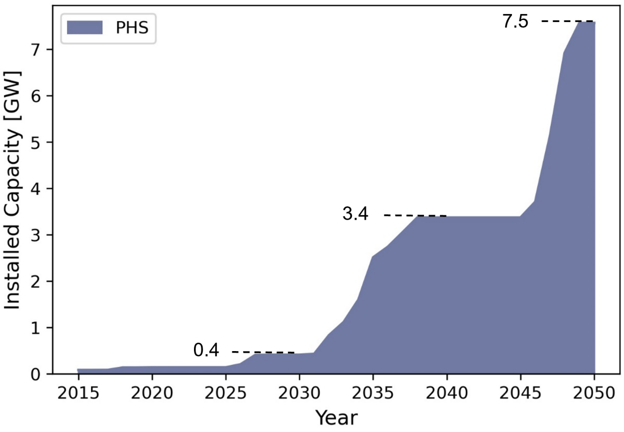
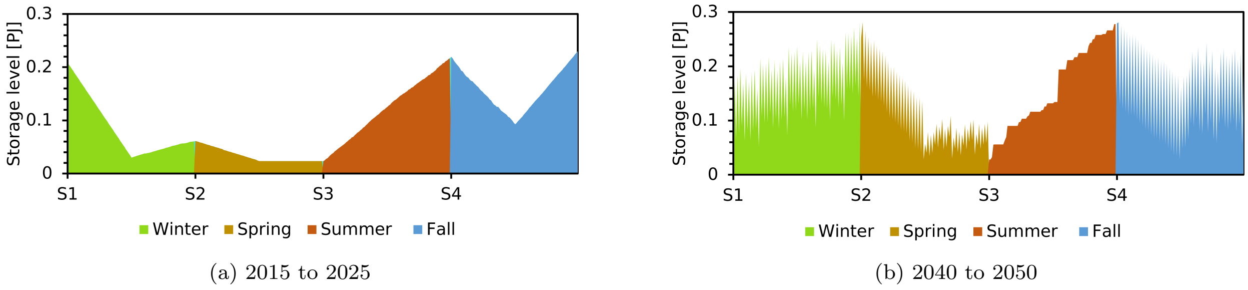


Figure 40: Small Storage (SS): Installed pumped hydro storage capacity [GW]

The step-wise construction of PHS capacity follows a realistic path. A property, and in some instances drawback, of pumped storage is the long construction time of ten years or longer, depending on the size of the project. If a reservoir or system is finalised, there is a sudden jump in capacity. The results in figure 40 adheres to their construction periods. Furthermore, the expansion first of 0.4, then 3 and then 4 GW are also considered realistic compared to existing PHS reservoirs and projects. Middle- to large-sized PHS projects are often constructed at over 1 GW of generation capacity with the largest operational station at 3.6 GW of power capacity, namely Fengning Power Station in China.

4.2.2.3 Storage dynamics Figure 41 presents the average storage patterns for (a) 2015 to 2025 and (b) 2040 to 2050. The storage pattern for the complete period is discussed in section 4.1.3. The discrepancy between the two scenarios illustrates the differences between energy pathways with high wind and low solar power integration from 2015 to 2025 and a system with high wind and solar integration from 2040 to 2050.



(a) 2015 to 2025

(b) 2040 to 2050

Figure 41: Average storage level [PJ] for decades (a) 2015 to 2025 (b) 2040 to 2050

Figure 41a is characterised by a straight, seasonal filling and discharging pattern without any inter-day variability in storage level. The reason is that wind is the sole technology connected to PHS in the first decade. For wind, this seasonal pattern is more dominant then the diurnal variability in capacity factors. In contrast, figure 41b sees a much higher incorporation of solar power in the pathway, which adds the diurnal pattern to the system. The seasonal pattern is blurred by the daily variability in storage level. Nevertheless, seasonality remains dominant throughout both periods.

4.2.3 Large storage (LS)

The second pathway that includes storage for the base case accommodates a Large Storage (LS) capacity of 100% of the daily variable renewable electricity production in 2050, namely 1.4 PJ (390 GWh). This is up from 20% or 0.28 PJ (78 GWh) in the Small Storage (SS) case. This section discusses the implications of the increase in storage capacity on the electricity production in paragraph 4.2.3.1 and differences in storage dynamics in paragraph 4.2.3.2.

4.2.3.1 Electricity production A storage capacity of 1.4 PJ (390 GWh) facilitates a higher incorporation of solar power connected to PHS in the energy pathway compared to the SS pathway. Figure 42 illustrates the relative electricity production between the two scenarios, where LS is compared to SS as the zero line.

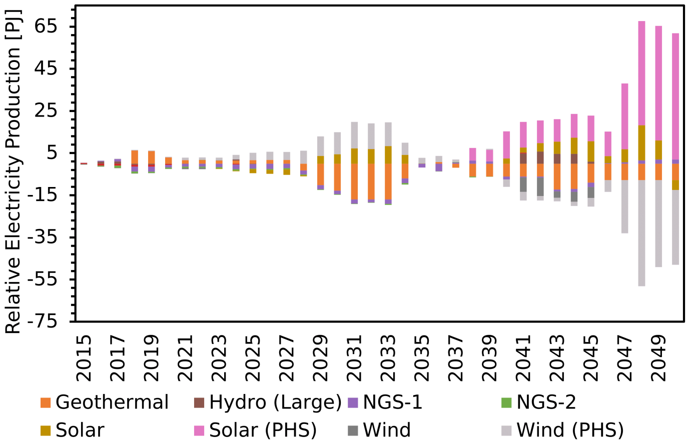
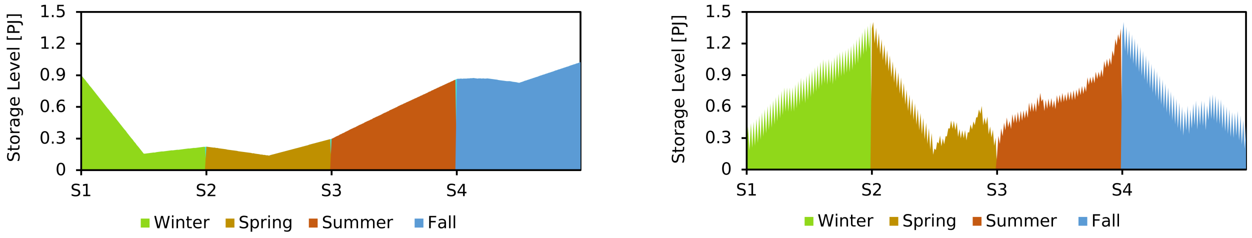


Figure 42: Relative electricity production [PJ] in the Large Storage (LS) vs. Small Storage (SS) pathway between 2015 and 2050

A total of 288 PJ of additional electricity by solar power is facilitated through the addition of this pumped reservoir to the pathway. It is notable that the total installed PHS generation capacity in GW does not differ greatly from the SS scenario, but the extra storage capacity in PJ allows for the incorporation of solar power. This is relevant as it allows the energy mix to become more heterogeneous, which increases the flexibility and resilience of the system by reducing dependency on a single source of energy whilst maintaining the same cost of the energy pathway. Furthermore, the same dynamics apply for the Large Storage (LS) pathway compared to the No Storage (NS) pathway as for the Small Storage (SS) pathway. Electricity production by gas power plants is reduced to zero and primarily geothermal power production is replaced by intermittent sources of energy i.e. solar and wind connected to pumped storage.

4.2.3.2 Storage dynamics The storage dynamics in the first and the last decade of the modelled period illustrate similarities as well as differences to the Small Storage (SS) scenario. Firstly, figure 43a shows a storage pattern that deviates from the SS path. Because the storage reservoir five times larger, the first ten years, the storage reservoir is only filled by 2021, also due to the low electricity generation compared to later in the period. In contrast, figure 43b shows congruent results to the SS pathway. The storage dynamics again converge towards the dynamics described in section 4.1.3.



(a) 2015 to 2025

(b) 2040 to 2050

Figure 43: Electricity production by renewable energy sources in 2021

4.2.4 Implications of results

A summary of conclusions and subsequent implications of the results are presented in the box shown below, with a detailed explanation provided after the summary.

Implications of results

- **Large storage (LS) boosts solar production**
  An increase in storage capacity from 0.28 PJ (78 GWh) to 1.404 PJ (390 GWh) boosts solar integration in electricity generation.
- **Heterogeneity in electricity production increases resilience**
  The diversification of electricity production boosts system resilience by decreasing the dependency on a single source of intermittent renewables for electricity production connected to storage.

As previously mentioned, the construction of a larger total storage capacity leads in the modelled pathway to greater incorporation of solar power in the energy pathways. The objective of this research is to investigate the role that pumped storage plays in strengthening the resilience of the Ethiopian energy system. Here, resilience increases as storage are incorporated, which provides energy security to the system. Additionally, the diversification from dominantly wind to a hybrid wind and solar combination has the potential to improve the quality of the electricity supply. The reason is that often the availability of solar and wind is complimentary.

4.3 Scenario WND: Varying wind capacity and seasonality

In this chapter, the results for three scenarios with varying wind capacity and seasonality are reported. The results for scenarios NS/SS are used again for this scenario. The base case is used as the first of the three scenarios and is based on data from Renewables.ninja for both the capacity factor and seasonality. Secondly, the capacity factor for both scenario CH-N/CH-S and AD-N/AD-S originates from the model supply regions from Sterl et al. (2022). Lastly, the seasonality for scenario AD-N/AD-S is based on operational data from the Adama wind farm. Table 12 displays an overview of these scenarios. Table 12 displays an overview of the pathways for which the results are discussed in this chapter.

Scenario	ID	Specification	Capacity Factor (CF)	PHS	CF Source	Seasonality
Base	NS[1]	No Storage	0.36	No	RE.ninja	RE.ninja
Weather	CH-N	Capacity Factor High	0.44	No	IRENA	RE.ninja
Weather	AD-N	Adama seasonality	0.44	No	IRENA	Adama Wind farm
Base	SS[1]	Small Storage	0.36	Yes	RE.ninja	RE.ninja
Weather	CH-S	Capacity Factor High	0.44	Yes	IRENA	RE.ninja
Weather	AD-S	Adama seasonality	0.44	Yes	IRENA	Adama Wind farm

Table 12: Overview Scenarios WND. [1]The scenarios from the base case (No Storage (NS) and Small Storage (SS)) are also used for the WND scenarios

The results for the base case are elaborated in section 4.2, and therefor are not explicitly reviewed in this chapter. Section 4.3.1 discusses the outcome of CH pathway and the differences with the base case. Subsequently, section 4.3.2 reviews the results from the AD scenario. Lastly, the implications of the results are shown in section 4.3.3.

4.3.1 High capacity factor (CH-N/-S)

Figure 44 illustrates the relative electricity production between the pathway with an average capacity factor for wind power that is 22% higher than in the base case, both without pumped storage. The seasonality for these scenarios originates in Renewables.ninja, which applies satellite data as a basis for their provided data.

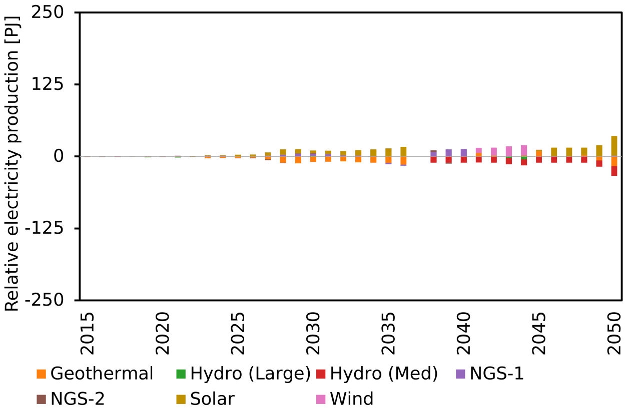


Figure 44: Relative electricity production [PJ] in the Capacity Factor High without Storage (CH-N) vs. Base Case No Storage (NS) pathway between 2015 and 2050

The results indicate that an increase of 22% in capacity factor for wind does not significantly alter the energy pathway for Ethiopia under the same seasonality. The pathway is not sensitive to these changes in the capacity factor. Other elements of the pathway including annual emissions, capital investments, total system costs and installed generation capacity are nearly identical to the base case without storage.

In pathway CH-S, pumped storage is added to the energy system. Figure 45 displays the relative electricity production between the pathways CH-N (No Storage) and CH-S (Small Storage).

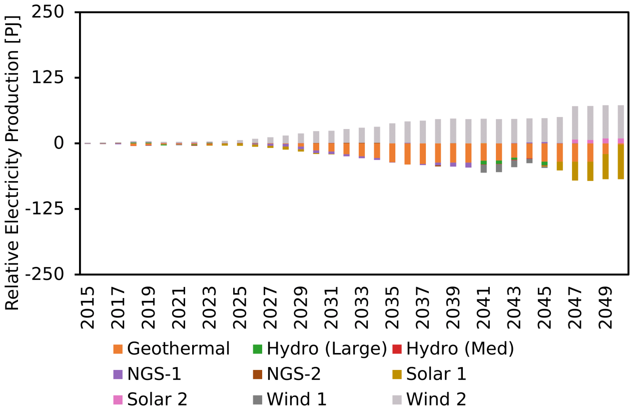
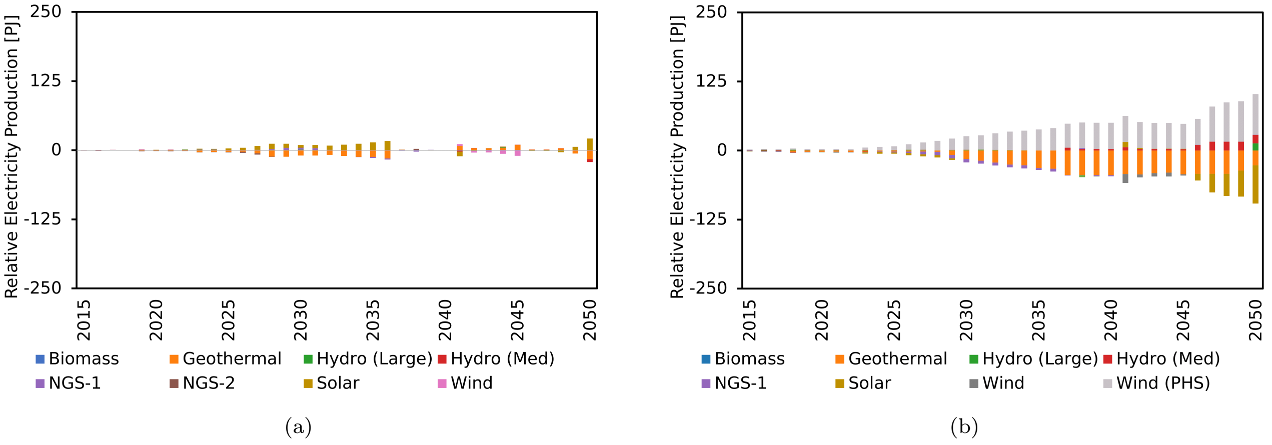


Figure 45: Relative electricity production [PJ] in the Capacity Factor High with Storage (CH-S) vs. Capacity Factor High without Storage (CH-N) pathway between 2015 and 2050

The dynamics as a result of the addition of storage to the network are similar to those seen in all pathways that include storage. Here, wind power connected to storage replaces primarily geothermal and solar power not connected to storage. The primary takeaway from this pathway is than the system is insensitive to this modelled change in capacity factor when keeping seasonality constant.

4.3.2 Adama seasonality (AD-N/-S)

Figure 46a illustrates the relative electricity production between CH-N and AD-N, two pathways that solely differ in the modelled seasonality of wind power at the same capacity factor. Here, the CH-N pathway is the zero line.

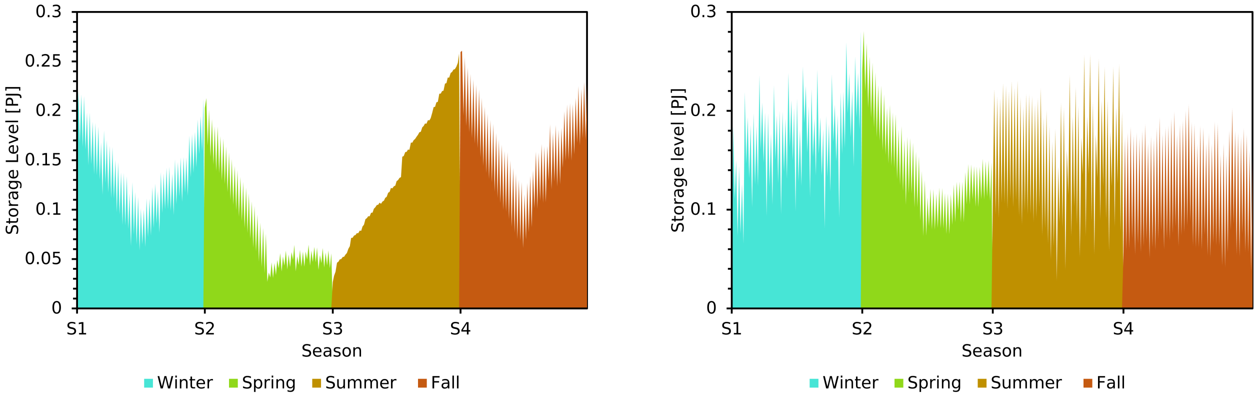


(a) (b)

Figure 46: Relative electricity production [PJ] in the Adama Seasonality pathway (a) vs. Capacity Factor High (CH-N) pathway, both without storage (b) with PHS vs without PHS

The main conclusion from these results is that the variation in seasonality has a minimal effect on the pathway for electricity generation and the power mix. Similar to the other pathways, the introduction of pumped storage strengthens the integration of wind power without increasing the overall costs of the system. The relative electricity production in between the Adama (AD) seasonality case with and without storage is displayed in figure 46b.

In contrast with the electricity generation, the storage dynamics change under different seasonality for wind power. This is expected as in the energy pathways where pumped storage is available, wind is the main source of electricity generation that is connected to PHS. Figure 51 displays the storage dynamics in the base case in figure 47a and the last ten years of the Adama (AD-S) case in figure 47b.



(a)

(b)

Figure 47: Average Storage Level [PJ] for scenario (a) Base Case Small Storage (SS), 2015 to 2050 (b) Scenario WND, Adama with Storage (AD-S), 2040 to 2050

The change in seasonality causes the seasonal storage pattern to change. In the other pathways, storage charges in Summer (S2) because of a high capacity factor for wind, and discharge in Spring, shown in figure 47a. However, the charging dynamics changes to winter when the Adama seasonality is adopted due to the capacity factor being the highest in this season. This is strengthened by the fact that solar power capacity is also highest during the winter season.

4.3.3 Implication of results

A summary of conclusions and subsequent implications of the results are presented in the box shown below.

Implications of results

- **Electricity generation pathways insensitive to changing capacity factor for wind power**
  A 22% increase in the average capacity factor for wind makes little to no difference for the pathway for electricity production.
- **Electricity generation pathways insensitive to the seasonality of wind power**
  Alternate seasonal patterns at a constant capacity factor for wind power have a minimal impact on electricity generation pathways.
- **Seasonality changes storage dynamics**
  Basing seasonality on operational data significantly changes the operational dynamics of the charging and discharging pattern.

4.4 Scenario EMI: Carbon Pricing

The EMI scenarios evaluate three carbon pricing scenarios: a slow, aggressive and policy scenario. All of these scenarios are studied with and without pumped storage. Table 13 shows the evaluated scenarios and the corresponding emission penalties.

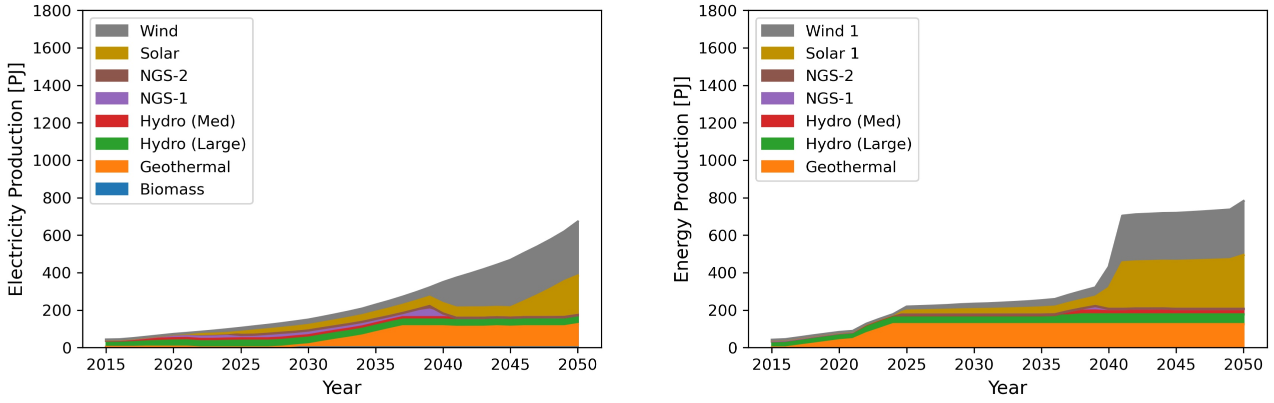
Scenario	ID	Specification	PHS	Emission penalty
EMI	SL-N	Slow	No	\$25 + 1% annual
EMI	AG-N	Aggressive	No	\$50 + 5% annual
EMI	POL-N	Policy	No	\$5 to \$30 (2030)
EMI	SL-S	Slow	Yes	\$25 + 1% annual
EMI	AG-S	Aggressive	Yes	\$50 + 5% annual
EMI	POL-S	Policy	Yes	\$5 to \$30 (2030)

Table 13: Overview Scenarios: Carbon pricing

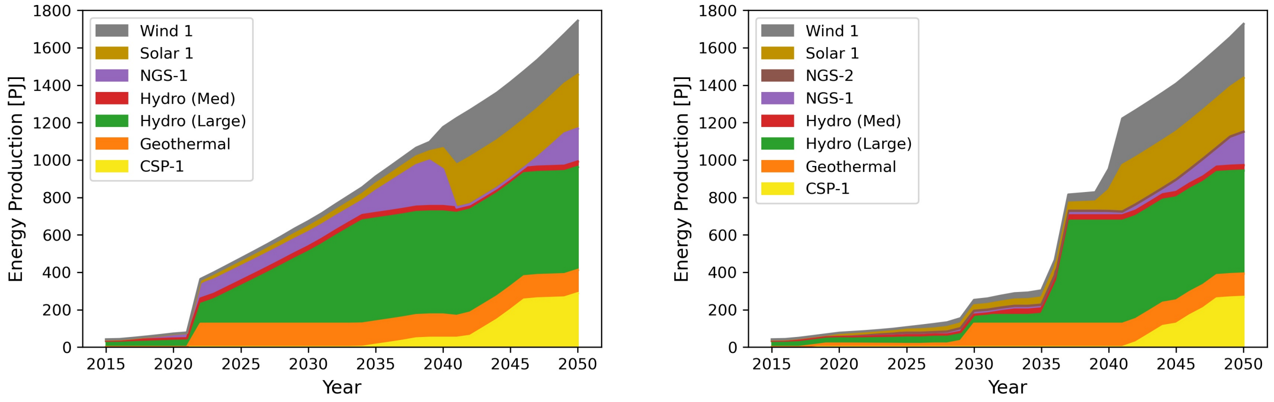
This chapter first elaborates on the different pathways for electricity generation in section 4.4.1. Here, the discrepancies between scenarios are explained and the effects of the introduction of pumped storage are explored. Subsequently, the effects of pumped storage on these pathways are reviewed in section 4.4.2. Section 4.4.3 displays the carbon emissions on an annual and cumulative basis. Lastly, the implications of the carbon pricing pathways are discussed in section 4.4.4.

4.4.1 Pathways for electricity generation

Figure 48 shows the electricity generation pathways for the base case (NS, top left) and carbon pricing scenarios without storage (-N). The electricity production on the y-axis is scaled differently to the base case and the WND case, as the electricity production is significantly higher in the EMI pathways.



(a) NS (b) SL-N



(c) AG-N (d) POL-N

Figure 48: Scenario EMI: Production by Technology [PJ] from 2015 to 2050

Firstly, the electricity generation pathway in the Slow scenario without storage (SL-N) is relatively similar to the base case. There, only in the last decade, the emission penalty has risen to a point where the technologies that produce carbon emissions are financially unattractive. This is mediated by larger electricity production by intermittent energy sources like solar and wind.

The Aggressive pathway (AG-N) projects a nearly three-fold increase in electricity production in 2050. The reason for this enormous increase in electricity production is that primarily residential cooking demand met by biomass, which makes up about half of total energy demand, is replaced by electricity. The rate at which this transition from biomass to clean cooking takes place is based on projection for electrification of cooking, which is described in section 3.4.3. In this pathway over 75% of residential cooking demand is met by electricity in 2050.

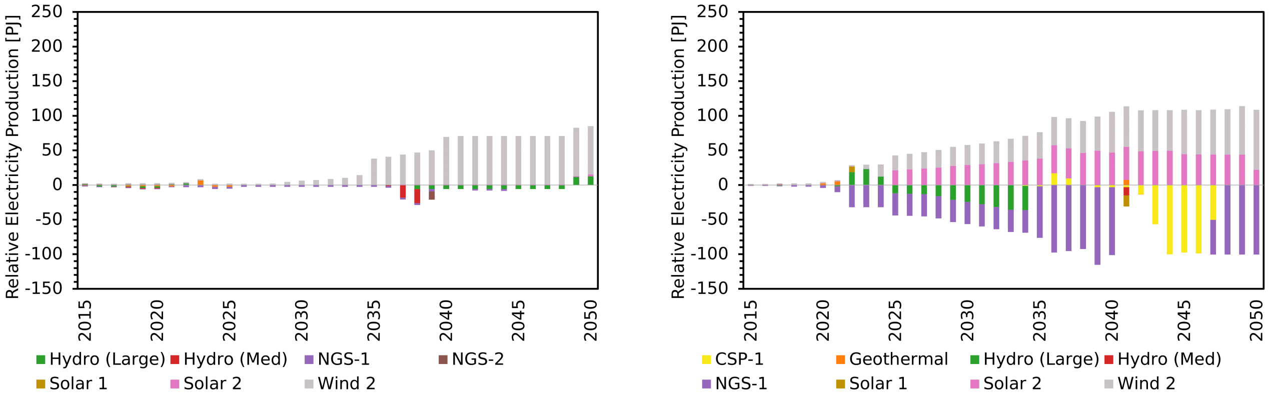
For the AG pathway, the technologies that are utilised for the spiking electricity generation are large hydropower and intermittent power sources i.e. wind and (concentrated) solar power. The incorporation of concentrated solar power (CSP-1) into the system starting in 2035 only occurs in the AG and POL pathways. The reason is that CSP is too expensive in other scenarios but becomes attractive when fossil fuels are heavily penalised.

The Policy (POL) pathway sees a clear distinction between the first (2015 to 2035) and second half (2035 to 2050) of the modelled period. The emission penalty increases at a rate which lies in between the SL and AG pathways. Here, in the first half, the penalty is too low to make it financially advantageous to severely decrease carbon emissions. However, from 2035, also the point in which the operational life of some technologies end and the costs of solar and wind has decreased significantly, the electricity production changes drastically. Here, residential cooking demand met by electricity spikes in 2035, when biomass, which is penalised, becomes financially too unattractive to invest in. Important to note is that both in the AG as POL cases, fossil fuels do not completely disappear from the pathway, as gas-powered plants still provide a part of the electricity supply.

In summary, carbon pricing has the possibility to drastically change pathways for electricity generation, depending on the severity of the penalty. Residential cooking demand transitions from being met by biomass to electricity.

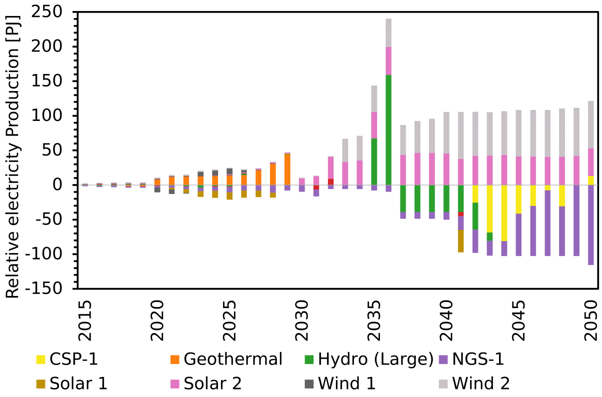
4.4.2 The effect of pumped hydro storage on carbon emission pathways

Figure 49 displays the relative electricity production between the three carbon pathways with and without storage. Figure 49a shows the results for the Slow (SL) pathway, 49b for the Aggressive (AG) case and 49c for the Policy (POL) scenario.



(a) SL-S vs. SL-N

(b) AG-S vs. AG-N



(c) POL-S vs. POL-N

Figure 49: Scenarios EMI: Production by Technology [PJ] from 2015 to 2050

Electricity production by wind power increases by 24% relative to the pathway without storage and rises 8% in total electricity production for the Slow (SL) scenario. The higher incorporation of wind power is the major effect from addition of PHS, which is similar to previous cases.

In both the aggressive and policy scenario, the impact of pumped storage to the system is that natural gas and concentrated solar power as replaced by solar and wind power connected to PHS. Solar power electricity production for the AG and POL pathways increases 7% and 14% respectively, with wind power increasing 30% and 24% for these scenarios. Pumped storage act as a facilitator for significant increases in intermittent energy sources used for electricity production. Natural gas power is completely replaced with clean electricity production.

4.4.3 Annual emissions

This section discusses the annual and cumulative carbon emissions in the EMI pathways. Figure 50 displays the annual emissions [Mt] for the EMI pathways.

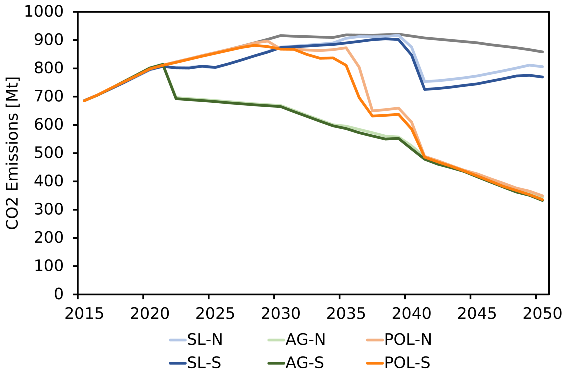
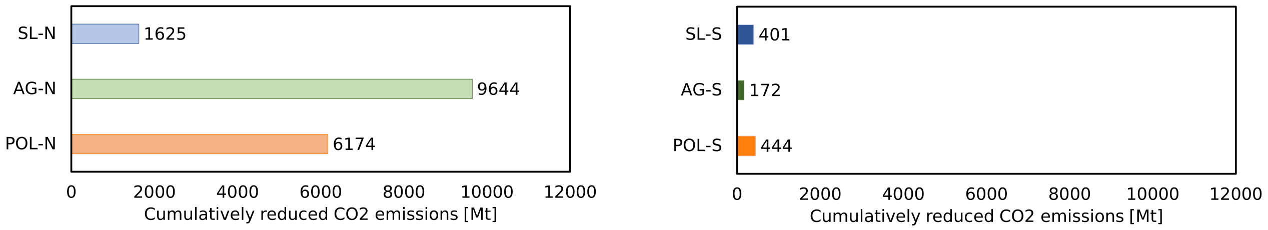


Figure 50: Annual CO_2 emissions [Mt]

The AG pathway in green directly goes to the lower limit of carbon emissions set by the transition rate of residential cooking demand from biomass to electricity. Therefore, because the lower emission limit is already reached in the scenario without storage, the influence of PHS is smaller than in the other two cases. Secondly, the POL pathway has the same annual emission as the base case in gray until 2030. From 2030 on, the emission penalty on CO_2 is at a limit where it is financially beneficial to transition into decreased fossil fuels usage. Eventually, the AG and POL scenario reach a 30% and 20% reduction in cumulative carbon emissions. Figure 51a illustrates the absolute cumulative reduction in carbon emission for the three pathways compared to the base case. Figure 51b shows the absolute cumulative reduction in emissions after the PHS is added to the pathway.



(a)

(b)

Figure 51: Cumulative reduction in CO2 emissions [Mt] for (a) EMI pathways compared tot the base case (b) EMI pathway with storage compared to without storage

4.4.4 Implications of results

A summary of conclusions and subsequent implications of the results are presented in the box shown below.

Implications of results

- **Carbon penalties incentivise lower emissions**
  All pathways that incorporate carbon penalties see a decrease in emissions.
- **Costs spike in all carbon pricing scenarios.**
  The carbon penalty severely increases the cost of the pathways, up to +160% in the most aggressive pathway.
- **PHS can decrease emissions by over 400 Mt over the modelled period.** In all pathways that include PHS, emissions are lowered even further, with a maximal reduction of 444 Mt of CO_2.

4.5 Potential locations for pumped hydro storage

Figure 52 illustrates the combination between potential pumped storage locations and the model supply regions for solar and wind power by Sterl et al. (2022). The locations shown in this figure represent location with 50 GWh of storage. All scenarios, except for the base case with Large Storage (LS), utilise 78 GWh of storage.

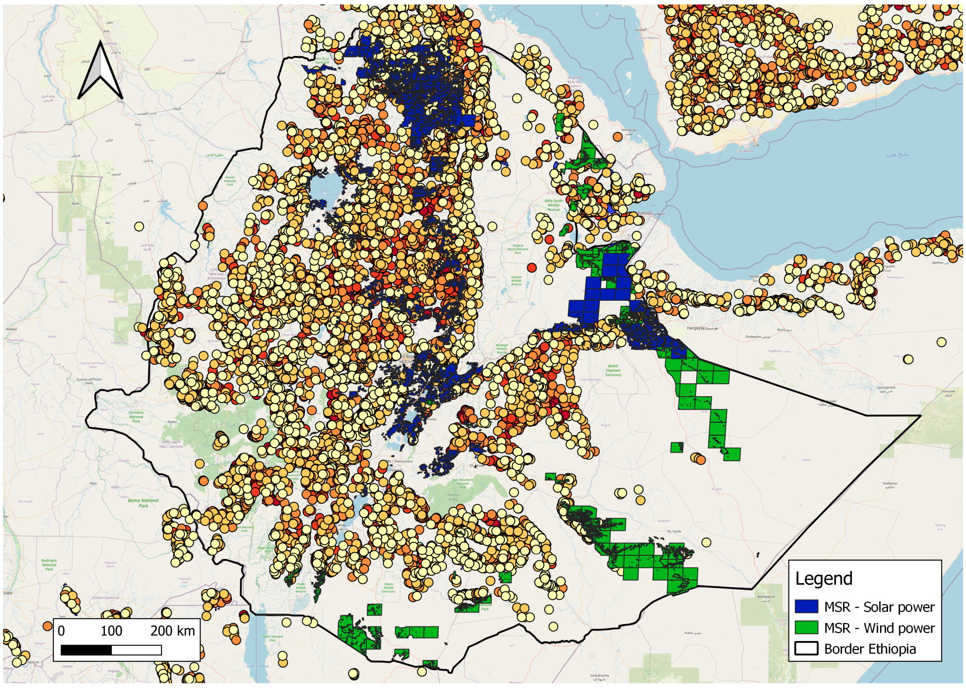


Figure 52: Potential PHS locations for 50 GWh at 18 hours combined with Model Supply Regions

The overlay clearly displays that the model supply regions for solar power are located in the region of Ethiopia where there is a plethora of potential locations for pumped storage. In contrast, the supply regions for wind power, located primarily in the South-Eastern part of the country, are located much further away from these sites. This result does not provide a conclusive determination of the construction sites of pumped storage. It does act as an indication for that if Ethiopia decides to adopt PHS into its energy system, which general regions are suitable. In this context, this means that the except for the south-eastern region, a large number of locations can be chosen.

Additionally, off-river pumped storage locations can be build outside of these model supply regions. With the construction of the Grand Ethiopian Renaissance Dam in the western region of Ethiopia, transmission infrastructure to the central districts of Ethiopia was constructed. Further research has to be conducted to evaluate the quality of the potential locations and the specific conditions regarding factors such as distance to the transmission grid.

5 Discussion

The objective of this research was to explore if the introduction of pumped hydro storage (PHS) increases grid resilience and reduces fossil fuel dependence in Ethiopia whilst still being financially viable. In the first section, the discussion points linked to the research questions are debated. Firstly, the findings on the potential of pumped storage are discussed, and the connection is made with variable renewable energy integration. Secondly, the consequences of the carbon pricing strategies, the tradeoff between conventional hydropower and PHS and the system's resilience are reviewed. Then the locations for PHS in Ethiopia are discussed. Lastly, the trends in storage dynamics are spoken about.

5.1 Research Questions

Discussion points

- **The implementation of PHS**
  Pumped hydro storage has a place in Ethiopia's future energy pathways and can act as an early accelerator for integrating intermittent energy sources. Other countries with a low renewable energy integration could benefit even more from PHS.
- **Consequences of CO_2 pricing**
  The carbon pricing pathways do not take reinvestment of money from penalties into account, might penalise too many carbon emissions and heavily penalises individual consumers.
- **Conventional hydropower versus PHS**
  Conventional hydropower is increasingly combined with solar and wind power for buffering under-capacity. However, this system only *discharges* water, where pumped storage has the ability to *charge* storage reservoirs as well.
- **The resilience of energy pathways**
  Pumped hydro storage can boost resilience, but future research has to be done into specific KPIs to study how this is possible.
- **Locations for PHS**
  The Pumped Hydro Atlas shows a plethora of possible locations for the construction of PHS, of which a lot of locations are close to the MSRs. The preferential locations depend on planned solar and wind projects and grid and transmission infrastructure.
- **Storage Dynamics**
  The seasonal pattern of the storage dynamics is highly dependent on the chosen capacity factor. OSeMOSYS is a rough estimation of the potential capacity of solar and wind, but does not accurately reflect the non-linear behaviour of storage dynamics.

5.1.1 Should Ethiopia implement pumped hydro storage?

This report shows that there can be a role for pumped storage in increasing variable renewable integration in Ethiopia, functioning as a bridging technology for the integration of variable renewables and increasing resilience, whilst keeping system expenses the same. Variable renewables benefit from storage, because of their intermittent availability. The storage functions as a buffer against periods in which the capacity factor is much higher or lower than demand.

All scenarios show a substantial increase in the integration of variable renewables into the Ethiopian energy system, with an expected share of 75% or more in 2050. However, in the cases where storage is added to the system, this integration is accelerated by 9% in the base case and 13% in the scenario for wind capacity and seasonality. In 2050, VRE connected to pumped storage makes up about 15% of electricity production in all scenarios. In these scenarios, the conservative limit for pumped hydro storage, 78 GWh, is implemented. This is only 0.04% of electricity production in 2050 but can facilitate the integration of a substantial quantity of variable renewables. If Ethiopia strives to implement large quantities of wind and solar, pumped storage accelerates integration and should be considered an option.

The conclusions of this research are significant; a previous study finds a minor role for pumped storage in Ethiopia. Oyewo et al. (2021) concludes from its current policy scenario for electricity storage for Ethiopia in 2050 that only 2.5 GWh of energy storage capacity will be installed, and not from PHS but by batteries. The study does take PHS into consideration. This is interesting because the installed electrical VRE capacity percentage is roughly the same level as for this study, between 75 and 80%. Total installed VRE capacity is comparable at 65 GW for this study and 80 GW for the study by Oyewo et al. (2021). The implication is that for the study by Oyewo, the suggestion can be made that there is a substantial overcapacity of VRE as there is virtually no electricity storage present in the system.

The potential of pumped hydro storage to increase renewable energy penetration is more significant in countries with low integration of renewables, unlike Ethiopia. Ethiopia's electricity production from renewable energy is high at over 80% for the modelled period. As shown in figure 36, pumped storage can act as a bridging technology for the early incorporation of intermittent renewables, making it financially attractive at an earlier stage to invest in PHS.

5.1.2 Consequences of CO_2 pricing

The carbon pricing scenarios heavily increase electricity production, especially in the Aggressive (AG) and Policy (POL) pathways. However, the current implementation of carbon pricing could be too aggressive and too a-specific on the type of carbon emissions. Firstly, biofuels, which do emit carbon but are also accounted for as renewable energy sources, are penalised in these pathways. Real-life policy decisions could opt to omit these emissions from the penalties. Secondly, carbon pricing benefits the system in that financial gains from carbon pricing are reinvested for policies benefitting renewable energy production or other energy projects. In OSeMOSYS, there is no method of reinvesting the cost of the penalties, which gives a skewed image of the severity of the penalties to the cost of the system. Lastly, penalising biofuels severely targets individual energy users, as biomass is primarily used for residential cooking demand. Policymakers could opt to specifically target commercial, transport or industrial demand, which would lower the impact of carbon pricing on the pathways. A more in-depth analysis of the penalisation of carbon, reinvestment of funds and the effects of policy decisions on Ethiopian energy pathways is subject to future research.

5.1.3 Conventional hydropower versus pumped storage

Conventional on-river hydropower is used for peak shaving of intermittent renewables like solar and wind. However, a major drawback is that conventional reservoirs are only able to *discharge* water for electricity generation. Conventional hydropower reservoirs exist where the reservoir is used for both seasonal and daily interaction with the grid. Still, the primary disadvantage is that once the water is used for electricity production, e.g. for peak shaving, the water is gone downstream. This drawback is much smaller with pumped reservoirs. Pumped reservoirs can cycle water between the upper and lower reservoir indefinitely when the water that evaporates is replenished by precipitation. Additionally, conventional hydropower is constructed primarily on rivers, which can also cause problems upstream if water is held in the reservoir for a prolonged period. Pumped storage has the advantage of not losing the energy carrier once it is used for power generation. Off-river pumped storage can even cycle water between the two reservoirs nearly indefinitely.

5.1.4 Does pumped hydro storage increase system resilience?

From the results of this study, it can be concluded that pumped hydro storage can potentially increase the resilience of Ethiopia's energy system. The scenarios show that with storage integration into the system, overall system costs do not rise significantly, variable renewable integration is boosted and fossil fuel dependency is reduced. As variable renewables are expected to become one of the cheapest options for constructing energy generation in the future, facilitating increased VRE penetration through pumped storage means that greenhouse gas emissions will decrease and the large solar and wind potential will be utilised better.

In Section 2.4, three indicators of resilience were identified that could be measured from the results of this research. The first measure is demand satisfaction. As demand is satisfied in all scenarios, no significant conclusion can be drawn about the role that the introduction of pumped hydro storage plays in satisfying demand. OSeMOSYS does not allow for the modelling of intricate demand dynamics, such as peaks or drops in production. This part of the quantification of resilience could be part of future research as there could be potential for pumped storage to increase resilience, especially in cases with substantial over- or under-capacity.

As shown in Section 4.1.5, the total renewable energy production does not increase significantly under the introduction of pumped hydro storage to the pathways. When renewable energy production as part of total energy production is used as an indicator of resilience, PHS makes no substantial difference to the pathways. The influence of PHS primarily constitutes itself in electricity production, where primarily variable renewables integration could benefit from PHS. Here, countries with a low electricity production from renewables could accelerate their renewable electricity production by using PHS, which in turn also could raise their renewable energy produciton. Nevertheless, this is subject to future research.

Lastly, the ratio of storage capacity versus the daily variable renewable electricity production is used as a metric for system flexibility. In all cases except Base Case LS, the storage capacity is 78 GWh, based on 20% of daily variable renewable electricity production. In all of the other cases, the ratio in 2050 of storage capacity versus daily electricity production remains between 15 and 21%. However, when the Large Storage (LS) scenario is analysed, it becomes clear that the larger storage capacity increases the system's flexibility. Base Case LS has a storage capacity of 100% of the daily variable renewable electricity production at 390 GWh. For this scenario, the ratio of storage to daily VRE production is 85% for this case. In this pathway, the total system costs do not rise, which indicates that additional storage capacity can be built without increasing system costs. In turn, this higher storage capacity realises a more flexible energy pathway. Also, solar power is added to the technologies that connect to pumped hydro storage in the LS pathway. This increased heterogeneity in energy sources decreases the dependency on a single technology for charging storage, decreasing vulnerability to fluctuating availability.

5.1.5 Locations for pumped storage

The Global Pumped Hydro Atlas does not give a specific indication of the specific geographical locations where pumped hydro storage should be constructed. Still, it is a way to estimate the general regions in Ethiopia where it would be possible. From Figure 52 illustrates that primarily the southeastern regions of Ethiopia bear no possibilities to construct PHS, whereas the western part of the country is rich in potential locations. Figure 52 shows the locations for 50 GWh of storage and illustrates that there is a plethora of locations possible. The same trends are observed with 150 GWh storage locations in the Pumped Hydro Atlas.

The MSRs are chosen on their distance to the grid and the lowest expected levelised cost of electricity (LCOE). Therefore, it can be attractive to place PHS facilities close to these MSRs, if Ethiopia opts to construct its future solar and wind facilities there. However, future studies have to look into the specific requirements for PHS sites, ease of connecting to the grid, constructing transmission infrastructure and optimal and planned solar and wind projects.

5.1.6 Storage Dynamics

The seasonality of storage dynamics is highly dependent on the chosen capacity factors for solar and wind. However, the availability of both wind and solar power is variable and differs from year to year. For this research, the same capacity factor is used for all years, influencing the storage dynamics. This is visible in the pathways where the seasonality from the Adama wind farm replaces the GIS data from Renewables.ninja. Here, the outcome of the pathway in terms of installed generation capacity does not change much, but the storage dynamics differ. To get an apt sense of the storage dynamics, future research has to focus specifically on these using models that allow for the investigation of these storage dynamics in a non-linear method.

5.2 Methodology

Discussion points

- **Reliability of results**
  Pathways should not be translated directly as policy decisions, but serve as a look into the potential effects of incorporating PHS, carbon pricing and discrepancies in data sources.
- **Quality of data**
  The starter kit provides a good starting point for inexperienced modellers of energy systems, but critical evaluation of the data is required.
- **OSeMOSYS as a modelling tool**
  OSeMOSYS fulfils its aimed function as a tool for long-term energy planning that is relatively easy to use and free from up-front investments. However, working with high-resolution storage dynamics is sub-optimal with OSeMOSYS. Also, intricate, large-scale pathways like Ethiopia's require meticulous work by the modeller and are open for human-errors.

5.2.1 Reliability of results

Modelled OSeMOSYS energy pathways are valuable tools that provide insight into the energy sector, but their results should not be used solely or directly as input for policy decisions. This is because the models are static. The behaviour of energy systems is highly dynamic, which is not captured by the linear optimisation of OSeMOSYS. Also, non-energy factors such as political decisions and economic incentives are not incorporated into the results. Changes in these areas can significantly impact energy markets and policy decisions. For example, a change in government policy can dramatically affect the energy sector, while economic incentives can influence the demand for specific energy sources.

OSeMOSYS models are usually based on historical data, which may not accurately reflect future trends. For this research, a demand pattern is assumed based on population growth, economic development, and technological advances for the starter kit. These results are highly likely to be an inaccurate representation of future system dynamics. The pathways for Ethiopia are validated against IRENA data (IRENA, n.d.) so that the system's dynamics up to 2020 are adequately represented.

To illustrate differences in the projected pathways, 14 compares the installed capacity [GW] for the planning prospects by IRENA (International Renewable Energy Agency, 2021) and the results of this research.

	Solar		Wind	
	2030	*2040*	*2030*	*2040*
IRENA	4.3	18.1	1.3	2.1
Model results	4.0	7.7	2.6	9.8
Delta	-0.3	-10.4	+1.3	+7.7

Table 14: A comparison between the projected pathway of installed solar and wind capacity [GW] for Ethiopia by IRENA with the results from this research. In the last row, the red color indicates a lower installed capacity in the results for this research, a green color indicates high installed capacity.

The planning prospect for Africa by IRENA finds similar pathways for 2030 as this research, with the primary difference being a more extensive integration of wind energy in the pathway. However, the results for 2040 diverge a lot more, with a balanced integration of installed solar and wind capacity found for the results of this research. The pathways by IRENA project focus on solar energy instead of wind power. These pathways are neither right nor wrong but illustrate the discrepancies between modelling choices and pathways when performing energy modelling, especially in the long term. It shows that the future of Ethiopia is highly uncertain and subject to many more factors than are considered by OSeMOSYS.

Additionally, OSeMOSYS models are based on policy, economic or social assumptions that may not be accurate. The model may assume that energy sources and subsequent fuel prices or costs will remain the same over time, or that certain technologies will be available. These assumptions may be inaccurate, as new technologies or energy sources may become available in the future.

Finally, OSeMOSYS models are limited in their ability to account for the impact of externalities such as environmental impacts, social impacts, and economic impacts. Ethiopia suffers from an unstable political climate, which cannot be incorporated into the modelled pathways for Ethiopia. These externalities can have a significant impact on energy markets and policy decisions e.g. a policy may have negative environmental impacts that are not accounted for in the model.

5.2.2 Quality of data

The starter kit provides a basis for creating scenarios for countries like Ethiopia where data collection can be difficult. However, if a kit is used, a critical evaluation has to be done of the dynamics in the system. An example from this study is the adaptation of the transport electrification pathway from having no restrictions on electric vehicle adoption to bounded integration speeds. In the original data, electric motorcycles made up 100% of motorcycle demand in 2027. The actual expected electrification rate of motorcycles in Ethiopia is much lower. Also, the integration of residential cooking demand was unbounded, resulting in an unrealistic transition to electricity-generated residential cooking demand in early scenarios. These examples extend to the factors as mentioned earlier such as the seasonality and capacity factors for solar and wind.

5.2.3 OSeMOSYS as a modelling tool

Incorporating storage dynamics with a high time resolution in an intricate energy system on a national scale necessitates using the supercomputer Snellius. This goes against the objective for which OSeMOSYS was created, namely, being easy to use and without any financial investment requirements. Of the scenarios elaborated on in this report, the ones without pumped storage were solved on a regular laptop with 32 GB of RAM in under 10 minutes. In contrast, solving the scenarios with a time resolution of 360 timeslices per year for 46 years meant that Snellius had to be used, which required 713 GB of RAM. This is because memory capacity is out of reach for most people. Also, using a supercomputer in the time frame of this project was solely possible because additional consulting hours were purchased with the service desk of Snellius.

Secondly, the method of using an excel file which has to be changed manually between scenarios, is highly error-prone. Multiple scenarios and significantly altering these scenarios requires meticulous work and accounting by the modeller. Therefore, the recommendation is to construct a more natural interface to work with. The datasets for this study counted roughly 350,000 data points, which all had to be created and entered manually. If a parameter in a scenario needs to be altered, this has to be done precisely and systematically. This is an issue because there are a lot of cases where a small error goes unnoticed, but it might have considerable implications for the result. Furthermore, there are no built-in error detection methods for the input data, which potentially allows mistakes to be incorporated into the energy pathways without the modeller's knowledge. If data is missing, the run will produce an error, but the validity of the input data is the sole responsibility of the modeller. For energy pathways as extensive as that of Ethiopia, especially when storage is incorporated, the chance of human errors, e.g. typos is present and not unrealistic.

6 Conclusion

This report described the thesis research to investigate the potential of pumped hydro storage in the energy pathways of Ethiopia under various scenarios ranging from different storage capacities, varying capacity factors and seasonality for wind power and carbon pricing scenarios. Furthermore, possible locations are shown in combination with optimal regions for solar and wind power.

The results of this research reveal that under the set modelling parameters, pumped hydro storage is adopted into the Ethiopian energy system without increasing the total costs of the system. In all pathways, incorporating pumped hydro storage accelerates and increases the integration of variable renewable energy sources like wind and solar power. Also, when the maximum storage capacity is increased by a factor of five, the pathways adopt a more heterogeneous mix of solar and wind, as opposed to primarily wind power in the pathways with smaller storage. This diversification of the energy sources increases flexibility and reduces the overall capacity required to satisfy demand. Furthermore, PHS can act as a bridging technology for integrating intermittent renewables. Lastly, the benefits for countries with a low current renewable integration could be even larger, as Ethiopia already has a high renewable penetration.

The pathways incorporating carbon pricing reveal that the electrification of the energy system increases by transitioning quicker from biomass to electricity when satisfying residential cooking demand. However, to adequately incorporate these pathways, more extensive economic and policy analysis has to be performed. In this study, all emissions are penalised in these pathways (residential, commercial, transport and industrial), whereas this might not be realistic when implementing this in real life.

From the results of this research, it can be concluded that pumped hydro storage has the potential to raise the flexibility and resilience of the Ethiopian energy system. Introducing pumped hydro storage to the pathways does not influence the percentage of demand that is met, provides flexibility with regard to buffering production of variable renewable energy sources and increases the integration of variable renewables. Nevertheless, future work has to focus on more detailed dynamics of supply and demand satisfaction and grid outages.

The Model Supply Regions (MSR) by IRENA indicate the optimal geographical areas in Ethiopia to construct solar and wind power concerning the lowest levelised cost of electricity. Parameters from these regions are used as input for the model. Additionally, the spatial data is used to locate potential PHS locations in Ethiopia in combination with the Global Pumped Hydro Atlas. The combination of the MSR with the Atlas provides insight into the locations where PHS could be built. This is because constructing PHS close to these MSR provides benefits regarding infrastructure, transmission, and energetic losses as the MSR takes distance to the grid into account. Future research should improve the spatial optimisation of constructing pumped hydropower with variable renewables.

7 Future work

In this chapter, a selection of recommendations for future research is provided. The extent of this study provides the basis for a plethora of new questions, and from these the subjects of resilience indicators and spatial modelling are discussed below.

7.1 Indicators of resilience and flexibility

To improve the quality of investigated pathways and to gain a better understanding of the resilience and flexibility of the Ethiopian energy system, the pathways, especially those that include PHS, have to be studied under more performance indicators for resilience and flexibility. Indicators that are interesting to include in future work on Ethiopia include, but are not limited to:

1. Self-sufficiency: the amount of time the energy system can operate without external inputs
2. Grid outages
   (a) Number of black- or brownouts experienced
   (b) Frequency of outages
   (c) Average duration of outages
   (d) Number of customers affected by outages
   (e) Economic cost of outages
3. Peak supply and demand satisfaction
   (a) Ability to meet peak demand
   (b) Ability to respond to rapid changes in supply
4. Resilience to changing policy decisions and guidelines e.g. carbon pricing

These are not included in this report, as research into these elements extends beyond the scope of the study. Also, indicators such as resilience to changing policy decisions and guidelines eg. carbon pricing, are not aptly measurable from the results from the studied scenarios in OSeMOSYS.

7.2 Spatial modelling

The pathways described in the report show the potential of introducing pumped hydro storage to Ethiopia. A first look into the potential locations of pumped storage in Ethiopia is described, but this can be improved greatly in quality. The Global Pumped Hydro Atlas gives only a range of locations, but future studies should focus on optimising the combination between grid and transmission infrastructure, planned solar and wind infrastructure and potential PHS locations combined with the Model Supply Regions. Already, infrastructure has been constructed for the Grand Ethiopian Renaissance Dam in the Western part of the country. This provides the potential for PHS, as transmission infrastructure is already there, which may decrease the capital costs of the project.

7.3 Storage Dynamics

OSeMOSYS utilises linear optimisation to calculate the objective function. Here, it linearises storage dynamics, allowing for only a single (dis)charge per timeslice. The interplay between intermittent renewable energy sources and pumped storage is non-linear and not properly represented by OSeMOSYS. This can lead to sub-optimal results in terms of storage dispatch and capacity planning. Complex interactions are potentially oversimplified. Future research should focus on more detailed modelling of the interactions of these storage dynamics of pumped hydro storage combined with intermittent energy sources.

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A Sets, units and parameters

A.1 Sets

In OSeMOSYS, sets constitute the temporal and spatial scale and contain the emissions, technologies, storage and fuels, making it the backbone of the model. In general, sets do not vary in between scenarios, as scenario variability comes from parameter decisions. However, pumped hydro is implemented through the incorporation of a set for storage, additional fuels and power generation technologies.

The sets used for this study are presented in table 15. In the right-most column, an explanation is given of how each sets is used in this research.

Name	Index	Definition	Example of utilisation
REGION	r	The regions to which the model applies	The region is on a national scale, namely Ethiopia. On this level, all operations are set and calculated. If one would want to model more countries or introduce a regional divide, it is defined in REGION.
MODE OF OPERATION	m	The modes of operation that apply to a certain technology	The charging of a pumped hydro reservoir gets a different mode of operation compared to the discharging of energy from the same reservoir.
TECHNOLOGY	t	The building blocks of the model, and represent all energy generating, converting or altering methods	Power plants, energy import or export, demand types are all examples of technologies. For a full overview, see reference energy systems.
EMISSION	e	Emissions as a result of operations of defined technologies	The emissions of CO2 is the primary contributor to emission for this study.
FUEL	f	All energy vectors that interact with the defined technologies	Biomass, solar potential and electric vehicle demand are examples of elements incorporated in the fuel set.
STORAGE	s	Storage facilities in the model	Pumped hydro storage is the storage facility that is incorporated in this modelled period.
YEAR	y	The number of years in the modelled period	This study evaluates a period between 2015 and 2050, leading to a set of 46 years.
SEASON	ls	The number of seasons in a modelled year	Ethiopia has four seasons: Winter, Spring, Summer and Fall. These are represented in this set.
DAYTYPE	ld	The types of days that exist in the modelled period	A separation can be made between weekend and work days. However, this is not relevant for this study.
DAILYTIME BRACKET	lh	The number of fractions into which a day is split	Days are divided into night and day, dividing the day into two.
TIMESLICE	l	The number of fractions into which a year is split	In this study, eight timeslices represent the yearly dynamics, namely four seasons each divided into a specific day and night.

Table 15: Overview of sets used in OSeMOSYS KTH-dESA (2021)

A.2 Units

The use of homogeneous units throughout the modelling process is imperative for a correct calculation of the objective functions and underlying variables. Table 16 displays the base units that the model uses and in which the parameters are defined.

Category	Unit
Energy	Petajoule [PJ]
Generation Capacity	Gigawatt [GW]
Emission	Kilotonne [kt]
Costs	Million USD [M$]

Table 16: Primary units used in OSeMOSYS

A.3 Parameters

In contrast to sets, parameters outline the specific functioning of a model and are used to create scenarios and pathways. The parameters elaborated on below represent a selection of parameters that are specifically relevant to this study. However, a complete overview of parameters is found in KTH-dESA (2021).

A.4 Capacity Factor

The capacity factor is a highly influential parameter regarding the production of energy by a technology as it indicates the capacity available for energy production. It is an instrument to adequately integrate energy generation tendencies of specific renewable or other heterogeneously available technologies. For renewable energies such as solar and wind power, the capacity factor varies significantly compared to traditional energy generation technologies. Where fossil fuel has a constant, predictable capacity factor, this not the case for variable renewables.

Depending on the time resolution, a capacity factor is assigned per season, day type or hour during a specific day. For example, solar energy is unavailable during the night, giving it a capacity factor of zero during half of the timeslices. Wind power is even more variable, changing inter-annually, inter-seasonally and between days. Therefore, the choice for the capacity factor of these renewable energy generation technologies is important for the subsequent energy production.

An example of the heterogeneity of capacity factors is the availability of wind in Ethiopia. The capacity factor for wind power varies greatly both spatially and temporally. Geographical variability leads to variance between a capacity factor of 0 to around 0.54 on a scale from 0 to 1. In figure 53, the spatial variability of wind is shown, emphasising the importance of construction wind power capacity at the right location, because a higher capacity factor leads to a increased power output. This information on the capacity factor of wind was retrieved from the Global Wind Atlas, an initiative to provide free, easily available wind capacity data by the Technical University of Denmark (DTU) and the World Bank Group. This study explores scenarios based on the variability in the capacity factor of intermittent energy sources. This scenario is shown in section 3.5.3.

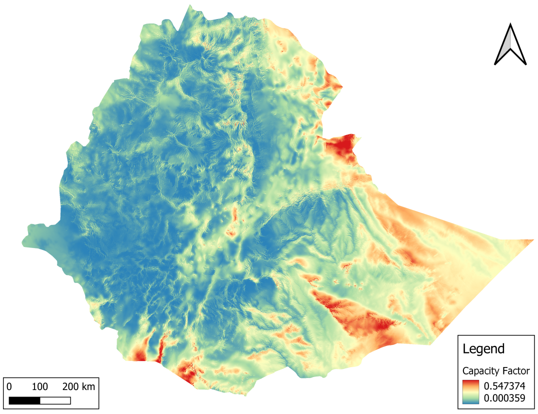


Figure 53: Capacity factors for wind power in Ethiopia

A.4.1 CapacityToActivityUnit

The CapacityToActivityUnit translates the capacity of a technology to the energy generation of that technology if it were to operate for a complete year. In OSeMOSYS, the primary unit for energy is Petajoules [PJ]. Secondly, generation capacity is expressed in Gigawatss [GW]. One GW of generation capacity produces 31.356 PJ in a year. Hence, all power plants and other energy generation technologies are given a factor 31.356 for the CapacityToActivityUnit to translate the production of power in GW to produced units of energy in PJ.

A.4.2 Input- and OutputActivityRatio

The efficiency of a power plant or other processes with efficiency losses is determined by the ratio between the *InputActivityRatio* and the *OutputActivityRatio*. For a pumped hydro storage plant, the efficiency of the cycle is set at 80%. Therefore, the InputActivityRatio for pumped hydro storage has been set to 1.25 to give PHS an efficiency of 80%, which is shown in equation 3.

$$\text{Efficiency} = \frac{\text{OutputActivityRatio}_{\text{(PHS)}}}{\text{InputActivityRatio}_{\text{(PHS)}}} = \frac{1}{1.25} = 0.8 \tag{3}$$

A.4.3 AvailabilityFactor

Pumped hydro storage is bound by a charge and discharge period, which limits the number of cycles that can occur in a certain unit of time. For this study, a maximum discharge time of 10 hours at 1 cycle per day is chosen as the designated maximum frequency. To implement this, the AvailabilityFactor, which delineates the time that a technology is available throughout a unit of time, is set to $\frac{10}{24} = 0.42$. This ensures that pumped storage is available for a maximum of 10 hours each day.

A.4.4 TotalTechnologyAnnualActivityUpperLimit / -LowerLimit

The activity limiting parameters set upper and lower boundaries on annual energy production by a specific technology. Through this parameter, restrictions are put in place on the output and thus penetration of technologies. An practical example of this is limiting the upper limit of modelled renewable energy penetration to 15% of total energy demand to reflect a gradual pathway for renewables as opposed to instant, limitless integration of solar and wind. Furthermore, the upper limit is used to restrict the speed of electric vehicle integration and the development of residential cooking demand that is met by electricity, shown in paragraph **??**. Both of these factors were not limited in the original data.

A.4.5 EmissionPenalty

The *EmissionPenalty* variable provides the possibility to decentivise investment in fossil fuels by putting a monetary penalty on the emission of greenhouse gases. Emissions are expressed in kilotonnes [kt]. Consequently, the penalty is million USD per kilotonne of produced emissions, in this case CO_2. Section 3.5.2 describes further implementation of the *EmissionsPenalty* parameter is described.

A.5 Storage Parameters

This section elaborates on the parameters in OSeMOSYS that specifically influence the dynamics of energy storage. An overview is provided of the most important storage parameters. A complete outline of the storage parameters is found in the OSeMOSYS documentation shown in KTH-dESA (2021).

A.5.1 CapitalCostStorage

The capital cost for storage is defined as a cost per unit of storage capacity in the form of energy e.g. kWh or PJ. However, for this study, the cost of pumped hydro storage is defined as a cost per unit of power i.e. GW. As a result, the cost of storage parameter is set to zero for this research.

A.5.2 MinStorageCharge

A pumped hydro reservoir will not empty completely when discharging energy. For this reason, a minimal amount of storage that remain in the reservoir is defined in the form of the *MinStorageCharge*, which is a value between 0 and 1 that indicates the fraction of storage that remains in the system at all times. In this study, the minimal storage charge is 10% at all times.

B Example Case: Combining variable renewable energy generation with pumped hydro storage

To illustrate the dynamics of pumped storage working in tandem with intermittent sources of energy such as solar and wind, a hypothetical energy system was created with only wind, solar and PHS. Figure 54 depicts this energy system. A backstop technology is present in case the power supply by these sources is insufficient. Important boundary conditions from these systems include:

1. No restrictions on investments per technology
2. No restrictions on capacity expansion
3. No limitations on storage capacity
4. Storage filling has a 100% full-cycle efficiency
5. Aggregated demand representation for simplification

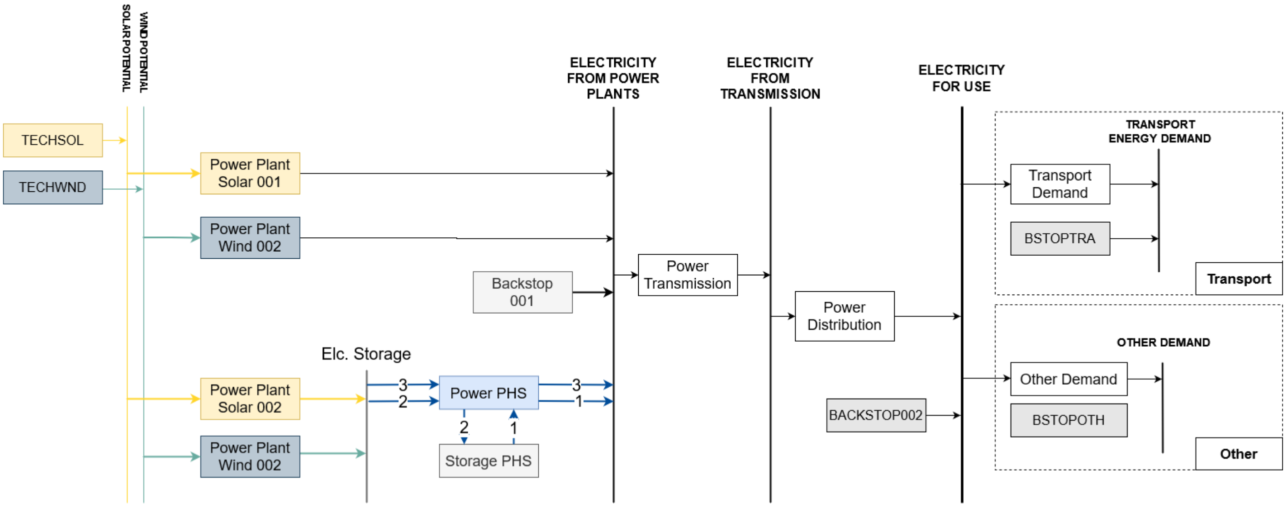


Figure 54: Example RES: Configuration with intermittent sources of energy, solar and wind, in combination with pumped hydro storage

The energy systems follow a comparable transfer of energy through the transmission to distribution and then to end-use utilisation in Ethiopia. In the next two paragraphs, two energy systems are presented with solar power and wind power, and with or without storage with the purpose of illustrating the difference in intermittency between these energy sources and the effect it has on storage in OSeMOSYS. In these examples, the year is divided into 4 seasons, divided into day and night, totalling 8 timeslices.

Timeslice	Season	Day / Night
1	Winter	Day
2	Winter	Night
3	Spring	Day
4	Spring	Night
5	Summer	Day
6	Summer	Night
7	Fall	Day
8	Fall	Night

B.1 Example Energy System: Solar power combined with pumped storage

In the first example, only solar power is available for electricity generation. The two scenarios investigated differ in their presence of pumped storage. The reference energy systems of these respective scenarios are illustrated in Figure 55 and Figure 56.

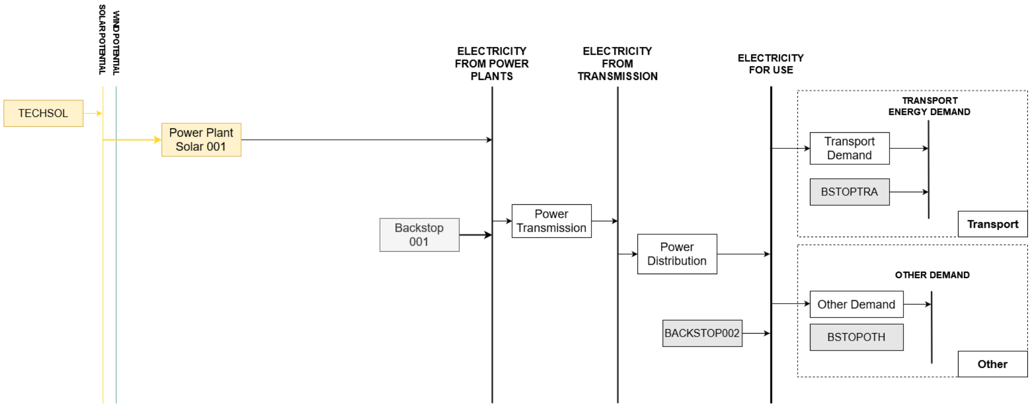


Figure 55: RES: Solar power without pumped hydro storage

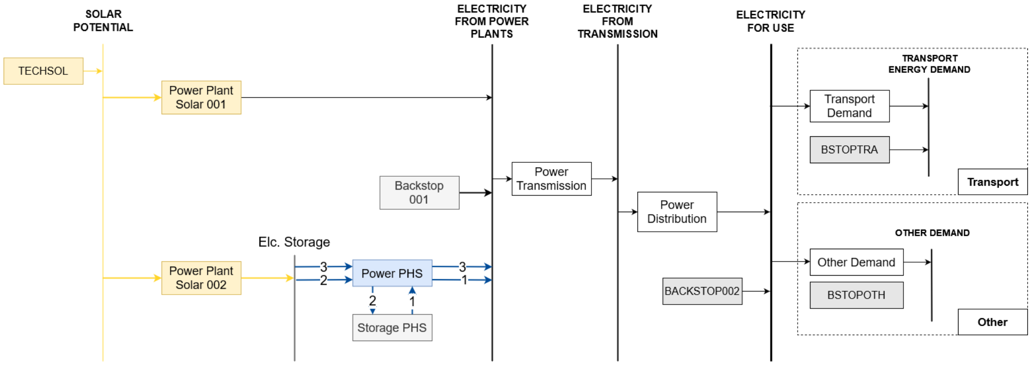
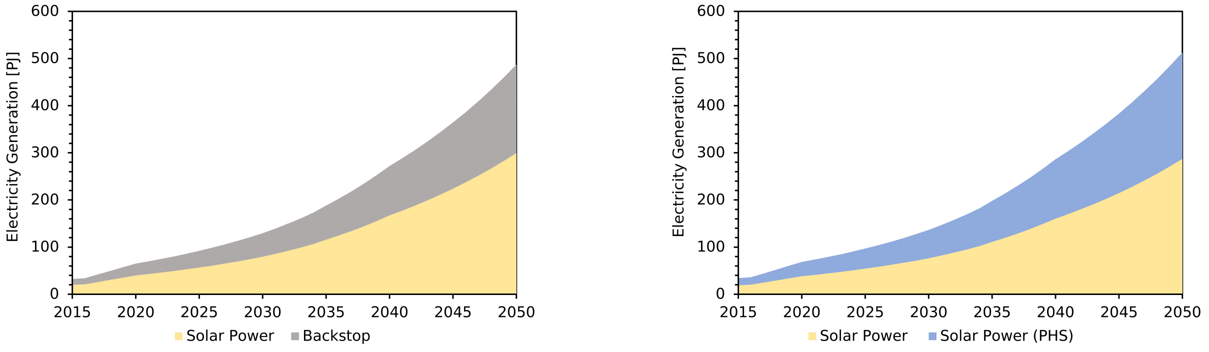


Figure 56: RES: Solar power with pumped hydro storage

Solar power is solely available during the day for the production of energy. The electricity production for solar power combined with and without PHS is illustrated below. In the first scenario, no storage is present. Due to the unavailability of solar power during the timeslices that represent the night time, the backstop technology has to facilitate power output during the night. This is illustrated in figure 57a. The implication of the usage of a backstop energy generation can include but is not limited to increased cost and high greenhouse gas emissions.

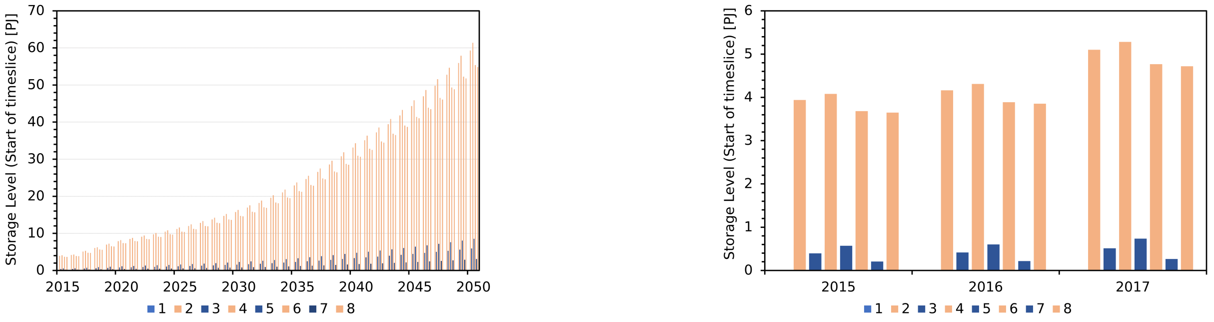
The results for a scenario in which pumped storage is present are found in figure 57b, where the electricity production previously executed by a backstop technology is now replaced by solar power connected to pumped storage. The storage enables charging during the daytime and the release of energy during the night.



(a) (b)

Figure 57: Example Case: Electricity generation in PJ for a system with only solar power from 2015 to 2050: Scenario (a) Without PHS (b) Including PHS

Figure 58a shows the storage level at the start of each timeslice for the complete modelled period. Here, it is clear that storage increases with the same trend as solar capacity. The day and night cycle is clearly visible in figure 58b, where at the start of the uneven timeslices (blue), which represent the day, the reservoir is nearly empty. In contrast, at the start of the uneven timeslices (orange), which represent night time, the storage is full. This shows the diurnal pattern of solar energy working in tandem with pumped storage.



(a) (b)

Figure 58: Example Case: Storage level at the start of each timeslice for a system with only solar power from 2015 to 2050 with (a) Full time resolution (b) 2015 to 2017

B.2 Example Energy System: Wind power combined with pumped storage

The reference energy systems for systems with only wind power and only wind and PHS are shown in Figure 59 and Figure 60

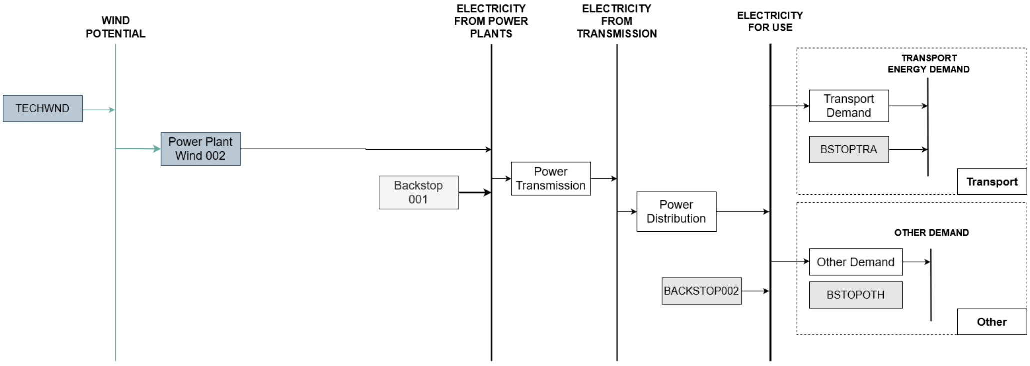


Figure 59: RES: Wind power without pumped hydro storage

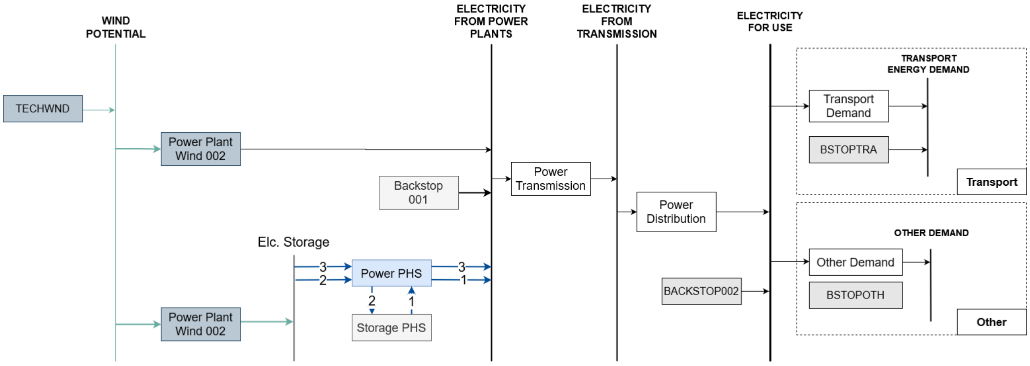
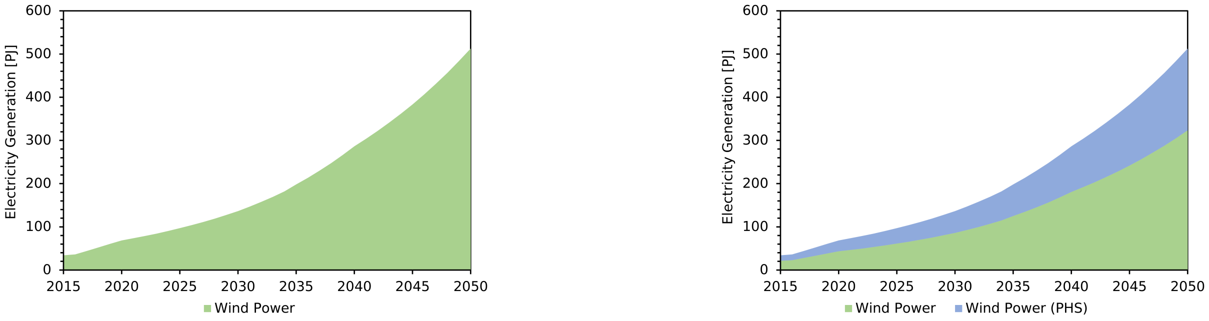


Figure 60: RES: Wind power with pumped hydro storage

In contrast with solar power, wind follows a much more unpredictable pattern, both daily and seasonally. The capacity factor for wind used in this scenario varies from 0.13 to 0.33, a near three-fold difference between different seasons. This variation leads to a high necessity for capacity during low-potential seasons and over-capacity during seasons with more wind capacity. In this scenario, there is no restriction on the investment or capacity of wind power, which is why the full energy demand can be met by wind, shown in figure 61a. However, this is not realistic. Figure 61b shows the configuration of the system if PHS is implemented. The production is identical, but system costs are higher in the first scenario due to the construction of overcapacity. This is including the construction cost of the storage reservoir.

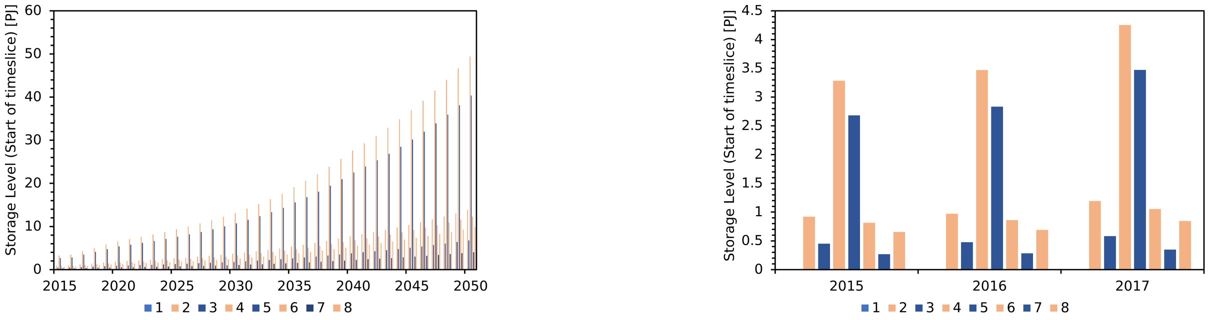


(a)

(b)

Figure 61: Example Case: Electricity generation in PJ for a system with only wind power from 2015 to 2050: Scenario (a) Without PHS (b) Including PHS

The temporal behaviour of storage under wind power is shown in figure 62. The difference between the charging of the reservoir between solar power and wind power is clear in that solar power follows a much more predictable daily pattern. Wind power varies a lot more during the year, as peak charge between the seasons jumps from around 1 PJ in seasons 1, 3 and 4 to over 3 PJ in season 2. This dynamic is highlighted in detail in figure 62b.



(a)

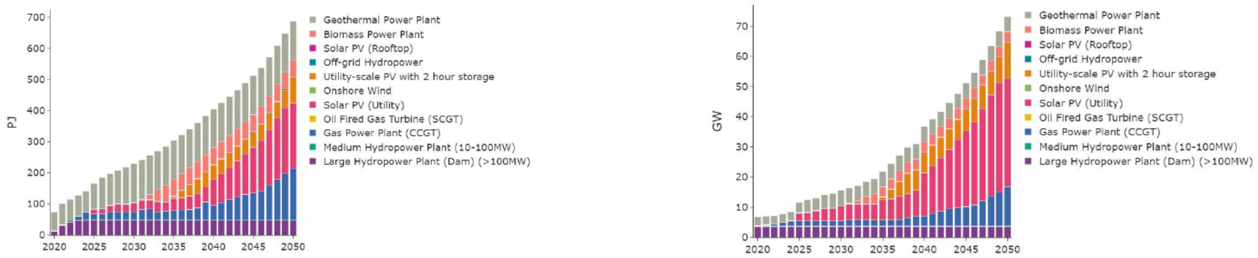
(b)

Figure 62: Example Case: Storage level at the start of each timeslice for a system with only solar power from 2015 to 2050 with (a) Full time resolution (b) 2015 to 2017

B.3 Implications of results

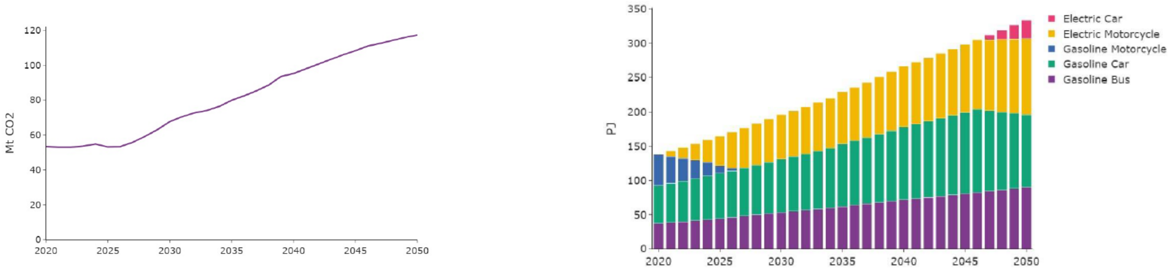
The intermittency of solar power and wind power is often complementary, which provides the potential for the combination of both techniques to be adopted in the energy system and also for the use of energy storage. If merely solar or wind is implemented without storage, the system has to accommodate the period with the lowest capacity factor. For solar power, this is during the night, when irradiance is zero and it means that additional technologies have to exist to produce energy during the night time. For wind, this pattern is much less predictable. The effect is that to prevent an under-supply of electricity, the installed wind capacity has to be increased. Here, the introduction of storage act as a buffer, to relieve the dependency on other generation technologies such as the backstop. In turn, the adoption of a combination of solar and wind with the addition of PHS into an energy mix potentially enables higher integration of variable renewables than in a system with storage.

C Starter Kit: Result from the Least-cost scenario



(a) Electricity production [PJ] from 2015 to 2050 for the Least-cost scenario

(b) Installed generation capacity [GW] from 2015 to 2050 for the Least-cost scenario



(c) Annual CO_2 emissions [Mt]

(d) Transport results

Figure 63: Starter Kit: Results from the Least-Cost Scenario for 2015 to 2050