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Doctoral Thesis in Energy and Environmental Systems

Trade-offs and conflicting objectives of decision making investments in low-carbon technology portfolios for sustainable development

National and continental insights offered by applying energy system models

IOANNIS PAPPIS

Stockholm, Sweden 2022

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"*Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs." (World Commission of Environment and Development, 1986) [1]*

Abstract

Energy infrastructure and appropriate energy policies are crucial for sustainable development and to meet Sustainable Development Goals (SDGs). Limiting global warming potential below 1.5°C would require “rapid and far-reaching” transitions and unprecedented changes in all aspects of society. Several factors influence investment decisions on energy conversion technologies and their specific locations. The choice, timing, and location of energy investments affect the total system cost, socio-economic development, the environment (e.g., emissions, water use), and a nation's energy security. However, existing national energy modelling initiatives only investigate a subset of these pillars for achieving sustainability.

This thesis examines the challenges associated with the energy transition of low-and middle-income countries (Paraguay, Ethiopia, Africa). This work considers national and global policies, focusing on achieving SDG7 and SDG13. The dissertation includes a cover essay and four appended papers. The research conducted in this Thesis examines how energy-systems models can assist in understanding an energy system's complex interactions for sustainable development.

Specifically, the results highlight hydropower and solar PV as key technologies to achieve climate change targets, energy security and energy access goals. Hydropower and other renewable electricity can be exported to bolster energy security for the exporting country, although export revenues are eroded by local demand growth and low export prices. The benefits of low-cost electricity provided by cross-border hydropower should be balanced against energy security concerns for the importing country. The research demonstrates the benefits of regional coordination, with trade enabling renewable resources to be harnessed and the electricity transmitted to demand centres. Although RET decreases carbon dioxide emissions and water use compared to fossil-fuel plants and creates more jobs, they require high up-front capital costs offset by the lower operating fuel costs in the long term. Thus, increasing the ambition of climate targets while achieving electricity access results in lower cumulative costs. Also, although hydropower and renewable technologies build climate resilience, hydropower operation depends on climate variability affecting energy security. Thus, mitigation strategies should consider the associated challenges of climate change in hydropower investments.

Hydropower and renewables are primarily grid-connected technologies, so off-grid and mini-grid systems are key complements to national-grid expansion when pushing for universal energy access. They also impact energy security, total system costs and socio-economic development.

This Thesis's outcomes can support governments in strategic energy planning to identify future renewable energy projects and ensure their financial viability. Energy systems in their transition need to be affordable, reliable and sustainable (e.g., energy secured, combat climate change) by being climate-resilient. The thesis findings demonstrate that nations need integrated energy planning, accounting for the geospatial characteristics of energy technologies, and water resources management to achieve SDG7 and build climate-resilient (SDG13). A broad portfolio of renewable technologies, interconnectors and a decentralized power generation system providing electricity closer to the end-user demand is needed to enhance energy security, decrease environmental pressures and provide affordable electricity for a nation.

Keywords:
sustainable development, energy systems analysis, modelling tools, energy policy, energy resources management, techno-economic analysis, low-carbon technology portfolios, energy access, OSeMOSYS, Paraguay, Ethiopia, Africa.

Sammanfattning

Energiinfrastruktur och lämplig energipolitik är avgörande för att uppnå de globala målen för hållbar utveckling (SDG). Att begränsa den globala uppvärmningen till 1,5 °C kräver "snabba och långtgående" övergångar och förändringar utan motstycke i alla aspekter av samhället. Flera faktorer påverkar investeringsbeslut och val av plats för olika energiomvandlingsteknologier. Energiinvesteringar, deras tidpunkt och plats påverkar den totala systemkostnaden, socioekonomisk utveckling, miljön (t.ex. utsläpp, vattenanvändning) och en nations energisäkerhet. Befintliga nationella initiativ för energimodellering undersöker dock bara en delmängd av dessa aspekter.

Denna avhandling undersöker utmaningarna i samband med energiomställningen i låg- och medelinkomstländer (mer specifikt Paraguay, Etiopien och övriga länder i Afrika). Detta arbete tar hänsyn till nationell och global policy, med fokus på att uppnå SDG7 och SDG13. Avhandlingen innehåller en omslagsuppsats och fyra bifogade artiklar. Forskningen i denna avhandling undersöker hur energisystemmodeller kan hjälpa till för att öka förståelsen av ett energisystems komplexa interaktioner för hållbar utveckling.

Specifikt lyfter resultaten fram vattenkraft och solenergi som nyckelteknologier för att uppnå målen gällande klimatförändringar, energisäkerhet och energitillgång. Vattenkraft och annan förnybar el kan exporteras för att stärka energitryggheten för exportlandet, även i fallen då exportintäkterna urholkas av lokal efterfrågetillväxt och låga exportpriser. Fördelarna med lågprisel från gränsöverskridande ledningar bör vägas mot energisäkerhetsproblem för importlandet. Forskningen visar fördelarna med regional samordning, handel som möjliggör att förnybara resurser kan utnyttjas och elen överföras till områden med hög efterfrågan av energi. Även om förnybar teknologi kräver höga initiala investeringar, minskar de koldioxidutsläppen och vattenanvändningen jämfört med fossilbränsleanläggningar, samt skapar fler jobbtillfällen och har lägre bränslekostnader. Att höja ambitionen med klimatmål samtidigt som man uppnår eltillgång resulterar således i lägre kumulativa kostnader. Även om vattenkraft och annan förnybar teknik bygger klimattålighet, påverkas vattenkraftdriften på klimatförändringar som påverkar energisäkerheten. Därför bör klimatåtaganden ta vattenkraften i beaktande.

Vattenkraft och förnybar energi är i första hand nätanslutna tekniker, därmed är lokala elnät viktiga komplement till nationell nätexpansion när man strävar mot universell tillgång till energi. De påverkar också energisäkerhet, totala systemkostnader och socioekonomisk utveckling.

Resultaten av denna avhandling kan stödja regeringar i strategisk energiplanering för att identifiera framtida projekt för förnybar energi och säkerställa deras ekonomiska bärkraft. Energisystem i sin övergång måste vara ekonomiskt överkomliga, tillförlitliga och moderna (t.ex. energisäkrade, bekämpa klimatförändringar) genom att vara klimattåliga. Resultaten av denna avhandling visar att nationer behöver integrerad energiplanering med hänsyn till olika teknologiers geospatiala egenskaper och vattenanvändning för att uppnå SDG7 och bygga klimattåligt (SDG13). En bred portfölj av förnybar teknik, och ett decentraliserat kraftgenereringssystem som tillhandahåller elektricitet närmare slutanvändarna behövs för att öka energisäkerheten, minska miljötrycket och tillhandahålla elektricitet till överkomligt pris.

Nyckelord:
hållbar utveckling, energisystemanalys, modelleringsverktyg, energipolitik, energiresursförvaltning, teknisk-ekonomisk analys, energiteknologiportföljer, tillgång till energi, OSeMOSYS, Paraguay, Ethiopia, Africa.

Preface

This doctoral thesis is conducted at the Energy Systems (ES) unit, previously Division of Energy Systems Analysis (dESA), at KTH Royal Institute of Technology, from December 2017 - to June 2022. My supervisors were Assist. Professor Will Usher and Professor Viktoria Martin (head of the unit). Until 2020, the former supervisor was Professor Mark Howells (head of the dESA unit). The research at the Energy Systems unit spans from applying energy modelling tools for strategic investment decisions achieving sustainable development pathways to science-policy-society interactions.

This thesis adds to the field of developing energy infrastructure for sustainable development in middle-income countries and those aspiring to become middle-income and quantitatively inform Sustainable Development Goals (SDGs), focusing on SDG7 and SDG13. The objective was to examine the trade-offs and conflicting objectives of achieving the three pillars for sustainable development in the energy transition of different regional case studies. Thus, the nations can formulate coherent energy policies and assess their energy systems performance to enable better-calibrated systems. In this thesis, the author investigated the energy challenges associated with the future energy transition of the energy systems of Paraguay, Ethiopia and Africa in separate case studies. Open-source modelling tools are applied in each one of the study areas to provide insights on decision-making investments in low-carbon technology portfolios to inform integrated approaches for sustainable development bridging the science-policy interface. The thesis findings demonstrate that nations need integrated energy planning, accounting for the geospatial characteristics of energy technologies, and water resources management to achieve SDG7 and SDG13.

Different institutions funded the research conducted for this thesis. The analysis undertaken for Paraguay was funded by the United Nations Department of Economic and Social Affairs in support of the project "Supporting developing countries in their transition from Millennium Development Goals-based development strategies to broader sustainable development strategies through modelling-based policy analysis". The study conducted for Ethiopia was funded by the Commonwealth & Development Office – UKAID under the project "Energy system development pathways for Ethiopia (PATHWAYS)". This is part of the Applied Research Program on Energy for Economic Growth (EED), led by Oxford Policy Management. Part of the research conducted for Africa is funded by the Joint Research Centre of the European Commission under the project "Energy projections for African countries". The views expressed

in this thesis are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission and the UK government´s official policies.

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This doctoral thesis is an outcome of 4.5 years of Ph.D. studies supported by various people. I want to express my gratitude for their involvement in the research projects leading to peer-reviewed journal articles resulting in this thesis.

I want to express my gratitude to Prof. Mark Howells, my former principal supervisor, for believing in me and joining the dESA team on different occasions. Thank you, Mark, for your constant motivation, technical and mental support throughout the international projects and the papers. Also, for allowing me to be involved and lead the organization of summer schools on modelling tools, energy modelling platforms and capacity building activities, meeting people from all over the world and exchange research ideas to broader my horizons and intellectual interests. I would also like to thank my former co-supervisor, Prof. Holger, for his willingness to assist throughout this process by providing constructive criticism and being a mentor.

I also want to thank Prof. Viktoria Martin for her support in my Ph.D. thesis as my new principal supervisor. I would like to express my gratitude to Assist. Prof. Will Usher for their continuous feedback, technical and mental support throughout the research papers and Ph.D. thesis. Their support is highly appreciated in this long journey, especially under COVID.

Special thanks to Thomas Alfstad, special advisor for sustainable development strategies at UNDESA, for being a role model, and our collaboration made me a better researcher and person. My gratitude also goes to Dr. Diana Alarcon, Dr. Linus Morfor and Dr. Eduardo Zepeda, where our partnership deepened my knowledge in energy challenges and in the science-policy interface.

This journey would not have been possible without the support and input from the people-friends at KTH-Division of Energy Systems. Working with such talented, skillful, impact-driven people is a unique experience. They made the Ph.D. journey and living in Stockholm an experience I will never forget. I would like to thank Abhishek Shivakumar for being such a good friend and Vignesh Sridharan and Eunice Ramos for their tremendous support and friendship throughout challenging times. Also, a big thanks to Constantinos Taliotis as a supervisor of my MSc Thesis, Dimitris Mentis and Alexandros Korkovelos for their project support and personal bits of advice. I am also thankful to Francesco-Gardumi, Gabriella, Maryna, Oliver, Andreas, Babak, Youssef, Shahid, Rebecka, Eftychia, Francesco Fuso-Nerini, Dilip, Mauricio, Saman, Alberto, Silvia, Joanna and Anneli.

I would also like to thank Kiriakos Trarpalias, Thanos Tselempanis, Ilias Minas, Giorgos Margellos for their friendship all these years and make a living abroad less challenging.

Last but not least, I would like to thank my amazing family, my father, mother, sister and grandparents, for their love, patience and continuous encouragement all these years. Everything seems impossible until it's done.

List of appended papers

This thesis is based on the following scientific papers:

Paper-I.

I. Pappis, C. Centurion, E.P. Ramos, M. Howells, S. Ulloa, E. Ortigoza, P.E. Gardel-Sotomayor, T. Alfstad, “Implications to the electricity system of Paraguay of different demand scenarios and export prices to Brazil,” *Energy Systems*, Jan. 2021, doi: 10.1007/s12667-020-00420-w.

Paper-II.

I. Pappis, A. Sahlberg, T. Walle, O. Broad, M. Howells, E. Eludoyin, W. Usher, “Influence of Electrification Pathways in the Electricity Sector of Ethiopia—Policy Implications Linking Spatial Electrification Analysis and Medium to Long-Term Energy Planning,” Energies, vol. 14, no. 4, Art. no. 4, Jan. 2021, doi: 10.3390/en14041209.

Paper-III.

I. Pappis, V. Sridharan, M. Howells, H. Medarac, I. Kougias, R.G. Sánchez, A. Shivakumar, W. Usher, “The effects of climate change mitigation strategies on the energy system of Africa and its associated water footprint”, Environmental Research Letters, vol. 17, no. 4, p. 044048, Mar. 2022, doi:10.1088/1748-9326/ac5ede

Paper-IV.

I. Pappis, “Strategic low-cost energy investment opportunities and challenges towards achieving universal electricity access (SDG7) in forty-eight African nations”. Environ. Res.: Infrastruct. Sustain., 2022, [under review]

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Glossary

Energy security measures a nation´s capacity to the uninterrupted availability of energy sources at an affordable price. It can be categorized in long-term energy security associated with timely investments to supply energy in line with economic developments and environmental needs and short-term which focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance [2]. The dimension covers the effectiveness of management of domestic and external energy sources, as well as the reliability and resilience of energy infrastructure [3].

Environmental sustainability is the responsibility to conserve natural resources and protect global ecosystems to support health and wellbeing, now and in the long term [4]. It represents the transition of a country´s energy system towards mitigating and avoiding potential environmental harm and climate change impacts. The dimension focuses on productivity and efficiency of generation, transmission and distribution, decarbonization and air quality [3].

Energy equity assesses a country´s ability to provide universal access to reliable, affordable and abundant energy for domestic and commercial use. The dimension captures basic access to electricity and clean cooking fuels and technologies, access to prosperity-enabling energy consumption levels, and affordability of electricity, gas, and fuel [3].

Electricity export price of Itaipu: It consists of the sum of both the Paraguayan energy cession rate and Itaipu´s average electricity generation cost [5]. Since Paraguay cannot use all the energy that is entitled to, by treaty, it must cede what it does not use to Brazil, which pays Paraguay a fixed cession rate in addition to the generation cost.

Electricity trade: The transfer of electricity between countries to satisfy the demands in the receiving country.

Gas trade: The transfer of natural gas between countries to satisfy the demands in the receiving country.

Power Pool: Power pool is an association of two or more interconnected electricity systems having an agreement to coordinate operations and planning for improved reliability and efficiencies.

Power Pools in Africa: CAPP (Central Africa power pool), EAPP (Eastern Africa power pool), NAPP (Northern Africa power pool), SAPP (Southern Africa power pool) and WAPP (Western Africa power pool).

Water withdrawal: is the amount of water removed from the ground or diverted from a water source for use [6].

Water consumption: is the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment and not returned to the original water source after being withdrawn (also called blue water footprint) [7], [8].

Total renewable water resources (TRWR): The sum of internal renewable water resources (IRWR) and external renewable water resources (ERWR). It corresponds to the maximum theoretical yearly amount of water available for a country at a given moment. [Total renewable water resources] = [Total renewable surface water] + [Total renewable groundwater] – [Overlap between surface water and groundwater][6].

Water availability for hydropower: refers to the availability of river flow and reservoirs modelled as changes in capacity factors for hydropower plants.

Water availability for thermal power plants: four different cooling types considered in the analysis in Paper-III (dry cooling, natural and mechanical draft tower, once-through cooling tower with freshwater and once-through cooling tower with salt water), so water availability refers to freshwater and saline water used.

List of Abbreviations

CLEWs	– Climate, Land, Energy and Water Systems
EGU	– European Geosciences Union
ICTP	– International Centre for Theoretical Physics
KTH	– Royal Institute of Technology
NDCs	– Nationally Determined Contributions
OSeMOSYS	– Open Source energy Modelling System
OnSSET	– Open Source Spatial Electrification Tool
GEP	– Geospatial Electrification Platform
SDGs	– Sustainable Development Goals
UNDESA	– United Nations Department of Economic and Social Affairs
UN	– United Nations
UNDP	– United Nations Development Programme
UNECA	– United Nations Economic Commission for Africa

1 Introduction

Energy infrastructure, appropriate energy policies and transition mechanisms are crucial for sustainable development and to meet Sustainable Development Goals (SDGs). Ensuring access to affordable, reliable, sustainable and modern energy for all (SDG7) is a prerequisite for sustainable development [9]. Also, sustainability is closely linked with limiting global warming to 1.5°C for climate action (SDG13) and its impact [10]. At the 2015 UN General Assembly, the 2030 Agenda for Sustainable Development was approved and addresses the economic, social and environmental pillars of development by 2030 [11]. For this agenda, each of the 17 goals are closely interlinked with synergies and trade-offs to consider in decision-making in the energy sector [12]. The International Council for Science identifies goal 7 as the second most interconnected goal, with links to goals SDG1, SDG2, SDG3, SDG6, SDG8 and SDG13 [13]. To achieve the targets of the 2030 Agenda, the timing of actions is critical due to the path dependencies and risk of lock-in of the large, capital-intensive energy investments needed to meet the growing energy demand. The evolution of the energy sector is a core aspect of achieving SDGs, so planning is essential for measuring and monitoring future performance and formulating plans to manage risks for solving future challenges [14]. Specifically, strategic energy planning can optimize energy production and services investments, consider energy resource management, and support appropriate measures to mitigate and adapt to climate change [15], [16]. These mitigation and adaptation measures include emission reduction and increasing resilience through technology and infrastructure investment choices and changes in consumers' behaviour and policies. Also, different electricity generation technologies influence socio-economic development through job creation potential [17], [18].

Several factors (e.g., interest rate, energy demand, capital cost, technological development, grid distance, government policies) influence investment decisions on energy conversion technologies and their specific locations [14]. The choice, timing, and location of energy investments affect the total system cost, the environment (e.g., emissions, water use), and a nation's energy security. However, existing national energy modelling initiatives only investigate a subset of these pillars.

The transition towards low-carbon technologies requires the engagement of various stakeholders since the energy planning approaches are different globally. Decision-makers can plan actions to combat climate change to maximize benefits and limit trade-offs with sustainable development. However, they need to account for the multiple pressure points of the energy-water nexus in the energy transition adding complexity to decision-making [10].

Strategic energy planning approaches can be informed by using quantitative energy system models [22], [23]. Such models enable decision-makers and researchers to consider the trade-offs between the availability of energy resources, system requirements (e.g., financial, technical capacity, water withdrawals and consumption) and demand projections. Models are also used to formulate scenarios of energy transition pathways that provide insights into the evolution of the energy system. These scenarios can also account for socio-economic development in fuel demand projections. By examining a broad range of scenarios, the decision-makers can explore the influence of uncertainties (e.g., fuel prices, technological development, interest rates) in the system. The modelling tools can also support policy analysis in countries to assess SDG interactions and establish clear metrics and targets tailored to national priorities [24].

The process of developing long-range policies is of particular importance in countries that are developing rapidly and have under-developed energy supply systems (e.g., the African continent). As these countries develop, they must carefully navigate the trade-offs between energy security, environmental impact and the cost of investments. In these countries, we can find clear links between energy investments and other sectors such as water. As the population is expected to increase alongside rapid urbanization and economic growth, energy and water demands are also foreseen to grow [14]. Thus, sustainable energy resources and water resource management are needed to free up water for other uses such as agriculture, food, and cities. As climate change is expected to exacerbate water scarcity further and increase the number of water-stressed countries [12], the links between energy and water need to be considered in the energy system´s expansion. For example, climate change alters water availability, which then affects the power sector through supply disruption [26]–[29], an increase in electricity prices [30] and further creates environmental impacts [10], [31]–[33]. Enhancing the resilience of electricity systems to climate change can assist developing countries in ensuring reliable electricity access [34].

A unique example of the interdependency between energy and water is presented in countries that rely primarily upon large hydropower for their energy supply, presenting opportunities (affordability) and challenges. Hydropower constituted 18% of the world´s total installed power generation capacity and 48% of the global renewable power generation capacity in 2020 [35], [36]. Hydropower can provide efficient, reliable and low-cost electricity. Low-cost renewable electricity can assist in socio-economic development [37], [38]. Contrary, a few of the associated drawbacks are causing geopolitical tensions in transboundary systems and being vulnerable to climate change [39]–[41]. Also, a hydropower-dam plant's planning and construction time is too long and capital intensive with low operational costs, but the dam will operate for 50 to 100 years [39], [40]. Thus, properly investing in hydropower requires planning considering these parameters. However, not all countries have hydropower resources to invest in, so the role of other RET has to be investigated in accelerating clean energy.

Depending on the socio-economic conditions and the status of a nation´s power system transformation, different challenges and opportunities may arise. High-income countries can lead technological innovation due to their financial capacity to increase low-carbon investments. Besides, low-income countries are more dependent on external funding and technological developments, decreasing capital costs of power generation technologies [14]. The penetration of renewable energy technologies (RET) and energy efficiency measures in the nation´s energy supply system can significantly limit global climate change [16]. Nevertheless, many countries base their energy production on fossil fuel resources rather than renewable energy technologies. A fossil-fuel-based energy system negatively impacts the environment and energy security, adding complexity to achieve sustainable development. Thus, it is crucial to sustainably exploit the available energy reserves to meet current and future increased demands while minimizing vulnerability to risks such as climate change, energy security, and fuel price fluctuations that would derail economic development.

Moving from examining national case studies to a continental one can provide broader policy insights on energy trade opportunities and how they influence sustainability. Energy trade can assist in decarbonizing the energy sector and achieve national climate change targets by integrating a higher share of renewable energy sources in the power system and supporting socio-economic development [43]. In some cases, renewable electricity cannot be produced locally in the necessary quantities to satisfy the electricity demand, so cooperation with other countries is needed. Energy trade links as enablers or disablers for collaboration can enhance a nation´s energy security, especially for fossil fuel importers, avoid geopolitical conflicts and assist in environmental sustainability by strategically exploiting its country´s energy resources (e.g., renewable, hydropower). They can also transform nations with significant renewable potential into major electricity exporters, increasing their national revenues to be used for socio-economic development [42]. However, there are also challenges associated with implementing interconnectors in energy systems expansion. Depending on the type of interconnector, the associated capital costs increase the total investment costs of energy systems expansion. Although interconnectors aim to reduce the costs of the energy supply system, the challenge is quantifying the expenses for the involved nations-stakeholders, considering the project´s profits and making the involved governments agree for the project implementation [44].

Lastly, RET, including large hydropower and fossil-fuel technologies, are primarily grid-connected technologies presenting opportunities and challenges in the energy transition. However, decentralized systems could play a key role in improving energy access levels. They are more resource-efficient since they are located closer to the end-user demand or connected directly to the distribution network and are not affected by losses in the T&D network [20], [45]. However, investments in transmission and distribution networks are essential, but the penetration of these systems can improve energy security and increase resilience to future economic and environmental shocks [46]. Also, the citizens can become both producers and consumers, assisting in socio-economic development [47]. However, based on the size of the DG, the point of connection to the network limits the power which can be fed into this network level [21].

1.1 Rationale and aim

Energy use and access (SDG7) are important for economic growth and social prosperity [48]. Sustainable, renewable energy is fundamental to a nation´s future transitioning to combat climate change (SDG13). National energy policy plans examine the tensions among energy security, environmental pressures and socio-economic development in isolation and not in an integrated way to manage challenges associated with energy system expansion. The risk in the energy transition is to not lock in high-emitting power generation technologies in the long term and their operation to be less vulnerable to climate change (e.g., cooling water use). Also, investment options on technologies need to account for the associated water footprint of the future energy transition. Thus, this dissertation aims to provide insights on the synergies and trade-offs of the penetration of low-carbon technologies for achieving sustainable development in low and middle-income countries. Quantitative energy system models can support decision-making by analyzing different scenarios and measuring the impact of policy decisions on energy system expansion.

The power sector of Paraguay, Ethiopia, and Africa's energy sector are selected as study areas to understand the transition to hydropower and other RET in achieving sustainability. Limited studies using least-cost optimization tools for energy system expansion are applied so far in the respective study areas, including stakeholder´s engagement, to understand better the factors affecting sustainability (in detail, **Sections 9** and **3.3**). The evolution of the energy systems are examined in isolation

(Paraguay, Ethiopia) and on a continental scale (Africa) to investigate the implications of more diversified energy resource systems and the role of trade links in achieving energy security, electricity access and socio-economic development in an interconnected scheme.

The current studies in the literature show that RET can decrease carbon dioxide emissions, water withdrawals in the power sector and decrease overall system costs [16], [42], [49]–[51]. Nevertheless, the penetration of RET in the power system affects a country´s energy security, and the government is not vulnerable to fuel price fluctuations and import dependency on fossil fuels. However, one limitation associated with RET's efficiency, which affects energy supply, is that they are not always available as fossil-fuel technologies since their operation depends on weather conditions. Thus, there isn't enough power generated from RET for everyone in some cases if storage does not exist and may not be available during peak demand [52]. However, the research on this topic is limited for Africa, especially how RET affect water withdrawals and consumption to satisfy future energy needs and enhance the nation´s energy security. Previous studies on RET penetration in Africa focused either on a national, power pool level, Sub-Saharan or for the whole of the continent [16], [28], [51], [53]–[56]. So far, there is currently no study examining the effect of RET and other technologies in decarbonizing the future power sector for forty-eight African nations under climate change mitigation pathways, achieving universal electricity access and for job-creation potential [28], [57]–[59]. Also, since RET can influence energy security and consequently sustainable development, the role of interconnectors for clean energy and geopolitical tensions are helpful to be investigated to provide insights on the trade-offs in the fuel trade flows among nations. The examined research gaps mentioned above on the penetration of RET and interconnectors for clean, low-cost energy transition lead to exploring the following research questions.

Research question 1*: What role do low-carbon technologies and energy trade-links play in achieving energy security and universal electricity access goals in low-and middle-income countries?*

Previous studies conducted on estimating water requirements in the energy sector focused on either a continental [60]–[63] or regional [26], [53], [64], [65] level indicating the multiple pressure points of the energy-water nexus. Nevertheless, there is a lack of research investigating the associated tensions of reducing carbon dioxide emissions by investing in low-carbon technologies and the associated water footprint of a nation's future energy transition.

Research question 2*: What are the implications of climate change mitigation strategies for energy security and the use of water in energy systems in low-and middle-income countries?*

Decentralized systems and RET play a crucial role in achieving universal electricity access, improving energy security levels and assisting in socio-economic development [20], [45], [47]. Since hydropower and other RET are primarily grid-connected technologies, the role of decentralized systems in achieving energy security, electricity access and job creation had to be further investigated in this thesis. It is important to account for location-specific techno-economic characteristics of power generation technologies to mitigate challenges associated with investment decisions in developing cost-optimal future energy infrastructure. To date, insights into these aspects are limited, leading to the investigation of the following research question.

Research question 3*: How can centralized and decentralized systems assist in achieving energy security, energy access and job creation in low- and middle-income countries?*

The three research questions investigated in this thesis lead to the overall objective of this thesis.

Thesis Research Objective

Examine the trade-offs and conflicting objectives of decision-making investments in low-carbon technology portfolios for achieving sustainable development in low-and middle-income countries.

1.2 Research outline in brief

This thesis addresses the research gaps and the identified research questions via four peer-reviewed journals contributions appended. I developed least-cost energy systems models on a national and continental level to examine the penetration of RET, the impact of energy trade, climate change and policies in achieving SDG7 and SDG13 in the energy transition. I also investigated a broad range of long-term energy transition pathways to analyze the factors affecting sustainability. In **Paper-I**, I used the open-source energy systems modelling tool (OSeMOSYS) to examine Paraguay's least-cost power system expansion. I soft-linked it with an accounting project finance model to address RQ1. Also, in **Paper-II,** the OSeMOSYS tool was used and soft-linked with an open-source spatial electrification planning tool (OnSSET) which uses geographic information system mapping [66] to address the **RQ1** using Ethiopia as the study area.

In **Paper-III**, I used OSeMOSYS to develop a continental scale energy systems model for Africa to address research questions **RQ1** and **RQ2**. Lastly, in **Paper-IV**, the model developed for Africa in Paper-III enhanced with decentralized systems, considering country-specific un-electrified demands settlements locations identified by applying geospatial information systems mapping (GIS) to inform SDG7 and its sub-targets (**RQ1, RQ3**) [67]. The model developed in Paper-IV is soft-linked with an input-output model to inform job creation potential. The methodology is presented in detail in **Section 3**. The overview of the organization of the research –the thesis layout – is presented in **Figure 1**.

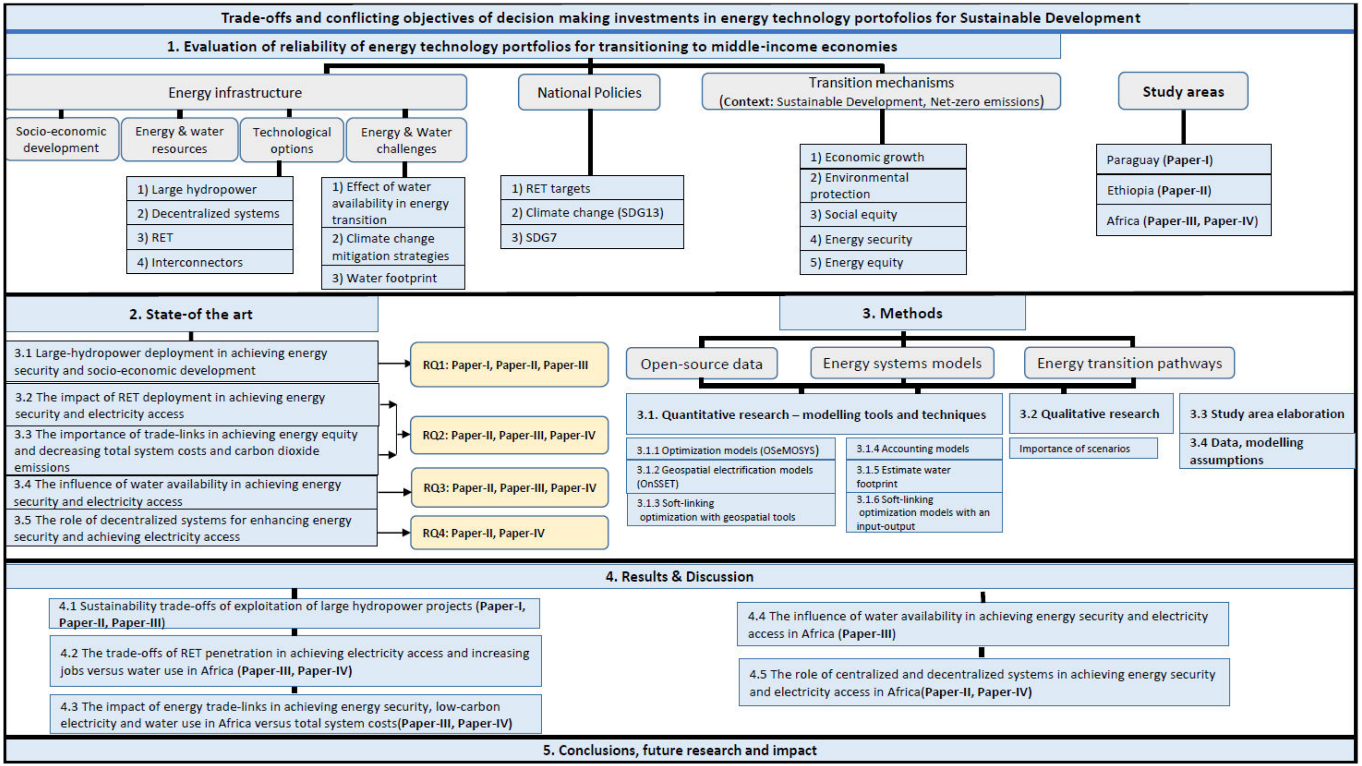

Figure 1. Organization of research – Thesis layout

This thesis consists of two main parts. The first part is organized into six chapters: ***Chapter 1*** introduces the energy challenges and the research objectives, ***Chapter 2*** relates to the state-of-the-art and the identified gaps which led to the research questions, ***Chapter 3*** refers to the methods and the three examined regional study areas and finally in ***Chapter 4-5*** the results and conclusions of the thesis are presented. The second part of the dissertation consists of compiling the research articles (papers).

1.2.1 Appended papers

The four individual peer-reviewed research papers (**Paper I-IV**) presented below form the basis of this thesis. Three papers (Paper-I, II, III) have been published in refereed journals, while the last one (Paper-IV) is pending peer review decisions. Also, additional reports and scientific papers were produced as an outcome of this thesis (**Section 1.2.2**).

This thesis is based on the following scientific papers:

Paper-I

I. Pappis, C. Centurion, E.P. Ramos, M. Howells, S. Ulloa, E. Ortigoza, P.E. Gardel-Sotomayor, T. Alfstad, "Implications to the electricity system of Paraguay of different demand scenarios and export prices to Brazil," *Energy Systems*, Jan. 2021, doi: 10.1007/s12667-020-00420-w.

Author's contribution to the paper:

I. Pappis led the coordination of the paper and undertook the writing and the core analytics that are reported. The main author developed the methodology in collaboration with the co-authors.

Paper-II

I. Pappis, A. Sahlberg, T. Walle, O. Broad, M. Howells, E. Eludoyin, W. Usher, "Influence of Electrification Pathways in the Electricity Sector of Ethiopia—Policy Implications Linking Spatial Electrification Analysis and Medium to Long-Term Energy Planning," Energies, vol. 14, no. 4, Art. no. 4, Jan. 2021, doi: 10.3390/en14041209.

Author's contribution to the paper:

Model structure and conceptualization of the research. I developed the methodology followed in conducting the study and undertook the writing and core analytics.

Paper-III

I. Pappis, V. Sridharan, M. Howells, H. Medarac, I. Kougias, R.G. Sánchez, A. Shivakumar, W. Usher, "The effects of climate change mitigation strategies on the energy system of Africa and its associated water footprint," Environmental Research Letters, vol.17, no. 4, p. 044048, Mar. 2022, doi:10.1088/1748-9326/ac5ede

Author's contribution to the paper:

Development of the energy model and data curation. Writing-original draft preparation, methodology, conceptualization and visualization. The rest of the authors contributed to the methodology, development of the model, visualization and review-editing of the paper.

Paper-IV

I. Pappis, "Strategic low-cost energy investment opportunities and challenges towards achieving universal electricity access (SDG7) in forty-eight African nations". Environ. Res.: Infrastruct. Sustain., 2022, [under review]

Author's contribution to the paper:

I wrote the paper and the reported core analytics and developed the methodology.

In the following table, the research questions addressed in each one of the papers are presented. In some cases, more than one research question has been addressed in the same paper.

Table 1. *The relation between appended papers and the research questions of the thesis.*

No	Research Questions	Papers			
		I	II	III	IV
1	What role do low-carbon technologies and energy trade-links play in achieving energy security and universal electricity access goals in low-and middle-income countries?				
2	What are the implications of climate change mitigation strategies for energy security and the use of water in energy systems?				
3	How can centralized and decentralized systems assist in achieving energy security, energy access and job creation in low-and -middle income countries?				

Note: Dark blue shaded cells show the significant contribution of each paper to address the research questions.

1.2.2 Additional reports and publications

The additional reports and publications in peer-reviewed journals listed below enhanced the technical capacity experience of the author of this thesis to investigate the topic of the thesis better.

1. **Pappis, I.**, Howells, M., Sridharan, V., Usher, W., Shivakumar, A., Gardumi, F. and Ramos, E., Energy projections for African countries, Hidalgo Gonzalez, I., Medarac, H., Gonzalez Sanchez, M. and Kougias, I. editor(s), EUR 29904 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-12391-0 (online), DOI:10.2760/678700 (online), JRC118432.

2. Gardumi, F., Petrarulo, L., Sesay, S., Caulker, D., Howells, M., **Pappis, I.**, Co-creating an energy planning ecosystem: lessons from Sierra Leone, Energy for Sustainable Development, [under review].

3. Ramos, E. P., Howells, M., Sridharan, V., Engström, R., Taliotis, C., Mentis, D., Gardumi, F., De Strasser, L., **Pappis, I.**, Peña Balderrama, J.G., Almulla, Y., Beltramo, A., Ramirez Gomez, C., Sundin, C., Alfstad, T., Lipponen, A., Zepeda, E., Niet, T., Quirós-Tortós, J., Angulo-Paniagua, J., Shivakumar, A., Ulloa, S., Rogner, H., The Climate Land Energy Water systems (CLEWs) Framework: A retrospective of activities and advances to 2019, Environmental Research Letters, 2020, doi: 10.1088/1748-9326/abd34f.

4. Ramos, E. P., Gardumi, F., Niet, T., Sridharan, V., Alfstad, T., **Pappis, I.**, Strasser, L.D., Shivakumar, A., Howells, M., Holger, R., 2021. "Capacity development and knowledge transfer on the climate, land, water and energy nexus" in Brouwer, F. (ed.), in: Handbook on the Water-Energy-Food Nexus. Edward Elgar Pub. [in press]

5. Howells, M., Sridharan, V., **Pappis, I.**, Taliotis, K., Sahlberg, A., A Climate, Land Energy and Water Analysis for Ethiopia, Technical report, United Nations Economic Commission for Africa, 2017.

6. Usher, W. **Pappis, I.**, Sahlberg, A., Kebede, F., Walle, T., & Teferi, S. (2021). Energy system development pathways for Ethiopia: Work Package 3 Final Report (v1.0). Zenodo. https://doi.org/10.5281/zenodo.5046169

7. Lucy Allington, Carla Cannone, **Ioannis Pappis**, Karla Cervantes Barron, Will Usher, Steve Pye, Edward Brown, Mark Howells, Miriam Zachau Walker, Aniq Ahsan, Flora Charbonnier, Claire Halloran, Stephanie Hirmer, Constantinos Taliotis, Caroline Sundin, Vignesh Sridharan, Eunice Ramos, Maarten Brinkerink, Paul Deane, Andrii Gritsevskyi, Gustavo Moura, Arnaud Rouget, David Wogan, Edito Barcelona, Taco Niet, Holger Rogner, Franziska Bock, Jairo Quirós-Tortós, Jam Angulo-Paniagua, Satheesh Krishnamurthy, John Harrison, Long Seng To, "Selected 'Starter kit' energy system modelling data for selected countries in Africa, East Asia, and South America (#CCG, 2021)," *Data in Brief*, vol. 42, p. 108021, Jun. 2022, doi: 10.1016/j.dib.2022.108021.

8. Sahlberg, A., Usher, W., **Pappis, I.**, Broad, O., Kebede, F., Walle, T., Exploring long-term electrification pathways dynamics – A case study of Ethiopia, Energy for Sustainable Development, [submitted]

9. Koutsandreas, D., Trachanas, G., **Pappis, I.,** Nikas, A., Doukas, H., A multicriteria modeling approach for evaluating power generation scenarios under uncertainty: The case of green hydrogen in Greece, Energy Strategy Reviews [under review]

2 State-of-the-art and identified gaps

This section reviews the current literature to identify research gaps. In **Section 2.1,** I explore the benefits and drawbacks related to the challenges of large hydropower penetration in achieving energy security and socio-economic development. **Sections 2.2** and **2.3** investigate the impact of renewable energy penetration and the importance of trade links in securing energy supply, achieving electricity access and decreasing carbon dioxide emissions. In **Section 2.4**, I examine the influence of water availability in power system expansion in achieving energy security and electricity access. Lastly, in **Section 2.5**, I explore the role of decentralized systems in enhancing energy security and achieving electricity access.

Together, these form the basis for the thesis's research questions via the three study areas.

2.1 Large-hydropower deployment in achieving energy security and socio-economic development

In many low-and middle-income countries, large hydropower has the potential to play an important role in supporting socio-economic development, enhancing security of energy supply and managing water.

Ethiopia is a country in which hydropower is the cornerstone of its power system. It is located at the headwaters of three significant transboundary rivers whose waters are shared with numerous riparian states [39]. Similarly, many countries with large-hydropower potential are located in Africa, such as Angola, Egypt, Ghana, the Democratic Republic of Congo, Mozambique, and Nigeria [68].

Large hydropower provides efficient, reliable and relatively low-cost electricity. Previous studies examined the role and challenges of hydropower in expanding a nation's power system in the context of sustainable energy supply. Several examples can be found in Europe [41], Brazil [69], [70], China [71], [72], Norway [73] and India[74]. However, there is a lack of research on the trade-offs of hydropower´s exploitation for increasing electricity exports and enhancing energy security in low-to middle-income countries.

Large hydropower has been studied in some national contexts, including DRC [75], Ethiopia [39], [76], [77], Paraguay ([78], [79]). These studies used a range of methods including spreadsheets [77], [79], regression models [40], [76], national energy system models [75], [78], [80] and qualitative research [81]. The links between large hydropower and socio-economic development is explored in Africa [75] and Brazil [40], between large hydro and energy security in South America [82] and large hydro and energy access in Ethiopia ([83], [84]). Despite the broad range of studies, there are a number of gaps in the literature either related to the methodology followed or the limited scope of the research. For more detail, see the literature review in **Papers-I** and **III**.

Hydropower can significantly increase the risk of the power system´s resilience to climate change affecting generation costs and energy supply, resulting in diverse penetration levels of fossil fuel and other RET technologies depending on the scenario. Previous studies investigated a similar topic for Africa ([26], [57], [85]–[87]), but none of these studies provided such a detailed analysis on an African, power-pool and country-specific level results as in this Thesis.

2.2 The impact of RET deployment in achieving energy security and electricity access

The previous studies focused on the challenges of achieving energy security and socio-economic development by exploiting large hydropower. Nevertheless, not all countries have hydropower resources to invest in, so other RETs ' role in the energy transition needs to be investigated to provide affordable, reliable and secured power systems. Also, the penetration of fossil-fuel and thermal power plants in the future power mix has implications on emissions, water use and energy security. Here, the African continent was examined to analyze the impacts of covering the future energy needs at a continental scale.

A broad range of existing studies was conducted focusing on Africa using quantitative [88], [89] and qualitative energy planning approaches to analyze the impact of RET penetration in achieving energy security, electricity access and decreasing carbon dioxide emissions.

Some of these studies focused on Sub-Saharan Africa achieving affordable electricity access [90] but missing the trade-links between decreasing carbon dioxide emissions and achieving security of energy supply, specifically under climate change. Hafner et al. (2018) (2019) [51], [87] indicated that RET could provide clean, affordable and reliable energy services if properly utilized to promote socio-economic activities and support sustainable development through increasing electricity access levels in Africa.

Solar and wind technologies are expected to be the leading renewable energy sources globally and enabling policy and regulatory frameworks are essential to accelerate renewable growth [88].

Flörke et al. [91] demonstrated the relationship between water use and global socio-economic development, concluding that securing water supply and reducing untreated wastewater discharges should be amongst the priority actions to be undertaken to reach the Millenium Development Goals. Specifically, as population growth and increased prosperity have led to increasing water demands. Lohrmann et al. [92] estimated regional and country-level water demand for global power production, with mitigation strategies for 2015-2050 considering a high temporal and spatial resolution. The study's outcomes assisted in understanding the challenges associated with ensuring global water and energy security and consequently provide more sustainable use of both, providing further insights into the modelling community of the energy-water nexus. Pavicevic et al. [93] modelled the power system of Africa with a higher temporal resolution (8760 time periods in a year) than the study in **Paper-III**, considering the effect of climate change (39 climate years). However, they only modelled the power system of Africa in a less detailed way than investigated in this Thesis [58], and it is a rolling-horizon optimal dispatch model and does not optimize power system capacity expansion.

Contributions of this work

The analysis conducted in **Paper-I** and **Paper-II** is a novel application to examine energy planning strategies for Paraguay and Ethiopia. An open-source power systems model for Paraguay was developed for the first time, using a cost-optimization modelling framework for long-term energy planning (OSeMOSYS), considering three levels of electricity demand projections associated with electricity export prices to Brazil from the use of the Itaipu hydropower plant for the period 2018-2040. The modelling outputs and specifically the electricity exports from Itaipu to Brazil soft-linked with an accounting (Microsoft Excel-based) project finance model to identify the annual revenues from electricity exports for each scenario. A series of workshops was held in Paraguay to develop the power systems model, collect the data, draft the narratives of the scenarios, and do quality control of the results.

Following a similar methodology, an open-source power systems model for Ethiopia was developed for the first time, which shows how hydropower influences variously the evolution of the power mix under three electricity demand scenarios, techno-economic parameters and trades to achieve universal electricity access as described in detail in **Section 3.3.1**.

Furthermore, broader insights are provided for the role of hydropower in an interconnected trading scheme in Africa under climate change scenarios and limited water availability (**Sections 3.3.2, 3.3.3**).

In **Paper-III**, I developed an energy model for the whole of Africa, constituted by the energy supply system of forty-eight African nations (**Annex-*Table 6***) to estimate affordable electricity, future energy supply, water withdrawal and consumption, power capacity requirements, CO_2 emissions and financial requirements to cover each country's future energy needs. It is the first open-source African model that covers each country's energy system with a focus on the power sector, in an interconnected trading scheme, in such a detailed way to estimate the role of RET in energy systems expansion, water withdrawal and consumption, energy supply, CO_2 emissions, financial requirements on a national and continental level on an annual basis (2015-2065). Also, water withdrawals are estimated for fuelwood consumption in the households sectors in each African country. Moreover, a list of the cooling types for the existing power plants and the upcoming ones were possible, in Africa compiled, missing from the current literature, to investigate the associate water footprint of the future energy transition in Africa. Moreover, climate change mitigation pathways were examined for the first time for each African country, modelling Africa as a region as well as examining scenarios addressing the effect of water availability on the operation of hydropower and thermal power plants.

2.3 The importance of trade-links in achieving energy security and decreasing total system costs and carbon dioxide emissions

The benefits and environmental implications of trade links to the associated nations remain in their infancy, imposing a significant gap in the literature [49], [94], [95]. In this thesis, I examined the African continent to capture the disparities in energy and water resources between nations and resulting energy trade flows which are essential for understanding a coordinated whole-Africa response to climate change.

On a continental scale, by applying the cost-optimization tool OSeMOSYS [96], Taliotis et al. [58] modelled the electricity system of each African country (45 in total) and linked them via electricity trade links to examine scenarios of power plant investments by exploiting trade potential in the continent from 2010 until 2040. They show that an enhanced trading scheme could reduce electricity generation costs but only the electricity sector is modelled on a national scale and not the rest of the sectors needed to satisfy the nation´s entire energy demand. Furthermore, only the electricity trade links included in the model and not other trades (e.g., gas) and the number of power-generating technologies are less than our study, decreasing the model's granularity. Shivakumar (2018) [97] examined a similar topic for Europe but focused primarily on policies and technology deployment such as energy storage and smart grids, which can enable an increased penetration of variable RES, providing flexibility to the system. The findings show that the cross-border interconnectors are expected to enable large-scale integration of variable renewable energy sources, preventing load loss and ensuring cost-effective power generation. Moura et al. (2015) [82] developed a continental model for South America, examining scenarios focusing on the future penetration of RET technologies and how they can affect the bargaining power trade of each country. The higher penetration of these technologies can assist in the system´s total annual costs saving through fuel savings and convert countries to importers and exporters. Brinkerink et al. (2019) [94] conducted a literature review of the benefits and challenges of global power grids and intercontinental interconnectors to cover future electricity needs worldwide. The authors concluded that intercontinental trade links and a global grid could support decision-making in decarbonizing the power systems. They found that while the challenges and opportunities are clearly qualified, the actual quantification of costs, benefits and environmental implications of the global grid concept remains in its infancy, imposing a significant gap in the literature. Interconnectors can assist in exploiting the significant RET potential in each country. However, the population density is a factor affecting the traded electricity since it increases the electricity demand [94].

Contributions of this work

The studies mentioned above focused either on a global level, other continents, or Africa. However, the quantitative least-cost analysis I conducted for Africa in such a detailed way in **Paper-III** is missing from the current literature. I analyzed the influence of trade links in covering the future energy needs in the continent and the associated implications (e.g., financial and environmental requirements, future power generation investments) for decarbonizing the power system and unlocking its country´s energy resources. The outcomes of the analysis and the developed model can assist in covering the gaps in the literature and be used to form a global power grid model. The trade links connecting Africa with the rest of the continents have already been included in the model and fuel exports with non-African countries, which can be used as inputs for a global power model to formulate coherent energy policies.

2.4 The influence of water availability in achieving energy security and electricity access

Large hydropower dams can increase irrigation and electricity production resulting in regional development opportunities for social inclusion, socio-economic development and poverty reduction, which lead developing countries to invest in these power generation technologies [99].

Current studies show that the technology can assist in meeting climate change challenges since hydropower can be used as an alternative to fossil fuels and high-quality water resources infrastructure can support countries in adapting to changes in hydrology [39]. However, energy planners need to consider integrated water and energy management in expanding the energy system. In that way, the nations can prevent not locking in long-term, capital-intensive future investments, which may affect their energy security and cause geopolitical tensions in transboundary systems [39].

Previous studies on estimating water requirements in the energy sector have focused on either a continental [60]–[63] or regional [26], [53], [64], [65] level.

However, the associated risks of climate change (SDG 13) and proper water resource management (SDG 6) need to be considered to ensure a nation's sustainable development and energy transition. Climate change mitigation measures are essential to decarbonizing the energy sector. Several studies have examined the effects of climate change upon the power sector, such as supply disruption [26]–[29], increase in electricity prices [30] and environmental impacts [10], [31]–[33].

Contributions of this work

In **Paper-III**, three main scenarios were examined for Africa´s energy model, the Reference and two mitigation scenarios (2.0°C, 1.5°C) [100], [101]. However, insights concerning the effects of climate change mitigation scenarios in the energy transition of each African nation on such a detailed level are missing from the current literature. Moreover, for each of the three scenarios, the influence of water availability in each country was examined, first by analyzing a dry and wet scenario associated with the operation of the hydropower plants and secondly by limiting the water withdrawal for the cooling of thermal power plants, resulting in a total of eighteen (18) scenarios.

The continental and national scale insights could inform the National Determined Contributions targets (to be reviewed in 2020) [102] by demonstrating the broader African context of national greenhouse gas emission targets and global-national policies [103] by addressing the challenges indicated in the United Nations Sustainable Development Goals (SDGs) in particular SDG6, SDG7, SDG13 [104]. National and governmental institutions and universities involved in capacity-building activities could benefit from this open-source study since the provided datasets could strengthen the capacity for developing others and extending existing energy systems models.

2.5 The role of decentralized systems for enhancing energy security and achieving electricity access

Achieving universal access (Sustainable Development Goal 7) to affordable, reliable and modern energy for all and modern energy services is critical for social development, livelihood improvement and economic growth [105], [106]. Increasing the penetration of renewable energy technologies in the power sector is also another target of SDG7. Considering the geospatial characteristics of energy technologies for energy planning is an important component for an integrated energy systems analysis [19].

Previous studies developed geospatial-based electrification analysis to improve the underlying electricity costs and consider technology-based location characteristics to answer key policy questions about electrification pathways in developing countries [19], [20], [50], [107], [108]. However, they primarily focused on using spatial systems, neglecting the relationship between energy and spatial systems and the trade-offs of achieving environmental sustainability.

In decentralized systems, energy conversion units are located closer to energy consumers. They can be more resilient, reliable, and environmentally friendly by reducing CO2 emissions and primary energy carriers' consumption and rapidly increasing access to basic electricity services as an alternative to the traditional energy systems [109]–[112]. Tomei and Gent (2015) [113] analyzed how to achieve energy equity to deliver sustainable energy access in low-income communities, indicating the need to consider local people´s needs and livelihood aspirations in the energy transition. They highlighted the complexity of analyzing energy poverty separately from energy security and climate change [113]. Mainali (2014) examined the sustainability of rural energy access in developing countries (Asia, Sub-Saharan Africa), focusing on analyzing policies and understanding their impact on the formulation of a renewable-based rural electrification market. They showed that rural electrification expanded due to market-oriented policies [114]. Alanne et al. (2006) [109] evaluated the political, economic, social and technological dimensions associated with regional energy systems based on the degree of decentralization. They concluded that distributed energy systems are a good option for sustainable development in the long term. Moreover, their operation in parallel to centralized systems can better balance the power mix. Nevertheless, the authors did not conduct their studies quantitatively using energy system models to provide these insights.

The following studies examined the role of the penetration of decentralized systems in the power mix quantitatively. Bazilian et al. [115] examined various energy access scenarios in Sub-Saharan Africa by 2030 using the OSeMOSYS framework to model the electricity sector. A detailed analysis of the energy demand projections is presented in their study, missing from Taliotis et al. [58]. However, other fuel demands are not included in the study of Bazilian et al. [115] to better capture the evolution of the energy system in Africa and the geospatial allocation of power generation technologies is missing. In another study, a cost-optimization modelling framework MESSAGE-SPLAT was used to model the power system of only two regions (Eastern and Southern Africa) and examine scenarios associated with their energy transition [55].

Previous techno-economic studies on electrification planning have only considered the spatial dimension of achieving universal access in Ethiopia, considering only the residential electricity demand and not other sector's demands [116], or focused either on a specific region in the country [117]–[119] or for the whole Africa[120]–[124]. Still other previous studies focusing specifically on Ethiopia have only used a simulation energy modelling tool (Long-range Energy Alternative Planning (LEAP)) [123], which is less suitable for financial planning. Furthermore, in another study, they applied an energy systems cost optimization model (TIAM-ECN) [124] coupled with geospatial analysis and examined the residential electricity demand in isolation [127]. The advantages of conceptualizing an integrated energy systems analysis linking an optimization model with a geospatial analysis are presented in **Section 3.1.3**. Lastly, few studies have been conducted to track the progress towards achieving SDGs in African countries [128], [129]. Another aspect to examine relevant to the energy transition on a global, regional or national level is the associated job creation potential of achieving universal access, which is missing from the literature [17], [18], [130]–[132].

Contributions of this work

Previous geospatial electrification studies or qualitative studies focused on analyzing the role of decentralized systems in power system expansion. Nevertheless, no previous work provided national electrification and energy system pathways for Ethiopia and Africa that are geographically explicit enough to inform SDG7 and the African Union Agenda goals for 2063 [133]. Instead, the studies examined the evolution of socio-economic factors in fuel demand projections under different demand scenarios, providing quantitative results on the three pillars of sustainable development.

In **Paper-II** and **Paper-IV**, I present the benefits of the penetration of decentralized technologies in the future power mix in Africa to achieve universal access, which this type of research lacks from the literature.

The novelty of **Paper-II** analysis stands in the level of complexity and the longer time frame and applying a mix of qualitative and quantitative research methods. In addition to using an open-source cost-optimization tool (OSeMOSYS) to model Ethiopia's electricity system, I also considered the spatial distribution of the future connections in the residential area to estimate the cost-optimal electrification mix by soft-linked the model with a geospatial analysis tool OnSSET [66]. The authors conducted a series of workshops in Addis Ababa in Ethiopia, including policy analysts, researchers and academics, to formulate long-term energy system scenarios. The scenarios focused on the targets associated with the national policy ambition, such as achieving universal access, transforming into an electricity hub exporter and increasing penetration of renewables in Ethiopia. Also, the model developed under this thesis was transferred to local partners for future uses in academia and national policy analysts through continuing capacity-building activities in Addis Ababa. In that way, human capacity and institutional development toward a sustainable energy future in Ethiopia were enhanced, which is highlighted in the literature [134], [135].

The study I conducted in **Paper-IV** built on previous work in **Paper-III**, modelling the electricity supply system of forty-eight African countries and linking it via electricity and trade links, including also all fuel demands and fuel exports, to examine scenarios relevant to achieving universal access. I used the OSeMOSYS tool to model Africa's least-cost energy system expansion [96]. I also used the open-access Global Electrification Platform (GEP) [136] to capture the spatial distribution of future electricity connections in the residential areas and define the centralized and decentralized mix and soft-linked it with OSeMOSYS to provide an integrated electrification analysis. In that way, grid, off-grid and mini-grid energy systems' role in meeting SDG7 can be examined and provide insights into energy transition and its associated challenges. The results are provided on an annual basis from 2015 to 2030. I also developed an accounting model to create a framework index with indicators to inform each African country's SDG7 and its sub-targets and an input-output model adapted to measure the socio-economic transition focusing on job creation. Lastly, I investigated four scenarios consisting of two electricity consumption levels per capita for the un-electrified settlements in the residential areas to analyze the economics and demographic factors as demand drivers to boost electrification, combined with two different capital costs of renewables (New Policies, Renewable Deployment) to form the overall scenarios.

3 Methods

In this chapter, the methods applied to the respective study areas to address the identified research gaps are presented. A literature review of varying energy system models and approaches (top-down, bottom-up) was conducted to identify the appropriate modelling techniques needed for each study area. A quantitative (using computational and mathematical models) and qualitative [137] analysis was conducted in each study area because the insights can assist national decision-makers in evaluating the challenges associated with the future energy transition [138]. Local stakeholders' engagement in developing the energy systems models and the narratives of the scenarios (e.g., capacity building efforts) can assist effectively in outlining policies [139]. A more detailed representation of the methods section (model structure, techno-economic assumptions, scenarios) off each research paper is presented in the appended papers. In the following sections, the description of the modelling tools used in the three case studies justifies why they are appropriate in quantifying the tensions among the pillars for sustainable development and provides modelling results and insights to formulate energy policies.

3.1 Quantitative research – Modelling tools and techniques

Quantitative energy planning can offer insights into how to decarbonize the energy sector (energy supply mix, least-cost portfolio of technologies, greenhouse gas emissions, etc.) [140], examine energy-water nexus linkages, climate change [141] and sustainable development [142]. The modelling tools can inform how universal access in each country can be better achieved by addressing uncertainties around the evolution of fossil fuel prices, renewable energy technology (RET) costs and demand projections, assisting governments, policymakers and funders in identifying proper financing mechanisms and strategic investments [124]. They can also measure the socio-economics (e.g., job creation) of diverse energy transition pathways [17], [130]. Lastly, considering the spatial dimension of energy access (location and size of un-electrified population, geophysical parameters and technology costs) can improve the medium-to-long-term assessments of least-cost power system expansion [50], [84], [143].

There are various modelling tools for sustainable development. They expand from economy-wide models, socio-economic microsimulations, energy systems models, geospatial electrification access models, Climate, Land-use, Energy and Water Systems model, input-output models [144], a model for the analysis of energy demand and the financial analysis of electric sector expansion plans [22]. Depending on each research question´s objectives, the most appropriate modelling tools and approaches (bottom-up, top-down) are applied, either in isolation or soft-linked, to overcome the associated limitations. Economy-wide models, developed based on economic theories that investigate the effects of policies with direct or indirect consequences within an economy, are not used in this thesis. The focus is primarily on identifying a cost-optimal portfolio of power generation technologies for sustainable development and not examining the effects of changes, such as fuel tax, in developing an economy. Only different discount rates in the energy transition of a nation were investigated to represent the cost of borrowing capita and address their implications in the deployment of future technology options. The authors in this thesis did not explore socioeconomic microsimulations. However, they examined changes in socio-economic development (e.g., GDP, population, urbanization) accounted for the fuel demand projections depending on the scenarios. Models for energy demand analysis could be used to investigate in more detail the evolution of fuels in the diverse end-use sectors of the economy, considering long-term socioeconomic, technological and demographic development. However, open data were not available. Implementing a financial analysis of the power sector expansion plan could further enhance the evaluation of the reliability of low-carbon technology portfolios and the associated investment decision-making; nevertheless, this was out of the scope of the respective case studies. Lastly, a CLEWs model could provide more policy insights into environmental sustainability and energy security. The model considers changes in agriculture productivity constrained by land requirements (irrigated, rainfed), water and crop production, which could be used for biofuel production in the transport sector, affecting food security.

In this thesis, open-source models and open data are used to enhance transparency and enable the reproducibility of the studies. Releasing the data under an open license improves the quality of the datasets by allowing public verification and updating the modelling assumptions. This open approach aims to overcome criticism and enhance sharing ideas and information through broader community engagement and adoption [145], [146]. Open-source data on technology characteristics, energy resources, energy targets and the evolution of the socio-economic conditions of a nation are some of the main aspects of the development of an energy system.

3.1.1 Optimization models

The characteristics of the various modelling tools for energy planning are examined in this thesis, [22], [56], [144], [145], [147], [148] before applying the long-term open-source cost-optimization tool (OSeMOSYS) for the quantitative research in this study in all examined case studies. Also, there are two wide-spread modelling approaches categorized in top-down and bottom-up, while in the current literature, studies are conducted that integrate those two modelling approaches [149]–[156]. The top-down models are more appropriate for analyzing the broader economy and the macro-economic relationship of the components of a system with the energy sector (changes in prices, incomes). On the other hand, the bottom-up models are primarily used to analyze the techno-economic performance characteristics of the energy system (e.g., energy supply processes, conversion technologies and end-use demand patterns). However, the optimization models do not account for price distortion or economy-wide interactions and income effects [157][158]. They assume a perfect competition between the market participants and provide a marginal production cost. They also account for perfect foresight, which means that the market participants are fully aware of all present and future conditions affecting the cost they provide or their purchase of energy. Lastly, the model decisions minimize or maximize overall system costs, which does not always reflect reality since decisions are also based on consumers' behaviour. The model computes the least-cost expansion of the energy system subject to carbon emission and operational constraints. Thus the model quantifies the trade-offs between cost-optimal future power plant investments, energy supply mix, generation costs which affect socio-economic development, carbon dioxide emissions, water use and socio-economic implications (as part of fuel demands).

3.1.1.1 OSeMOSYS

In this thesis, to address the examined research questions, the OSeMOSYS tool is used in all study areas (Paraguay, Ethiopia, Africa). It is an open-source optimization modelling framework for medium to long-term energy planning [96]. OSeMOSYS is a bottom-up model [153]. One of its advantages is that it can account for the domestic availability of energy resources and the techno-economic characteristics of centralized and decentralized technologies. Also, the model accounts for the energy system's infrastructure, starting from the supply technologies and extending to the transmission and distribution networks and energy trade links until the various end-user final demands. Also, the energy modelling tools can capture energy and economic targets and environmental constraints on a national and continental scale. OSeMOSYS uses linear optimization techniques to satisfy an exogenously defined energy demand. The objective function consists of the sum of discounted operational and capital costs. The modelling results contain, fuel supply requirements, power generation capacity, generation by technology, operation and maintenance costs, investment costs, annual emissions and electricity prices. Also, the tool allows one to examine various energy transition pathway scenarios and provide insights relevant to least-cost technological pathways, electrification pathways, climate change mitigation strategies and many more. However, the scenarios do not predict the future but rather provide insights that could be used to formulate energy policies [159]. Since OSeMOSYS is open-source, it assists in overcoming the lack of transparency needed to address future long-term energy system trajectories [146].

The OSeMOSYS tool is in a class with long-established energy system models such as MARKAL/TIMES [138], MESSAGE [139], PRIMES [140], EFOM [141] and POLES [142].

OSeMOSYS has been widely employed in the scientific literature to provide insights into possible transformation pathways of large energy systems (regional, national and continental scale) and their impacts on the economy, society and the environment[42], [58], [80], [160]–[162]. It has also been used in academic teaching and capacity building for energy planners [36].

Model structure – Reference Energy System

It is recommended that one draw on the Reference Energy System (RES), a schematic representation of an energy system, to develop a model in OSeMOSYS. The Reference energy system includes the “primary level” corresponding to the fuel supply technologies, the “secondary level” consisting of the energy conversion technologies and the transmission and distribution networks, and lastly, the “tertiary level” of final end-user sectors demands. The technologies are represented with boxes in the RES, while the fuels are indicated with lines. In addition, the analyst can include fuel-specific greenhouse gas emissions in the RES in the import and extraction technologies.

An example of the schematic representation of Paraguay's energy system (RES), which models only the power sector, is presented in the figure below.

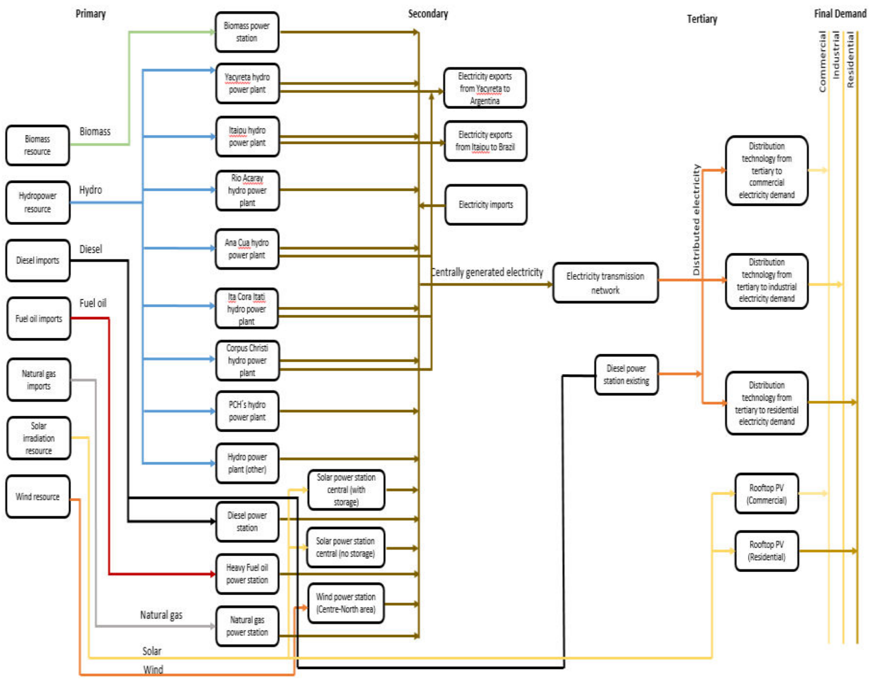

Figure 2. *The Reference Energy System (RES) of the examined study area of Paraguay [163].*

3.1.2 Geospatial electrification models

The authors applied a generation and transmission expansion planning tool in Paper-II and Paper-IV to manage optimal planning for generation and transmission systems using geographical information systems (GIS). This type of analysis can account for the geospatial allocation and characteristics of power generation technologies (off-grid, stand-alone and mini-grid systems) to achieve universal electricity access [164], [165].

The open-source spatial electrification tool (OnSSET) accounts for population settlements. It identifies the least-cost technology mix to satisfy the electricity demand of the current un-electrified settlements in residential areas [66], [124]. It considers as an input parameter the grid generating cost of electricity and the techno-economic assumptions of the respective power generation technologies and estimates which technology the country needs to invest in based on the Levelized Cost of Electricity (LCOE) for each technology option. The formula to calculate the LCOE for each technology option is presented below (1). Six technology options are considered in the geospatial tool: the national grid, PV mini-grids, diesel mini-grid, wind mini-grids, hydro mini-grids, stand-alone PV technologies and hybrid systems of these. The open-access Global Electrification Platform (GEP) is an improved version of the OnSSET model and it explores least-cost electrification strategies for 58 countries [67].

In this thesis, using these types of models, the role of the grid, off-grid and mini-grid energy systems to meet SDG7, are examined. These provide insights into the energy transition of Ethiopia and Africa and analyze its associated challenges. Integrating the spatial dimension of energy access (location and size of un-electrified population, geophysical parameters and technology costs) can improve the medium-to-long-term assessments of least-cost power system expansion [50], [84], [143].

The formula used to calculate the Levelized cost of generating electricity for each technology is the following:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

In year t, I_t is the investment cost, $O\&M_t$ are the operation and maintenance costs, F_t are the fuel expenditures, and E_t is the generated electricity. Further, r is the discount rate and n corresponds to the technology's lifetime. The average LCOE of all grid-connected power generation technologies is calculated to estimate the input grid cost to OnSSET.

The OnSSET tool has been widely used in national electrification studies for Ethiopia [84], Malawi [166], Kenya [167], Tanzania [168] and Afghanistan [169]. Also, the tool is applied in regional electrification studies for the whole of Sub-Saharan Africa ([124], [170]).

3.1.3 Soft-linking optimization with geospatial electrification models

The OSeMOSYS (optimization model) model [96] and OnSSET or GEP (geospatial analysis models) models can be soft-linked and form an integrated energy systems analysis for a nation that wants to achieve universal access. The challenges and advantages of linking energy systems analysis and spatial systems have been widely addressed in the literature [50], [143], [171], [172]. Since the OnSSET model does not optimize the technology mix that supplies the centralized grid and does not consider sectors other than the residential sector, the OSeMOSYs tool is needed to provide an integrated analysis. An integrated analysis can examine the cost-optimal power generation mix for satisfying future residential electricity demand in both electrified and currently un-electrified areas.

The spatial methods can improve the underlying electricity costs and demand assumptions (e.g., location and size of un-electrified populations) and consider location-specific technology characteristics to support key policy questions [116], [117]. The methodology has already been applied to study electrification pathways for Kenya [173] and Ethiopia (Paper-II) [84].

To soft-link the two tools, the electricity supply system of a country needs to be modelled first, considering all the available power generation technologies (on-grid, off-grid) and the residential electricity demands using the OSeMOSYS tool. Then, in order to consider the geographical characteristics of the energy resources and the spatial dimension of the residential electricity demand, a tool such OnSSET should be used. It is used to identify the least-cost split between on- and off-grid technologies. The methodology below soft-links the two tools (steps 1 to 4). In the first step, the energy supply system of a country is modelled considering the demands in all sectors to provide the least-cost power generation supply options. In the second step, the levelized cost of generating grid electricity is calculated as an outcome of the energy supply system. In the third step, the levelized cost of generating grid electricity is used as an input parameter to the OnSSET model to calculate the least-cost electrification mix (on-grid and off-grid) to satisfy the residential electricity demand. In the fourth step, the outputs of the OnSSET analysis, specifically how much each one of the off-grid technologies (demand split) supplies the electricity to satisfy the residential demand of the currently un-electrified population, the capacity factors of off-grid technologies and the transmission and distribution costs are calculated and used as inputs to update the initial OSeMOSYS model (step 1). This process will impact the cost-optimization process of the OSeMOSYS model and, eventually, the grid cost. It is recommended the process be followed more than two times until the levelized cost of generating grid electricity no longer defers among the iterations and the results are calibrated. The formula to calculate the LCOE is presented in the previous section.

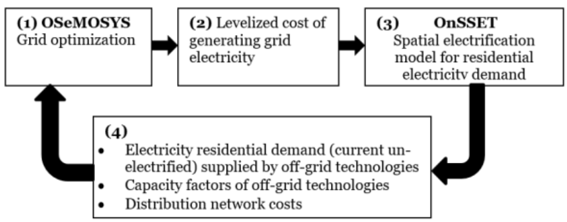

Figure 3. *Overview of the modelling approach: soft-linking the OSeMOSYS model with the OnSSET model.*

3.1.4 Accounting modules

In this section, the methodology of soft-linking an optimization model with project finance techniques to estimate national revenues from electricity exports is analyzed.

The outputs-modelling results of an OSeMOSYS national power system model can be soft-linked with an accounting model (Microsoft Excel-based) based on project finance techniques to estimate the annual revenues for the government from exporting electricity to another country. Project financing relates to where debt and equity are paid back only from the project´s cash flow.

First, a country's electricity supply system model needs to be developed using a cost optimization tool (e.g., OSeMOSYS) and examining energy transition pathways. The national electricity supply model can either be part of a regional-continental model that has trade links with other countries and considers the exporting countries' electricity demands, or the electricity demands of the exporting countries can be accounted for exogenously. Suppose the electricity export demands are not considered in the model. In that case, the cost-optimization process is based on the electricity export price assumed during the modelling period and not on supplying the final electricity export demands. The cost-optimization tool provides results for which least-cost power generation mix satisfies the final electricity demands, which year the model should invest in and what type of technology and how much electricity each power plant generates. In addition, based on the evolution of the domestic electricity demand and electricity exports and depending on any other constraints, the model decides how much electricity can be exported to other countries.

The following parameters can be used as outputs of the power system model: annual electricity exports, annual electricity export price, capital expenditure and operational and maintenance costs in combination with other project-specific finance parameters (e.g., loans, royalties) to estimate the total profits for a country generated from electricity exports to other countries based on the electricity supplied by a specific power plant project (e.g., hydropower).

In this way, the government or the investors can decide if it is profitable to finance the operation of a new power plant and at which electricity export price the country would benefit from the associated electricity exports.

Scenarios can be examined based on the electricity export price between the two countries, as a sum of the cost of generating electricity from a specific power plant (e.g., hydropower) and the cession rate, as well as the evolution of the electricity demand to address the uncertainty of the energy transition and estimate the total profits for the exporting country.

3.1.5 Estimate water withdrawal and consumption for the energy sector and the influence of water availability in the operation of the power system

To estimate the water withdrawal and consumption per type of technology associated with the energy transition pathway of a nation and consequently its water footprint, the energy supply system of the nation needs to be modelled first using a cost-optimization modelling framework for long-term energy planning such as OSeMOSYS. However, the objective function of the energy modelling tool is to minimize the total energy system costs rather than co-optimize the water availability. Still, insights can be provided on the trade-offs of identifying low-cost electricity generation options and the associated water withdrawal and consumption needs. After modelling the energy supply system of the nation to estimate the water withdrawal and consumption per type of technology, the cooling types of the existing and future power plants in the country need to be identified. Then, the water factors based on the associated cooling types for the operation of the thermal power plants such as dry cooling (AIR), natural and mechanical draft tower (MDT/NDT), once-through cooling tower with freshwater (OTF) and once through cooling tower with salt water (OTS) need to be assigned to each technology. Specific water factors must be assigned based on the respective cooling types per type of technology (power generation, fuel extraction, fuel processing). The water factors that account for the types of technologies associated with a country's energy supply system are presented in the appended Paper III.

The influence of water availability in the optimization process can be examined by implementing the water factors for the respective technologies to estimate a nation's water withdrawal. The analyst can construct a set of scenarios where the water withdrawal for thermal power plant cooling can be restricted based on the amount of water withdrawal from the reference scenario. In that way, policy insights can be drawn on future power plant investments and energy security levels based on water availability. Furthermore, dry and wet scenarios can be examined for the operation of hydropower plants by changing the capacity factors based on the climate change data available for dry and wet scenarios and analyzing their influence on the energy transition of a country. In that way, the analysts can examine the economic viability of investing in a future hydropower plant by analyzing the effect of water availability on its operation.

3.1.6 Soft-linking optimization models with an input-output model to estimate job creation

An analytical approach for the energy supply system of a nation or a continent to estimate direct energy jobs creation corresponding to the value chain of its energy transition is adopted by Rutovitz et al. (2015) [18], [132]. The method was applied and adjusted to estimate job creation for the African continent (Paper IV) using the associated techno-economic assumptions of the modelling inputs of Paper IV study. The Employment Factor (EF) method was applied amongst the other methods [174] primarily due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage, flexibility options and the transmission and distribution of electricity. The EF approach is preferable to other methods since it can be modified for specific contexts and applied over a range of energy scenarios [175]. The total direct jobs are estimated considering a sum of jobs in manufacturing, construction and installation, operations and maintenance, fuel supply associated with electricity, decommissioning energy plants at the end of their lifetimes and the transmission and distribution of electricity [132]. The methodology is further explained in detail in Paper IV.

3.2 Qualitative research

A literature review was conducted to identify the research gaps to address the research questions mentioned in **Section 1.2.1**. The author reviewed various energy system models and approaches (top-down, bottom-up) to determine the appropriate tool for each study area. After placing the case studies for each paper, the author gathered data related to the energy system of Paraguay, Ethiopia and Africa. Those data were used to develop the respective energy models and understand each study area's three pillars´ aspects and status. To develop the scope of the analysis and the narratives of the scenarios, as well as conduct a quality control of the results, capacity-building activities were held in the study on Paraguay and Ethiopia, including stakeholders' engagement.

The importance of scenarios

Models do not predict the future, but they provide insights into the alternative outcomes of energy transition pathways [176]. Thus, since the models require several techno-economic inputs and in the face of rapid change, there is high uncertainty associated with their evolution throughout time and their implications regarding the development of the energy system. The analyst must address the uncertainty associated with the energy systems analysis. It is useful to examine a range of diverse scenarios addressing changes in the cost of energy conversion technologies, fuel prices, fuel demand growth, future investments in power plants and trade links, environmental constraints and other factors. The evolution of fuel demand can be associated with the future transition of several socio-economic factors such as the evolution of GDP, population, urbanization and others. Thus, the change of the economy can also be captured in the development of an energy model.

The scenarios examined in **Paper-I** and **II** were developed with local stakeholders' engagement through several capacity-building activities in the corresponding countries. The workshops held in the respective countries engaged people from various organizations and backgrounds (e.g., academics, policy analysts, researchers, government analysts). They assisted in drafting the narratives of the scenarios and validating the modelling assumptions and results.

The narratives of the scenarios and the respective changes in the input parameters can assist in providing a better understanding of the tensions between the challenges associated with the three pillars for sustainable development and inform investment decisions. Thus, the following scenarios were examined in each paper to address the examined research questions in this thesis:

- A combination of electricity demand scenarios and electricity export prices to Brazil assisted in better understanding the tensions between energy security and socio-economic development (**Paper-I**).
- Electricity demand scenarios associated with changes in several drivers (e.g., GDP growth, population growth, household size, urbanization, electricity consumption per capita) and techno-economic factors (e.g., discount rate, future power plant investments, renewable costs and electricity interconnectors) provided a better understanding of what technical factors influence achieving electricity access in a country and RET penetration, what role off-grid technologies play in that success (**Paper-II, IV**).
- Two climate change mitigation scenarios modelled in **Paper-III** by applying environmental constraints on a continental level assisted in understanding the trade-offs between a nation's energy transition and its associated water footprint. Specifically, these were the costs and benefits of the technological enablers of a clean energy transition (e.g., thermal power plants versus renewables), the role of trade links in achieving energy security, the carbon footprint of the energy transition, and several others.

3.3 Elaboration of the study areas

The quantitative and qualitative research methods described in the previous section are applied to the examined research questions. The modelling results from the selected study areas, Paraguay, Ethiopia and Africa, assist in better understanding the tensions among the pillars for sustainable development. Specifically, they provide insights into the trade-offs of investing in large hydropower projects to enhance energy security, electricity access and socio-economic development in a country; the role of renewables in achieving electricity access and environmental sustainability; and how the trade links can decrease overall system costs and transform some countries into energy hub exporters affecting their use of water. Furthermore, the energy transition of a nation is associated with water withdrawals and consumption in the use of thermal power plants, which cause further tensions between environmental sustainability and the rest of the pillars for sustainable development.

Selected results as an outcome of the methods used for each study area are presented in ***Section 4***.

3.3.1 A project-specific large hydropower elaboration to examine the trade-offs between the demand risk and electricity export revenues – Paraguay study area

In **Paper I**, Paraguay's OSeMOSYS power system model was soft-linked with an accounting model (Microsoft Excel-based) using project finance techniques. The objective was to consider the electricity exports from a project-specific hydropower plant (Itaipu) as an output of the OSeMOSYS model and use these modelling results as inputs for the accounting model to estimate the national revenues from that specific project. The negotiation of the Itaipu Treaty in 2023, a bilateral power purchase agreement between Paraguay and Brazil, will have a socio-economic impact on Paraguay since the electricity imports from Itaipu constitute approximately one-fifth of Brazil's final electricity consumption [5], [177]. The domestic revenues for Paraguay from the electricity exports to Brazil can be affected by the electricity export price and the evolution of the electricity demand. Thus, the authors investigated four electricity export price scenarios combined with three electricity demand levels for the power system of Paraguay. The authors conducted this type of analysis to inform robust policy investment decisions and address the associated uncertainty (security of supply) concerning how the country could use the excess electricity from that specific project (***Table 2***). Hydropower plants are environmentally friendly since they are water-driven. They supply low-cost electricity, assist in job creation, and increase the liability of the power systems since they can shift their electricity generation accordingly to satisfy the final electricity demand. However, they are capital intensive, require significant infrastructure and their operation lasts for almost forty years. Thus the investors of the project need to be well-informed about the trade-offs of economic stability and environmental sustainability of the project.

This method can be used in the energy planning of other countries (e.g., Ethiopia) to address the techno-economic viability of a future power plant investment considering national revenues from electricity exports and an electricity export price.

Table 2. *Overview of the scenarios examined for Paraguay (Paper-I).*

Combination of scenarios
Electricity demand
1. Reference combined with ISC. 1-4 cases
2.Medium combined with ISC. 1-4 cases
3.High combined with ISC. 1-4 cases
Itaipu electricity export prices cases (compared with 2022 values)
ISC.1: Itaipu rate constant, Cession rate constant (constant electricity export price)
ISC.2: Itaipu rate 60% decrease, Cession rate constant (lower electricity export price)
ISC.3: Itaipu rate 60% decrease, Cession rate increase (higher electricity export price)
ISC.4: Itaipu rate 30% decrease, Cession rate increase (higher electricity export price, lower than ISC.3)

3.3.2 Exploring the role of RET and trade-links in Africa to decarbonize the energy sector and achieve energy security, electricity access and create jobs

In previous studies, the power system of the countries was examined in isolation. As a result, the effect of other interconnected nations' energy policy plans could not be examined. Thus, in **Paper-III**, the energy supply systems of forty-eight (48) African countries, with a focus on the power system, were modelled individually and linked via trade links using the OSeMOSYS tool (period 2015-2065) to analyze energy supply, power capacity requirements, carbon dioxide emissions, water withdrawal and consumption and financial requirements to supply each country´s future energy needs. In **Paper-IV**, the electricity supply system of all African countries (48 in total) modelled using the OSeMOSYS and GEP tools and linked via electricity and trade links, including all fuel demands and fuel exports, to examine scenarios relevant to achieving universal access in 2030. The results are provided on an annual basis from 2015 to 2030. In that way, grid, off-grid and mini-grid energy systems' roles to meet SDG7 are examined and provide insights into the energy transition in Africa (each African nation) and its associated challenges. The author, by using an accounting (Microsoft Excel-based) model assisted in creating a framework index with indicators to inform the SDG7 and its sub-targets for each African country. I also applied an input-output model to measure the socio-economic effects of the energy transition in Africa, focusing on job creation. The socio-economic benefits (e.g., job creation) of different energy transition pathways are another valuable aspect of being examined and covered in this thesis to provide broader insights into the development of low-cost technology portfolios [17], [18], [130]–[132]. The analysis's outcomes assisted in better understanding the factors influencing job creation (e.g., renewables instead of penetration of fossil fuels technologies, cost of renewables, type of power generation technologies, categories in the supply chain related to the evolution of the power system).

The government of Ethiopia, as mentioned at the beginning of this section wants to achieve universal access by primarily exploiting its hydropower potential and becoming an electricity hub exporter in the region. The country already has existing electricity trade links with Djibouti (100 MW) and Sudan (100 MW) and plans to connect with Eritrea, Kenya, Somalia and Tanzania. Consequently, how Ethiopia plans to construct its energy infrastructure will have implications for the neighboring countries and vice-versa [42]. These insights into developing the country´s infrastructure are presented in **Paper-II.** The energy system of many African nations is under-developed, with diverse socio-economic conditions (population, GDP) and electricity access levels. Achieving lower-higher electricity demand levels and the costs of renewables could transform countries accordingly into net importers or exporters depending on their future energy choices (**Paper-IV**). Also, based on the future energy investments of each nation, achieving SDG7 in an African country may have collective implications for several factors (e.g., the share of renewables, CO_2 emissions, energy intensity, the lifetime of fossil fuel resources, import dependency) and achieving one target may have conflicting objectives with others on a local level as well as regional level. Also, it is important to understand the role of grid-connected, off-grid and mini-grid technologies in achieving universal access and a green revolution in an African nation.

Investing in renewable technologies can provide low-carbon generation electricity, reduce import dependency and affect job creation. Northern African countries have considerable wind potential. In contrast, solar potential is significant among other African nations and hydropower is primarily located in the Central, Southern and Eastern African power pool. Fossil fuel reserves are scattered throughout countries where most coal reserves are located in South Africa and gas reserves in Nigeria. The

Eastern African Power Pool (EAPP) is expected to play a significant role in the trade since it has the highest potential for renewables. Moreover, countries with large fossil fuel reserves, such as South Africa and Zimbabwe and those with significant hydropower potential (e.g., the Democratic Republic of Congo, Ethiopia), are expected to be electricity exporters in the future. Thus, regional cooperation can assist countries in solving their energy challenges in a cost-optimal way. However, how the countries are expected to use their domestic reserves or potential to export electricity will affect their water availability. The fossil fuel reserves in the respective countries will need to be extracted strategically for domestic use and exports since their lifetime availability will affect the import dependency of the exported country (**Paper-IV**). Also, in **Paper-III**, interconnectors of fuels other than electricity are included among the African nations, such as gas pipelines and Liquified Natural Gas (LNG) terminals, missing in previous studies [58]. The scenarios examined in **Paper-III** and **Paper-IV** tried to cover all three aspects of achieving sustainable development and the trade-offs among the evolution of various factors (e.g., demand growth, economic growth, cost of renewables, climate change mitigation).

Table 3. *Scenario matrix input parameters for Africa (Paper-III).*

Scenario	**Description**	**Climate impact on hydropower**		**Decreased annual water withdrawals for cooling purposes**
		Dry	Wet	
Reference	Current renewable policy targets	Lower CF factors for hydropower plants	Higher CF factors for hydropower plants	By 5%, 10% and 15% on a power pool level from 2025 onwards than the Reference, the 2.0°C and 1.5°C scenarios accordingly.
2.0°C	Current renewable policy targets and annual emission limits aligned with the 2.0°C scenario trajectories. [178]			
1.5°C	Current renewable policy targets and annual emission limits aligned with the 1.5°C scenario trajectories. [178]			

In **Paper-IV**, the following four scenarios are examined for the modelling period 2015-2040 but provide results only until 2030, focusing on achieving universal electricity access in Africa by 2030.

- ***New Policies – Low un-electrified settlements residential demand*** scenario (***NPLs***): Universal access by 2030 is achieved under different electricity consumption per capita targets for each African country, depending on their current electricity consumption levels. The low demand scenario considers tiers of electricity in rural household areas of Tier 1 with urban areas similar to each country's current per capita consumption. The Electrification Tiers (1-5) are defined by ESMAP´s Multitier framework [179]. The scenario considers the future implementation of current commitments to power generation projects and electricity and gas interconnectors.
- ***New Policies – High un-electrified settlements residential demand*** *scenario (**NPHs**):* the only difference with the NPL scenario is the different tiers of electricity in the household's current un-electrified settlements in the residential areas. In this scenario, the rural household areas that are currently un-electrified reach Tier 3. Respectively, the households in urban areas are elevated one Tier higher than each African country's respective electricity consumption per capita.
- ***Renewable Deployment – Low un-electrified settlements residential demand*** *scenario (**RDLs**)*: This aims to combat climate change by considering renewable energy technology costs lower than the New Policies scenarios and examining their effect. The electrification mix is different than the New Policies scenario. In this scenario, the current un-electrified settlements get Tiers of electricity similar to the NPLs scenario.
- ***Renewable Deployment – High un-electrified settlements residential demand*** scenario (***RDHs***): The techno-economic assumptions are similar to the RDLs scenario. The electrification mix is different than the New Policies scenario. The demand projections are similar to the NPHs scenario meaning that the un-electrified settlements in the residential areas will receive higher Tiers of electricity than the SDLs scenario.

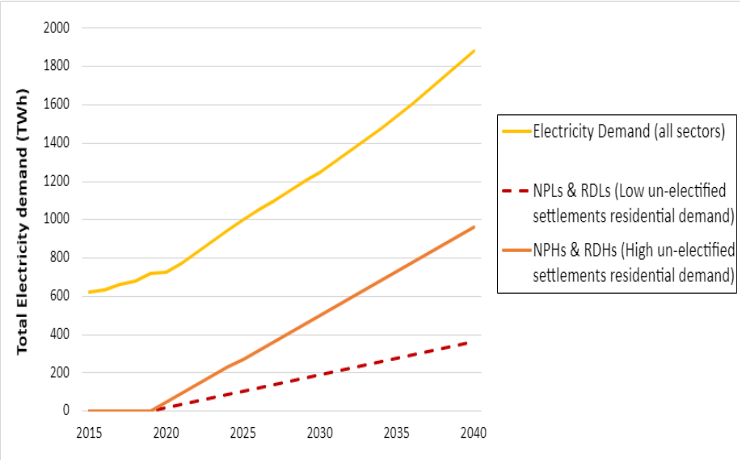

Figure 4. *Evolution of the electricity demand (in TWh) among the scenarios at the African level for the period 2015-2030 (Paper-IV).*

3.3.3 Examining the influence of water availability in achieving energy security and electricity access in Africa

Paper-III investigated the influence of water availability on hydropower plant´s operation and thermal power plants. Water availability is a primary aspect of a nation's energy transition since it will put at risk its energy supply, import dependency, and, in some cases, other countries' energy security causing geopolitical tensions [7],[10]–[15], [19],[20], [186]. Continued use of fossil-fuel-based power plants in the future will result in both an increase in greenhouse gas emissions and water use, leading to a vicious cycle.

The influence of future water availability in each country is considered in the optimization process in two ways. For hydropower plants, country-specific capacity factors are assessed according to a dry and wet scenario developed by Sterl S et al. (2021) [187]. The capacity factors from Sterl S et al. (2021) [187] have been adapted to the timescale considered in **Paper-III**. For thermal plants with cooling systems, another option is considered. The water withdrawal for cooling is restricted, implemented as a share of the withdrawal from the scenarios (Reference, 2.0°C and 1.5°C) accordingly. In the first case, water availability refers to the availability of river flow and reservoirs modelled as changes in capacity factors for hydropower plants. In the second case, water availability is linked to water withdrawal for thermal power plant cooling. Four cooling types are considered in the analysis (dry cooling, natural and mechanical draft tower, once-through cooling tower with freshwater and once-through cooling tower with salt water), where water availability refers to freshwater and saline used water. However, water availability is not categorized in terms of freshwater or others in this study nor the optimization process. A similar study using OSeMOSYS has not previously been conducted for Africa.

3.3.4 Exploring the role of decentralized systems in achieving electricity access and energy security in Ethiopia and Africa

The power system of Ethiopia is underdeveloped and the government wants to achieve universal access by 2025 (SDG7), increasing its electricity access levels from 45% in 2018. Thus, it will require large infrastructure investments in the power sector in the upcoming decades. However, similar to Paraguay, the national electricity tariffs have been quite low to generate public earnings and foster private investor interest, approximately 0.0187 USD/kWh (2005-2017), with revised tariffs to 2021 reaching 0.0765 USD/kWh [188]. This study (**Paper-II**) informs policy investment decisions on the type of power generation technologies the government could invest in and which year to provide affordable least-cost electricity to achieve universal access and cover its future electricity needs until 2065. It also looks at environmental and electricity export implications [84].

Ethiopia has very significant available energy resources, the second-largest hydropower potential in Africa, 90% of which remains untapped [84]. It is planning to invest in other renewables than hydropower to diversify its power generation mix and be resilient to climate change to managing significant risks associated with the use of hydropower [189]. Developing its high levels of renewable energy resources strategically, the government aims to become an electricity hub exporter to the neighboring East African Power Pool (EAPP) and the Northern Corridor (Ethiopia-Sudan-Egypt)[190].

In **Paper-II**, I applied an integrated energy system analysis, along with a geospatial electrification analysis, for the power system of Ethiopia. The study's objective was to identify the cost-optimal power generation mix for the country to achieve the energy policy targets set by the government and provide insights into the location-specific investments of future off-grid investments. The study assessed how geospatial analysis could enhance the energy system modelling to account for geospatial drivers of choices between electrification technologies and how they improve the results considering this extension. In this study, the OSeMOSYS model was soft-linked with a geospatial analysis model to estimate the cost-optimal mix of both grid and off-grid technologies [84]. This soft-link is formed because OSeMOSYS does not draw on the GIS information needed to find the least-cost split. Besides, the OnSSET model calculates only the optimal split of technologies to satisfy the residential electricity demand (future connections) and does not include the electricity demand in the rest of the sectors examined in this study.

I developed three scenarios to examine the development of the power system of Ethiopia sustainably and provide possible future outcomes for how to achieve socio-economic development, energy security and decrease carbon dioxide emissions. The scenarios analyzed the following: i) the evolution of the electricity demand growth considering drivers of GDP, population and urbanization, ii) achieving universal access in different years, iii) electricity consumption per capita levels for the newly connected population, iv) technology costs, v) availability of future power generation projects and vi) electricity export levels providing broader insights into future investments (***Table 4***). The scenarios examined in this paper are more detailed than those analyzed for Paraguay to formulate more coherent energy policies for understanding the drivers to achieve sustainable development more effectively.

Table 4. *Overview of scenario analysis and key parameter differences for Ethiopia (Paper-II).*

Scenario	ELC Demand in 2065	Future Committed Investments	Delay of Future available Investments & ELC trade-links	Discount Rate
New Policy	Electrified (total): 365TWh Residential (newly electrified)**: 33TWh Total: 398TWh	As per current policies	No	10%
Slow Down	Electrified (total): 121Twh Residential (newly electrified)**: 10TWh Total: 131TWh	Five years delay*	Five years delay	20%
Big Business	Electrified (total): 449Twh Residential (newly electrified)**: 33TWh Total: 481TWh	As per current policies	No	8.5%

*The delay refers to the current implementation year. **Achieving universal access in 2025 (New Policies) rather than in 2042 (Slow Down, Big Business).

An overview of the total system costs and the national revenues from the electricity exports as well as the project financing techniques as an outcome of the study in **Paper-I** can assist the government in seeking financial resources for power system expansion and identify socio-economic pathways for development.

The role of decentralized systems in covering future energy needs and achieving universal access in Africa using the OSeMOSYS and GEP tools is analyzed in **Section 3.1.3** and in more detail in **Paper-IV**.

The outcomes of the analysis conducted in **Paper-III** and **Paper-IV** could assist in identifying future low-cost power generation investments in each African country for other studies, inform SDG7 and interlinked targets and determine job creation potential in Africa.

Selected results from the examined case studies are provided in **Chapter 4** of the dissertation. More detailed results of all the reviewed scenarios for each paper are presented in the appended papers.

3.4 Data, modelling considerations and assumptions

The development of an energy systems model requires many input parameters. Some of these parameters are import/extraction technologies, available power plant projects (existing, future), energy conversion technologies, techno-economic parameters, transmission and distribution networks, and the associated losses of interconnectors and final energy demands. Depending on the available data, the modeller can aggregate the list of the various power plants based on their technical characteristics or the final demands instead of representing the various sectors that consider them only as fuels. Furthermore, capacity factors specifically for renewable technologies need to be calculated to capture the variability in their operation depending on the seasonality. Climate change mitigation pathways can be examined based on the available data for the operation of hydropower plants and thermal power plants under climate change. A high temporal resolution can increase the granularity of the model and identify when it is cost-optimal for the renewable technologies to operate or the countries exchange electricity. Nevertheless, in cases such as the development of continental-scale models, a higher temporal resolution and a large amount of input data (e.g., list of power generation technologies) will increase the computational time of the model by a significant margin. The increase of the computational time is also one of the reasons why the model developed for Africa in **Paper-III** and **Paper-IV** does not have a considerable number of timeslices. A higher temporal resolution would also mean that data would need to be further analyzed, in terms of, for example country-specific hourly generation profiles, to account for the electricity demand's seasonality which is not relatively easy to find for each African country. However, a higher temporal resolution in a continental model will assist in better investigating the effect of renewable deployment in respective countries, specifically hydropower, since the modeller can capture the discrepancies in the generation between rainy and dry seasons.

The importance of better data (e.g., available country information on future power plant investments, cooling types) and spatial techniques (e.g., soft-link with GIS) to help identify and allocate the individual cooling technologies for future thermal power plants is explained in **Section 3.1.5** and the respective research studies in **Paper-III** and **Paper-IV**.

In this thesis's study areas (Paraguay, Ethiopia, Africa), country-specific input parameters were used wherever possible, otherwise, data was derived from international sources. Only the modelling assumptions and narratives of the scenarios in **Paper-I** and **Paper-II** were developed in collaboration with stakeholders who assisted in their validation. However, the open-source nature of the models developed in this thesis overcome transparency. The models are available to future energy policy analysts, researchers and modellers to improve if better data are available or more scenarios need to be investigated. The models and input data are publicly available in both Github[1] and Zenodo[2].

The continental African models run in the PDC Center for High-Performance Computing (HPC) at the KTH Royal Institute of Technology using the Tegner high computer. To run models with large-input data in the PDC-HPC computers, you first need to apply for an allocation of time in the systems by submitting a proposal and then preparing-submitting a batch file to run the model at any time. Then depending on the size of your model, a specific time allocation need to be applied to use the PDC systems. The applications of proposals for large time allocations are handled through the Swedish National Infrastructure for Computing (SNIC)[191].

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[1] Paraguay: https://github.com/JoPapp/Paraguay-study

[2] Ethiopia: https://zenodo.org/record/4529104#.YZ4VFtDMJaR, Africa (Paper-III): https://zenodo.org/record/4889373#.YZ46TdDMJaQ, Africa (Paper-IV): https://zenodo.org/record/5814977#.YdLfZ2jMKUk

4 Results and discussion

This chapter contrasts the modelling results and insights of each study area to understand and provide further insights into the reliability of low-carbon technology portfolios and their trade-offs in achieving socio-economic development, energy security and electricity access. The research questions posed in **Section 1.1** are addressed and mapped to the results in this section.

4.1 Sustainability trade-offs of exploitation of large hydropower projects

4.1.1 Paraguay – energy security and socio-economic development

Paraguay needs to expand the capacity of its power system to cover its future electricity needs and sustain national electricity export levels. Since the country is an electricity hub exporter in South America, any decisions on the country's national energy plan will substantially affect neighboring countries.

Paraguay has an available hydropower potential of 56GW. Its power system is almost entirely based on hydropower (99%), with considerable renewable potential for the country to invest in the future to expand its power system. Decision-making investments need to consider the current low electricity consumption per capita levels due to low GDP per capita levels and the limited revenues earned from selling electricity from the Itaipu Dam to Brazil. Paraguay has overcapacity in the power system. Thus, investing in new hydropower plants and producing cheap electricity through the existing large hydropower plants makes the alternative of investing in RET less profitable at some level.

In **Paper-I**, I explored three electricity demand scenarios combined with four export prices from Itaipu to Brazil. The electricity needs of Paraguay are expected to increase from 12TWh in 2018 to a range from 24TWh (Reference) to 58TWh (High) in 2040. In the Medium and High demand scenarios, the assumptions associated with industrial growth and improved socio-economic conditions increase the domestic electricity demand. As the electricity demand increases among the scenarios (Reference, Medium, High), the power grid of Paraguay continues to be predominately reliant (99%) on hydro resources by 2040 since new hydropower plants are installed in different years of the modelling period. The excess electricity from hydropower, depending on the scenario, could be used to supply cheap electricity to electro-intensive industries, reduce fossil fuel dependency and costs on fuel imports (e.g., integration of electric vehicles) and also increase the revenues from exports. Nevertheless, the government needs to finance the expansion of capital-intensive infrastructure and the low electricity tariffs may prevent co-financing of private investors. Investments of approximately 18 – 31BUSD are required across the scenarios during 2018-2040 to cover future electricity needs.

The results demonstrate the effect of increases and decreases in export prices and how these interact with different levels of indigenous demand. As the electricity export price for Itaipu (ISC.1) remains constant, the future investments in the generation capacity are the same among the three electricity demand scenarios. It is not cost-optimal to invest in new power plants to increase electricity exports (***Figure 5***). When export prices increase, in the ISC3 and ISC4 scenarios, the installed capacity increases less in the Reference scenario (11.8GW, 2040) compared to the Medium and High scenarios (13.7GW, 2040). The only variation between the scenarios is the installation year of the new hydropower plants among the scenarios. When export prices decrease, in the ISC2 scenario (60% decrease), less capacity is required in the Reference and Medium demand scenarios (11.5GW, 2040) compared to the High demand scenario (11.7GW, 2040).

Under high levels of demand, as the export price changes, hydropower plants penetrate the power system in earlier years.

By increasing the generation capacity in the power system, the country could increase its electricity exports to neighboring countries, increasing their revenues and improving socio-economic conditions.

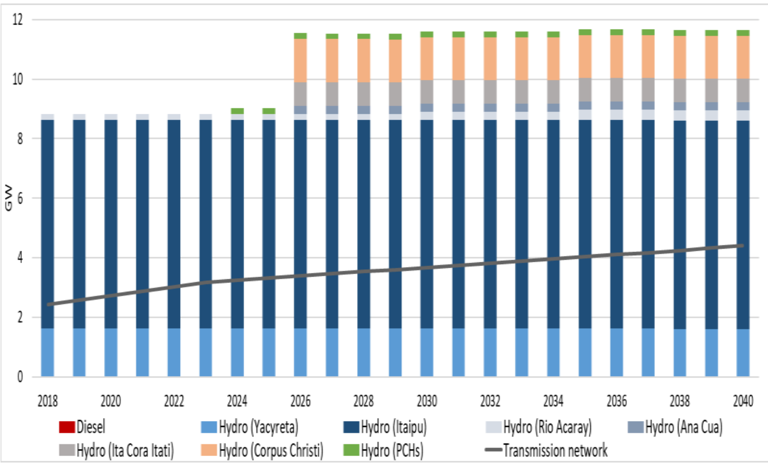


Figure 5. *Total installed capacity by technology (GW) in the Reference – ISC. 1 scenario.*

The electricity generation mix changes among the scenarios primarily affected by both electricity exports and local electricity demand. The estimated electricity export price of Itaipu and Yacyreta involves the future installation of the power plants shown above. Thus, the new investments hold only if they are financially attractive solutions and their generation costs are lower than the estimated electricity export prices. However, hydropower continues to be a significant part of the power mix, enhancing the security of the energy supply in the country.

In the ISC.1 case, the electricity generation from 60TWh in 2018 increases to 91TWh in 2040 in the Reference scenario (***Figure 6***). The rise in demand leads to a substantial decrease in the country´s overall electricity exports by approximately 28% (Medium) and 41% (High), correspondingly during 2018-2040 as compared to Reference scenario one. In this case (ISC.1), the electricity export price of Itaipu is assumed to be lower than Yacyreta´s (exports to Argentina), so it is not profitable to increase the levels of electricity exports to Brazil. Also, sufficient reserve generation capacity needs to be maintained to cover peak demand. In the Reference scenario, electricity exports to Brazil decreased from 34TWh in 2018 to 24TWh in 2040. While, in the Reference and Medium demand scenarios, the electricity exports to Argentina increased from 10TWh in 2018 to 24TWh in 2040. However, in the High demand scenario, the electricity exports to Argentina increase to 24TWh in 2026 and then gradually decrease to 11TWh in 2040. Thus, increased levels of national electricity demand associated with a low electricity export price are estimated to result in lower socio-economic development through decreased electricity exports.

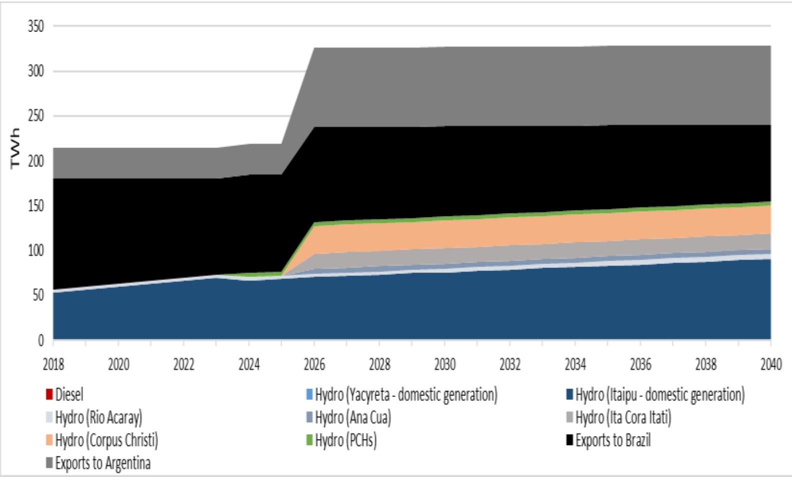


Figure 6. *Electricity generation mix by technology (TWh) in the Reference – ISC.1 scenario.*

The higher electricity export prices to Brazil from Itaipu (ISC.3-4), compared to the price agreed until 2022 (ISC.1), and Argentina's current ones could allow the government to increase its revenues further and improve power infrastructure on a national level. In the opposite case, it would be profitable to decrease the electricity exports to Brazil from Itaipu and use Itaipu's generation instead to cover most of the country's electricity needs and increase the electricity exports to Argentina. Nevertheless, in the High demand scenario, the country's electricity exports would substantially decrease by 2040. The country´s overall exports decline by 50% by 2040 between the High demand scenario and the Reference scenario, assuming the electricity demand in the High demand scenario could approximately double by 2040.

To meet future electricity demands, Paraguay needs to expand its energy system. The results from **Paper I** show that there are important interactions between the level of demand, the revenues from exporting electricity and the decision to invest in new capacity.

The analysis of the trade-offs in electricity exports to Brazil and Argentina between the evolution of the national electricity demand growth and export prices is presented in the following figures.

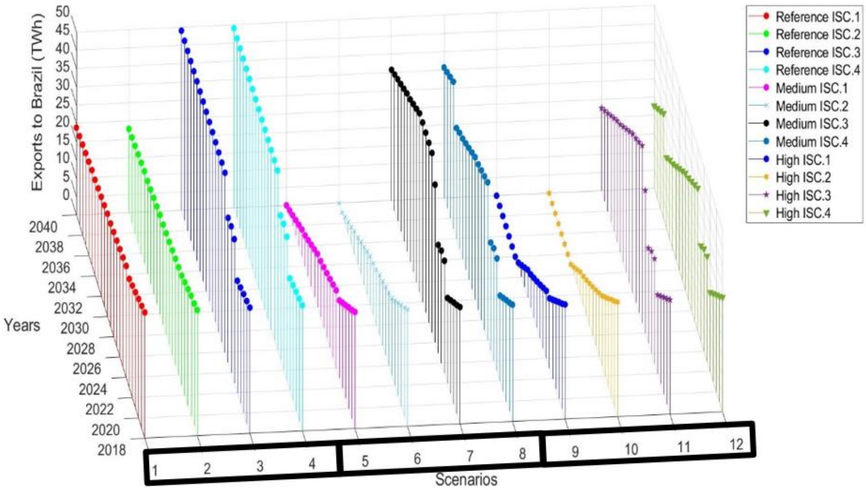


***Figure 7.** Electricity exports to Brazil among the three electricity demand scenarios combined with the electricity export price of Itaipu.*

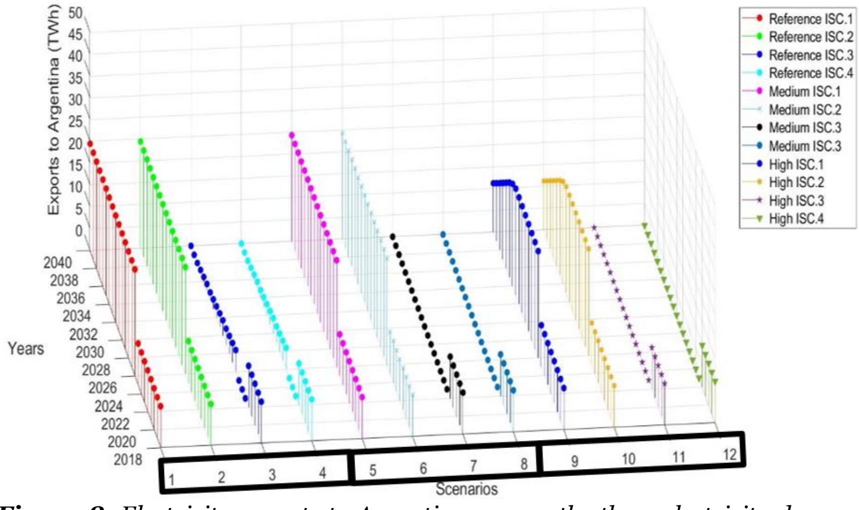


***Figure 8.** Electricity exports to Argentina among the three electricity demand scenarios combined with the electricity export price of Itaipu.*

As the Itaipu debt is expected to be paid by 2023, the government could boost Paraguay´s economy with the electricity export revenues to Brazil from Itaipu.

The total earnings for the government from Itaipu follow the electricity export price between Itaipu and Brazil. As the electricity export price to Brazil increases and is higher than the electricity export price to Argentina, Itaipu increases its electricity exports to Brazil.

The total exports to Brazil (TWh) and the total accumulative earnings (BUS) for Paraguay from Itaipu electricity generation in the Reference scenario are presented below. Although hydropower requires significant upfront capital expenditure offset by the lower operating costs, the total accumulative revenues from 0.8BUSD in 2018 could reach up to 33BUSD by 2040, depending on the scenario (Reference, Medium, High) and its associated implications in the energy transition.

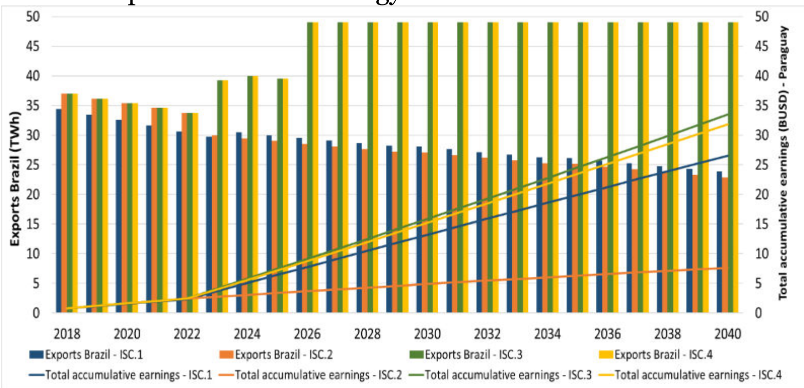


Figure 9. *Reference scenario.*

4.1.2 Ethiopia – electricity access and energy security

In comparison to Paraguay, Ethiopia is a low-income country with low electricity access (45%) and an inefficient power transmission network that aims to achieve universal access and become an electricity hub exporter in the region by 2025. Hydropower is the primary source of centralized electricity production (4.2GW, 2018), while the country hosts 45GW of hydropower potential (2nd largest in Africa), 90% of which remains untapped.

In this section, I describe the modelling insights from Paper II of three scenarios (New Policies, Slow Down, Big Business), focusing on examining the effect of key factors in the energy transition of Ethiopia (e.g., the evolution of the electricity demand, higher power generation costs, lack of financing) (***Table 4***). Universal electricity access is not achieved in the same years. In the New Policies scenario, the goal for universal electrification is 2025, while in the remaining two (Slow Down, Big Business) is 2042. This study sheds light on the type of power generation technologies the government could invest in and in which year to provide affordable least-cost electricity to achieve universal electricity access and security of its future electricity needs until 2065. It also looks at emissions and electricity export implications.

The overall installed capacity of the power system of Ethiopia (4.9GW, 2018) is less than that of Paraguay, although it is more diversified (86% hydro, 3% fossil fuel, 11% RET). However, the population in the country is considerably higher (112 million, 2019) and the high T&D losses result in the electricity consumption per capita being relatively low (83kWh/capita, 2018). These low electricity consumption levels are in stark contrast with the country's very significant levels of available energy resources. Ethiopia also relies on fossil fuel reserves (natural gas, oil). As the population is expected to increase (170 million, 2040), together with GDP and urbanization, this will lead the total electricity demand to grow from almost 14TWh in 2018 to 131TWh (Slow Down), 398TWh (New Policies) and 481TWh (Big Business) (***Table 4***). Without considering the risk to hydropower generation in a changing climate, the scenario results show that hydropower could make up to 80% of the new capacity prior to 2026 (as shown in **Section 4.4**). In recognition of this risk, the Climate Resilient Green Economy Strategy (CRGE) plan seeks a more diverse portfolio as the system develops [192]. One of the government's objectives is to ensure a reliable energy supply at an affordable price [190].

The country needs to expand its power generation capacity from 3GW in 2015 to 169GW (New Policies), 42GW (Slow Down) and 215GW (Big Business), respectively, by 2065 to achieve universal electricity access and cover its future energy needs. The diverse electricity demand and consumption levels of the scenarios lead the power system to evolve differently. When electricity demand increases faster and universal access is achieved earlier, higher penetration of RET technologies is shown in earlier years. Hydropower is fully exploited in different years but at different rates, if investments are allowed in the New Policies and Big Business scenarios. However, the country still diversifies its power generation mix in the future with the penetration of RET technologies such as solar PV and CSP, followed by wind, geothermal and biomass (***Figure 10***). After hydropower, as electricity demand increases, solar technologies play a more significant role in the country's energy transition. If future investments in hydropower and other renewable technologies (Slow Down) are limited due to a lack of finance we see a higher penetration of fossil fuel technologies to maintain energy security and meet electricity access goals.

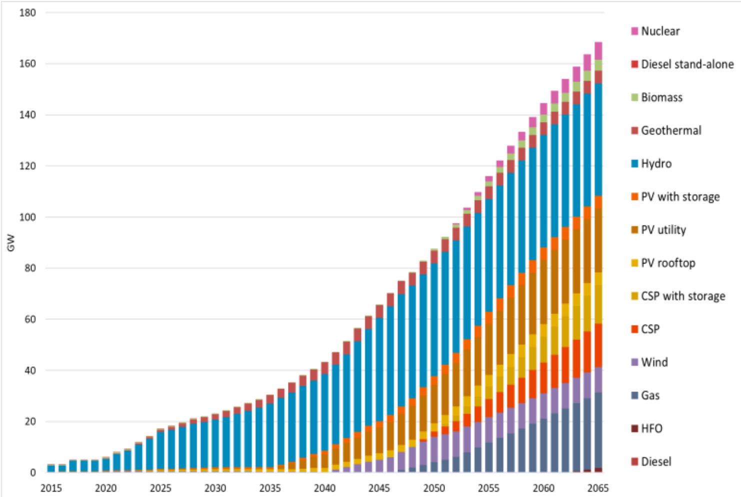


Figure 10. *Power generation capacity of grid-connected technologies in the New Policies scenario.*

In the New Policies scenario, the electricity supply increases from 12TWh (95%RET) in 2015 to 517TWh in 2065 (89%RET), the RET share constituting primarily hydro (40%), CSP (28%), solar PV (14%) and other in 2065. The rest of the electricity supply mix is being supplied by fossil fuels (1%) and nuclear (10%). As hydropower reaches its maximum electricity generation in 2046, natural gas and nuclear technologies gradually penetrate the electricity supply mix. Natural gas also assists in maintaining the adequate reserve margin indicating that as hydropower is fully exploited, the penetration of fossil fuels is needed to achieve energy security and electricity access if storage for RET is not available. Besides, as hydropower reaches its maximum potential (New Policies, Big Business), in the Big Business earlier years (2041), nuclear power gradually comes into the power system, providing low-cost electricity. In the Slow Down scenario, the electricity needs are lower, than the New Policies, at 168TWh (75%RET, 44% hydro) by 2065. Since hydropower does not reach its full potential and nuclear investments are not allowed, natural gas penetrates in the earlier years to bolster the security of the energy supply. The electricity supply grows to 611TWh (90%RET) in the Big Business scenario by 2065. The higher electricity demand and achieving universal electricity access by 2042 will lead to a higher electricity supply from RET, specifically hydropower, from 2023 to 2046 (**Figure 11**). In all scenarios, investments are required in future improvements in transmission and distribution networks.

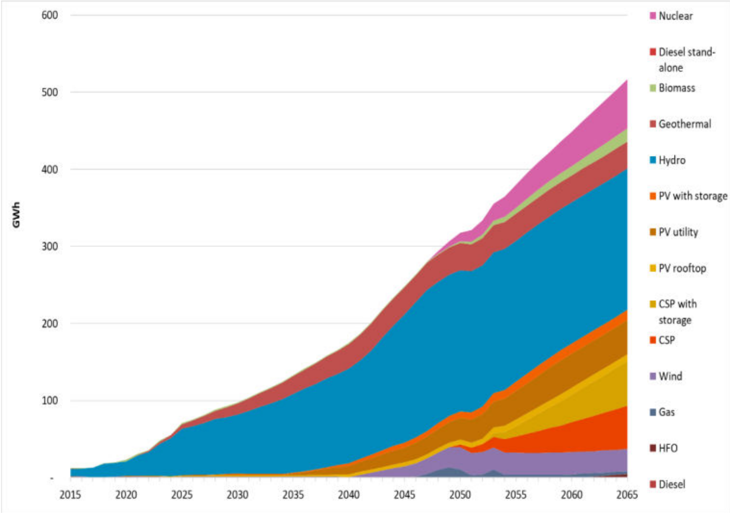


Figure 11. *Electricity supply mix of grid-connected technologies in the New Policies scenario.*

The energy transition of Ethiopia is associated with two challenges. Firstly, the full exploitation of the hydropower resource potential could create a geopolitical crisis with other countries due to lower water resource availability. Specifically, most of Egypt´s population (90%) lives alongside the Nile River, which supplies most of Egypt´s and Ethiopia´s water [193], [194]. Secondly, as the size of the power system increases (Big Business) constrained by the limited availability of domestic gas reserves, nuclear capacity gradually increases, which may be both advantageous and challenging [90].

Financial implications

Supporting the government´s future ambitions, both domestically and abroad, the energy transition requires significant infrastructure investments in the power sector, leading to a range of capital expenditures between 173BUSD (Slow Down), to 548BUSD (New Policies) and 669BUSD (Big Business) for the period 2015–2065.

In the New Policies, achieving universal electricity access and covering the country’s future energy needs requires approximately 40BUSD of capital investments in power generation technologies from 2020 to 2025. Since hydropower is a grid-connected technology, and higher capital investments are needed for grid expansion to electrify remote areas, investments in decentralized technologies are cost-optimal to achieve electricity access closer to the end-user demand. This transition includes

38BUSD of grid-connected technologies, 1BUSD of mini-grid, and 1.5BUSD of stand-alone technologies. Nevertheless, during the same period, the penetration of mini-grid technologies requires 37MUSD of mini-grid extension and 6BUSD of expansion of the transmission and distribution network. Also, the overall operational and maintenance costs are lower in the Slow Down than in the other two scenarios as fossil fuel penetration is lower, to be in the range of 117 BUSD (Slow Down) to 265BUSD (Big Business) during 2015–2065. These costs are primarily fixed costs in the New Policies and Big Business scenario, while in Slow Down, the higher penetration of fossil fuel technologies leads to higher variable costs (***Figure 12***).

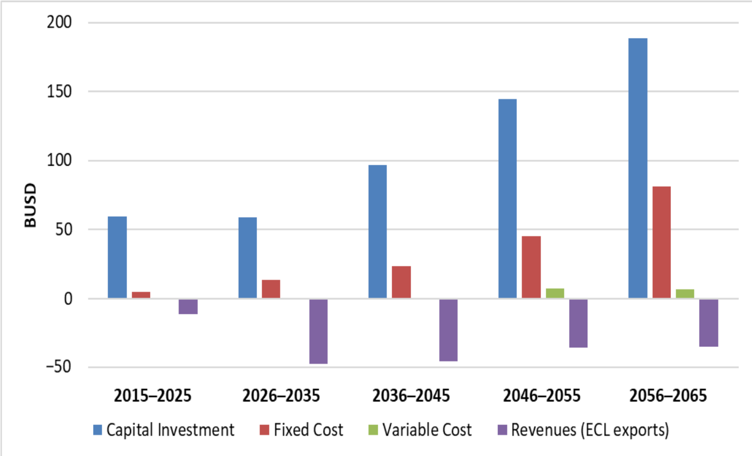


Figure 12. *Total system costs and electricity export revenues in the New Policies scenario.*

Thus, the green energy transition of Ethiopia is expensive and together with the low national electricity tariffs to generate public earnings and the future increase in the supply of hydro-based electricity, private investor interest in the country may be challenging. Alternative ways can be applied to finance future power sector investments. Firstly, the investments can be funded through public-private partnerships by increasing the national tariffs, but this would lead to citizens paying at higher levels which is difficult due to the socio-economic situation in the country. Secondly, the government could sign-up for profitable electricity export prices with neighboring countries exploiting its cheap hydro-based electricity to increase revenues and supply a less-costly domestic tariff (***Figure 12***). One of the government's ambitions is to develop international trade and become an electricity exporter in the region. Thus, an analysis between the trade-off of changes in future electricity demand and power generation supply is required, specifically as hydropower is vulnerable to climate change, and electricity exports.

Emissions

The government has long signaled its commitment to green growth and achieving future goals needs to be aligned without increasing greenhouse gas (GHG) emissions during 2010-2030. The emissions in the power sector represented just 3% of the 2010 baseline. Since the future energy transition is expected to rely heavily on renewable energy technologies, in the New Policies scenario, Ethiopia's CO_2 emissions increase from 0.4Mt CO_2 in 2015 to 4Mt CO_2 in 2065, compared to the Slow Down (30Mt) and Big Business (4Mt) scenarios. The future penetration of natural gas power plants leads to higher CO_2 emissions between 2015 and 2065, influencing the country´s environment.

Centralized vs decentralized technologies

Hydropower is the primary source of centralized electricity production. 80% of the country's population lives in rural areas. Electrification is currently concentrated in denser urban areas, and only a low number of households are connected to the national grid infrastructure (34%, 2019). The rest of the population is off-grid. Satisfying electricity access targets requires a more complex system design [119], [195], [196]. To meet future electricity needs and achieve universal electricity access, is it cost-optimal for the government to invest in grid-connected, off-grid, or mini-grid technologies or expand the grid. An integrated distributed energy resources system can enhance the security of a nation's energy supply, and decentralization can create new actors in energy markets. Also, distributed energy resources can assist in reducing carbon dioxide emissions locally and on a national scale, assisting in environmental sustainability (**Section 4.5**).

4.1.3 Africa – electricity access and decarbonization and affordability

The research studies conducted for Paraguay and Ethiopia showed how the nations could exploit their hydropower resources strategically to expand their power system and revealed trade-offs between the electricity exports and security of energy supply by achieving low-cost electricity access. The respective study areas examined the implications of different hydropower regimes on energy security, carbon dioxide emissions, and socio-economic development. However, these power systems are analyzed in isolation and not interconnected with other countries' energy systems and examined with respect to climate change mitigation pathways.

The Democratic Republic of Congo, Ethiopia, Cameroon, Kenya and Zambia have some of the most considerable hydropower potentials in Africa and globally. However, so far only a limited amount of this potential has been exploited in each country. In **Paper-III** and **Paper-IV**, I examined the role of hydropower potential on a continental and national scale to achieve different targets (e.g., decarbonization, electricity access) associated with Africa´s energy transition and sustainable development. Specifically, in **Paper-III**, the model selects hydropower as a cheap and less carbon-emitting technology to achieve RET targets in African countries and achieve security of energy supply and climate change mitigation pathways compatible with 2.0°C and 1.5°C pathways. In **Paper-IV**, the model selects hydropower as the least-cost power source to gain universal electricity access in the short term (by 2030) in all scenarios.

In **Paper-III**, in the Reference scenario, the total final electricity consumption from 53Mtoe in 2015 in Africa increases to 461Mtoe in 2065. Due to energy efficiency measures, the total final electricity consumption increases to 406Mtoe in the 2.0°C and 414Mtoe in the 1.5°C scenarios in 2065, which is less than the Reference scenario for the nations to achieve climate change mitigation pathways.

In the Reference scenario, the overall generation capacity in Africa grows from 181GW (2015) to 1863GW (2065). The share of renewables increases from 19% to 78% accordingly, leading the thermoelectric capacity to decrease from 82% to 22% in the same years. Hydropower was the dominant renewable source on the continent in 2015, and even though it has increased significantly, solar power is becoming the dominant technology in 2065. Most of the hydropower capacity was located in EAPP in 2015. Nevertheless, CAPP is expected to be the leading hydropower-based power pool in Africa, presenting the highest increase from 2015 to 2065. The countries that constitute most of Africa's hydropower capacity in 2015 and 2065 are presented in **Figure 13**. These countries could exploit their hydropower potential significantly to supply domestic least-cost electricity throughout those years and export the excess electricity through an interconnected trading scheme to assist other countries in covering their electricity needs in a cost-optimal way (**Section 4.3**). The potential implementation of mega hydropower projects such as the Grand Inga project in the Democratic Republic of Congo, the Grand Ethiopian Renaissance Dam in Ethiopia, the Lauca project in Angola and other projects are expected to assist the respective countries in achieving their renewable energy targets as well as unlock least-cost power transition mechanisms to increase socio-economic development and meet peak demands.

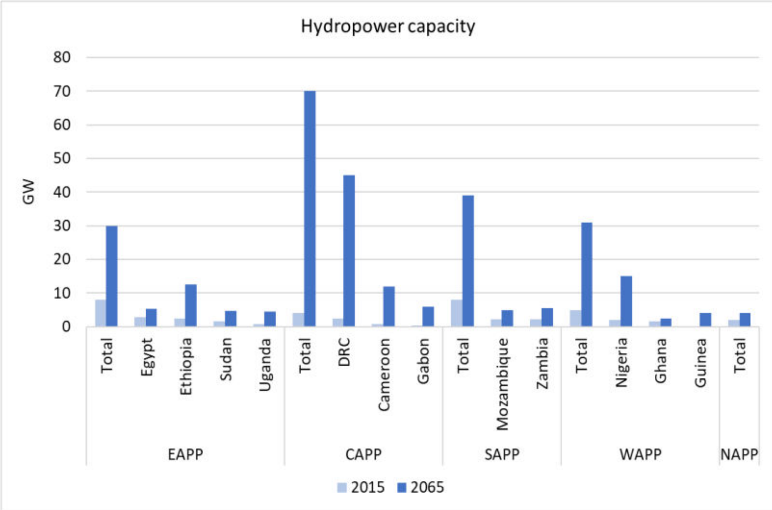


Figure 13. *Hydropower capacity in Africa in the Reference scenario in 2015 and 2065.*

In the 2.0°C and 1.5°C scenarios, the overall generation capacity in Africa grows to 1,843GW and 1,833GW accordingly by 2065, less than the Reference scenario due to lower electricity demand levels. However, as the costs of renewable (solar, wind) technologies decline over those years, solar PV technologies represent most of the continent's installed capacity by 2065. In the decarbonization scenarios, renewables reach even higher figures than the Reference scenario, while thermal capacities lower levels by 2065. Specifically, in the 1.5°C scenario, the RET capacity is less than the 2.0°C scenario, since the thermal generation capacity is more. In each scenario that year, the thermoelectric capacity reaches 296GW and 315GW, respectively. More hydropower capacity is needed to further decarbonize the power system in Africa, highlighting its essential role in the future energy transition to secure energy supply and electricity access. Specifically, its capacity increases to 180GW (2.0°C) and 188GW (1.5°C) accordingly by 2065, which is more than the Reference scenario. The Democratic Republic of Congo, Cameroon, and Rwanda are the countries that primarily increase their hydropower capacity more to decarbonize their power system further (**Figure 14**).

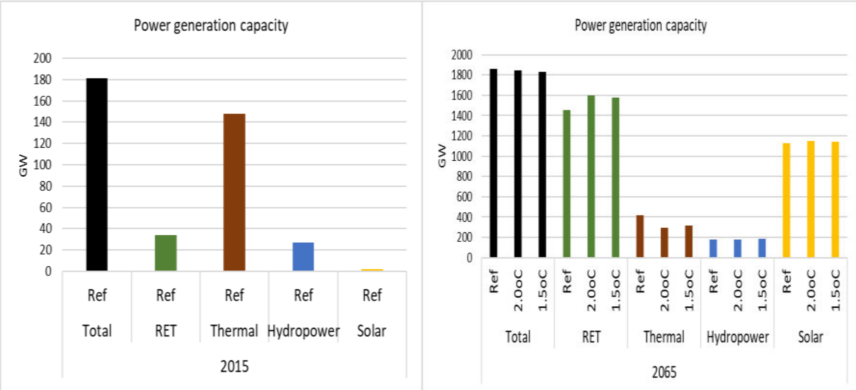


Figure 14. *Overall installed capacity by a power source in Africa for each scenario in 2015 and 2065.*

The overall electricity generation in Africa increased from approximately 3,000PJ in 2015 to 21,000PJ in 2065 in the Reference scenario, compared to 18,800PJ and 19,000PJ in the 2.0°C and 1.5°C scenarios, respectively. Renewables constitute about 18% of the generated electricity in 2015, while by 2065, this share gradually increases in the Reference scenario to 57% and 75% in the 2.0°C and 1.5°C scenarios. The hydropower-based generation is higher in the decarbonization scenarios than in the Reference scenario, achieving a lower carbon energy transition. Consequently, the higher penetration of RET technologies in the energy transition of the decarbonization scenarios in Africa resulted in less thermal-based power generation by 2065. Nevertheless, the thermal power generation is higher in the 1.5°C scenario than in the 2.0°C scenario due to the higher penetration of nuclear and carbon capture with storage technologies. Solar technologies, followed by hydropower, are the dominant power generation renewables in the future. In the Reference scenario, coal-based power generation is the primary thermal power source in the long-term instead of natural gas in the decarbonization scenarios (**Figure 15**).

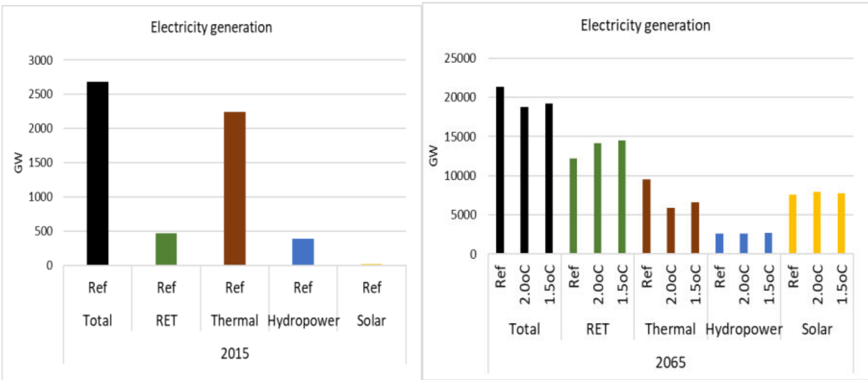


Figure 15. *Overall electricity generation by power source in Africa for each scenario in 2015 and 2065.*

As CAPP becomes the leading hydropower region in Africa due to primary investments in the Democratic Republic of Congo, it further increases its hydro-based power generation between the Reference to the 2.0ºC and 1.5ºC scenario. The increase in the generation is to cover more of the domestic electricity in the region as electricity demand is higher in the decarbonization scenarios, increasing the net electricity exports. This transition results in lower CO_2 emissions in CAPP between the Reference (148Mton), 2.0ºC (43Mton) and 1.5ºC (8Mton) scenarios by 2065. Similar insights are presented in the energy transition for only the Democratic Republic of Congo.

Thus, hydropower in an interconnected trading scheme could be used to assist other countries in various ways. Firstly, by decreasing their CO_2 and satisfying part of their domestic energy supply and secondly, by providing low-cost electricity without relying on international fuel sources, enhancing their energy security. Nevertheless, the importing and exporting countries have contrasting incentives for energy trade. The exporting government needs to finance the hydropower plant's construction, using its electricity export revenues as an option and analyzing the influence of the evolution of its electricity demand for future exports (**Section 4.1.1**). At the same time, the importing country will be dependent on other countries´ imports, affecting energy security (demand risk) and the need to define a price to be cost-optimal.

In Ethiopia's case, the government increased its electricity demand from 30PJ in 2015 to 722PJ in 2065 in the Reference scenario, while in the 1.5ºC scenario it grows to 725PJ to further decarbonize the energy system. The government fully exploits its hydropower potential in both scenarios, resulting in 23% and 21% of the generated electricity in 2065, respectively, and increasing its natural gas penetration (3%) (1%), solar power (58%) (62%) and other renewables (16%) (17%). It also becomes an electricity net exporter in the region in the Reference scenario during 2015-2065 and although the electricity demand increases in the 1.5°C scenario, the country increases its net exports cumulatively. In the Reference scenario, the total system costs of the energy system are less than the 1.5°C, during 2015-2065, due to lower final consumption of coal and oil products resulting in fewer fuel costs in the non-power sector. The country increases its RET-based generation to 1.5°C scenario to balance the lower generation of natural gas compared with the Reference scenario but it also uses this electricity to increase its exports.

The penetration of a non-water intensive technology, such as hydropower, also benefits the overall water withdrawals in the power system's transition. This trade-off is because it doesn´t consume water but only withdraws water for the operation, which is returned to the river. However, water loss due to evaporation in hydropower dams is included in the analysis, increasing as a hydro-based generation grows. The agriculture sector is primarily responsible for most of the water withdrawals in a region. However, water withdrawals for cooling power plants are still essential for their continuous operation, especially under climate change, where the available water may not cover all energy needs in an African nation. South Africa is one of the countries where the primarily coal-based power generation and coal mines further threaten water insecurity.

Each power pool presents a unique transformation pathway regarding water withdrawal and consumption (**Section 4.2**). National and regional policies need to differ based on African nations' specific energy and water context.

The penetration of hydropower, a grid-connected technology, requires investments in grid expansion and improvements in the T&D network to supply adequate electricity to the citizens, specifically in Africa, where the T&D losses are quite high. Moreover, hydropower requires high upfront capital investments; however, in the long-term, it results in lower operating costs for the system and can be used to meet the peak demand.

The capital costs to further decarbonize the energy sector are higher in the 1.5°C scenario than in the 2.0°C and Reference scenarios. Nevertheless, the overall system costs are lower due to the higher penetration of renewable and hydro technologies, resulting in less CO_2 emissions.

The trade-offs of exploiting hydropower and other renewables in the energy transition in Africa in terms of water withdrawals, water consumption, costs and emissions in achieving security of energy supply and electricity access is further presented in **Section 4.2**.

Although hydropower and RET build climate resilience, hydropower operation depends on climate variability affecting energy security. Thus, mitigation strategies should consider the associated challenges of climate change in hydropower investments. Climate change may cause disruptions in the electricity supply and increase the cost of generating electricity, affecting socio-economic development, as presented in **Section 4.4**.

4.2 The trade-offs of RET penetration in achieving electricity access and increasing jobs versus water use in Africa

In the earlier results section, we showed the important role of large hydropower in maintaining energy security, how this interacts with the opportunity for energy exports, and how large hydropower has a smaller role in rural electrification. However, other renewable technologies also play a role in the Africa context.

In this section, we explore how RET penetration in the power mix of a country has benefits such as decreasing carbon dioxide emissions and water use, enhancing the energy security of a nation by supplying more electricity and balancing any potential electricity exports by providing low-cost electricity. Nevertheless, renewables require more capacity to be invested in the power system since their availability is lower than fossil fuels. Their operation depends on the weather and their capital costs are higher than investing in fossil fuel technology, but the operational costs are lower in the long term. Also, the penetration of renewables in the energy system has implications for water withdrawal and water consumption evolution since fewer water withdrawals are required for cooling than thermal technologies, which assists in achieving environmental sustainability. Furthermore, the country is not dependent on fossil fuel price fluctuation and is more energy-dependent (**Section 4.4**).

Carbon capture with storage technologies (biomass, coal, natural gas) is another alternative for decarbonizing the power system, as shown in **Paper-III**´s analysis. Nevertheless, their technological maturity and costs are not attractive yet to the investors. While nuclear power is another technology with similar benefits to renewable technologies, its operation is not dependent on weather. There are, however, social concerns with its availability and cooling requirements are needed for its operation.

Section 5.1.3 shows that the penetration of renewables is essential to decarbonizing the energy system as well as achieving universal electricity access and climate change mitigation pathways for 2.0^{o}C and 1.5^{o}C scenarios in Africa. In these scenarios, hydropower was the leading renewable technology in 2015, while by 2065, solar became the dominant renewable technology, followed by hydropower. An aspect of achieving SDG7 in Africa, apart from the diverse electricity consumption per capita levels that each African nation wants to achieve, is the evolution of renewable technology costs. Africa can not afford a cost-increasing green energy transition pathway. Thus, how the costs of renewables will evolve will affect future decision-making investments in power generation technologies. **Paper-IV** shows that if by 2030, solar costs decrease by 50% in Africa, solar technology is expected to be the dominant renewable technology instead of hydropower, enhancing the climate change resilience of the system.

Each power pool presents a unique energy transformation pathway based on its available energy resources, policy plans, and financing which affects its future water withdrawal and consumption.

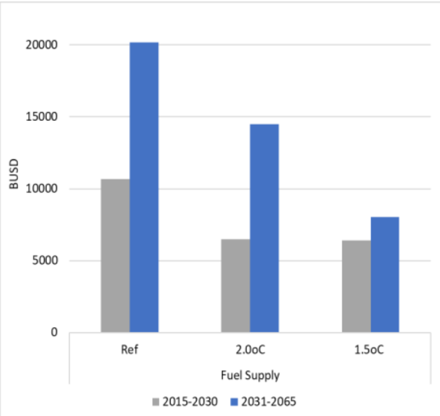
In the Reference scenario (**Paper-III**), water withdrawals in Africa grow by almost eight times between 2015 and 2065, reaching 159 billion cubic meters (bcm). This increase corresponds to approximately 3% (in 2065) of the Total Renewable Water Resources (TRWR - 5,290bcm in 2015) on the continent, assuming no changes in future precipitation patterns. This growth is mainly due to the penetration of high water-intensive technologies (coal, oil). However, water consumption remains relatively constant between 2015-2065, reaching 2bcm in 2065, primarily due to the penetration of renewable energy technologies.

In the mitigation scenarios, overall water withdrawal increases over time (2.0°C, 52bcm, TRWR 1%) (1.5°C, 85bcm, TRWR 2%) by 2065. However, the more aggressive decarbonization pathway (1.5°C) leads to higher overall water withdrawals compared to the 2.0°C scenario, although with lower water consumption levels by 2065. By 2065, investments in low-carbon energy infrastructure increase annual water withdrawals from 1% (52bcm) in the 2.0°C to 2% (85bcm) in the 1.5°C scenarios of total renewable water resources in Africa compared to 3% (159bcm) in the baseline scenario with lower final energy demands in the mitigation scenarios. Water consumption decreases from 1.2bcm in the 2.0°C scenario to 1bcm in the 1.5°C scenario, compared to 2.2bcm in the baseline scenario by 2065, due to the lower water intensity of the low-carbon energy systems. To meet the 1.5°C pathway, the energy sector requires a higher water withdrawal than the 2.0°C scenario, both in total and per unit of final energy, due to increased nuclear and carbon capture with storage technologies.

Financial implications

In the Reference scenario, the total system costs associated with the energy sector in Africa, including only the costs for the supply and conversion of energy and excluding costs on the demand side, are estimated at USD_{2015} 24,500 trillion. Under the mitigation scenarios, the total costs, excluding the costs of energy efficiency measures and welfare losses due to demand reduction, are lower by 29% (2.0oC) and 54% (1.5oC) compared to the Reference scenario for 2015-2065. In the mitigation scenarios, the penetration of renewable technologies leads to fuel supply savings of 32% (2.0°C) and 53% (1.5°C) compared to the Reference scenario. As expected, mitigation scenarios are capital-intensive and the capital investments in the power sector are higher by approximately 9% (2.0°C) and 19% (1.5°C) compared to the Reference scenario (**Figure 16**). Despite that, the lower operating expenses show that decarbonization options, including energy efficiency measures, are cost-efficient pathways. This indicates that increasing the ambition of climate targets results in lower cumulative costs. All scenarios assume universal access to clean energy by 2065, hence the high investment projections in 2030-2065.

a. **b.**



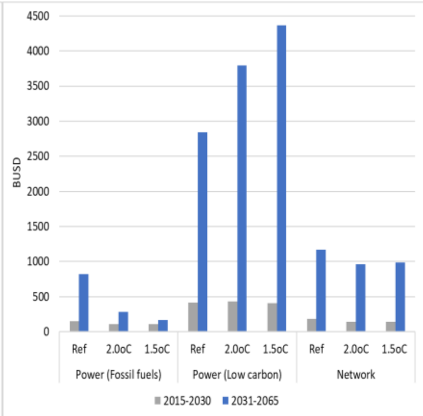


Figure 16. *Comparison of fuel supply costs in the energy sector and capital investment costs in the power sector in Africa among the scenarios (in BUSD).* ***a.*** *Comparison of fuel supply costs in the energy sector in Africa among the scenarios,* ***b.*** *Comparison of capital investment costs in the power sector in Africa among the scenarios.*

Emissions

In the Reference scenario, carbon dioxide emissions increased from 1,200Mt in 2015 to 3,500Mt of CO_2 by 2065. Nevertheless, the emissions in the 2.0°C and 1.5°C scenarios decreased by 65% and 125%, respectively, in the same year, since higher penetration of renewables and carbon capture with storage technologies are presented in these scenarios. The higher penetration of RET in decarbonization scenarios maybe require higher capital investments, but the overall environmental benefits, lower emissions and water withdrawals substitute these challenges.

Paper-IV shows that higher electricity consumption levels lead to a higher penetration of fossil fuel technologies in the power mix of Africa to achieve electricity access, energy security and meet peak demands. However, to achieve the same electricity demand levels, decreasing renewables' costs can assist in a less carbon-intensive power system, although higher capacity needs to be installed. The penetration of renewables in the power system of an African nation results in lowering the average electricity cost of generating electricity.

Higher penetration of renewable energy sources in the energy mix of Africa reduces dependence on imported fuels, creates local jobs, and increases cost efficiency. However, this energy transition and achieving electricity access can create several jobs that were lost. In Africa, approximately 7 million direct jobs can be created by expanding the power generation capacity and the T&D network in the NPLs scenario, compared to 9 million jobs in the NPHs scenario, 7.0 million jobs in the RDLs scenario and 10 million jobs in the RDHs scenario from 2020 to 2030 across the supply chain. The increased share of renewables in the energy transition in Africa can boost job creation, while fossil fuel development can support jobs in various ways. Increasing the electricity consumption levels in Africa (NPHs, RDHs) leads to higher total system costs, but it is estimated to create more jobs. Also, the decreasing costs of renewables (RDLs, RDHs) could further increase the penetration of renewables in the energy mix, leading to a higher number of jobs.

Despite the gradual penetration of renewable energy and solar off-grid technologies in the continent's energy mix, which grows higher as renewable costs decrease, Africa is still struggling to achieve its green revolution. Domestic identified fossil fuel reserves and fossil-fuel technologies are still the least-cost options to satisfy future energy needs in Africa and provide resilient power grids in the short term. Consequently, the total carbon dioxide emissions of the future energy transition in Africa increased from 1,200Mton in 2015 to 2,800Mton (NPLs), 2,900Mton (NPHs), 2,800 (RDLs) and 2,900Mton (RDHs) depending on the scenario in 2030. Thus, a decreased cost of renewables could further assist an African nation in evolving its power sector in a less carbon-intensive way.

4.3 The impact of energy trade-links in achieving energy security, low-carbon electricity and water use in Africa

Previous sections highlighted the role of hydropower and renewables in the energy transition of a nation. However, as renewable potential and energy reserves are scattered among the different nations (e.g., Africa), an interconnected trading scheme (e.g., electricity, gas) can exploit strategically country-specific energy resources. Decision-makers can strengthen their efforts, progressing to address more than one pillar for sustainable development, such as energy security and decarbonization, depending on the government´s policy plans. Trade links can be used as enablers or disablers of the future energy transition of a nation.

Ethiopia has an existing interconnector capacity with Sudan (200 MW) and Djibouti (180 MW). Together, these factors supported 1.5 TWh of electricity exports representing 11% of the Ethiopian generation in 2018 [197]. Future infrastructure plans reach much higher (**Section 3.3.2**).

Thus, the volume of electricity exports varies between scenarios (**Paper-II**). In the Slow Down case, investment limits gradually reach exports to zero, significantly affecting Ethiopia´s ambitions. While exports continue at high levels under the New Policies and Big Business cases, their levels tend to decline over the modelling period before stabilizing, so Ethiopia may struggle to provide for large domestic industrial ambitions while also converting into a regional export hub for the EAPP. Domestic constraints on both the availability of finance and power system capacity growth will affect Ethiopia´s ability to meet its regional export ambitions (***Figure 17***). Most of the electricity is exported to Sudan, followed by Kenya, Tanzania, and Djibouti, highlighting Ethiopia´s energy transition into neighboring countries' electricity supply.

The country´s total export revenue potential ranges from 46BUSD (Slow Down) to 174BUSD (New Policies) for 2015-2065, primarily from electricity exports to Sudan, followed by Kenya. A heavier industrialization electricity demand level (Big Business) decreases export revenues to 150BUSD (***Figure 12***).

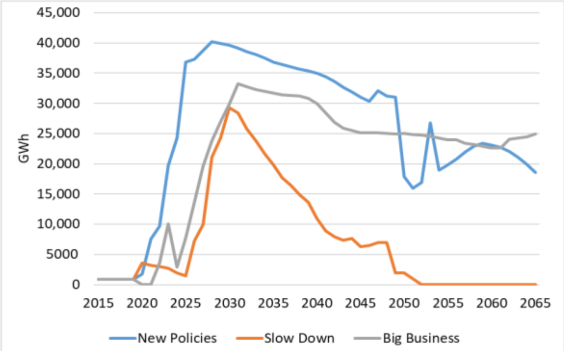


Figure 17. *Comparison of electricity exports (GWh) among the scenarios.*

In **Paper-III,** I show how trade among African countries could support more affordable attainment of lower emission levels, decrease electricity generation costs and influence water resources management.

Nevertheless, trade drivers minimize the overall energy system costs (on a continental level) and interact with the differences in the national energy resources of interconnected countries, in addition to their energy demand, and technological availability (also presented in **Paper-IV**).

The largest electricity net exporters by 2065 are Kenya, South Africa and Sudan, while the main net importers are Uganda, Burkina Faso and Mali (**Paper-III**). The high potential for renewables in the EAPP makes the region the largest net exporter of electricity. Although the RET share increases relatively significantly in Ethiopia, specifically with respect to hydro, solar and geothermal power, as electricity demand rises among the scenarios, the country also starts producing electricity from natural gas power plants in the NPH and RDH scenarios from 2028 onwards. These results are also compatible with the analysis in **Paper-II**, where the power system of Ethiopia was examined in isolation. To cover the increased fuel needs in these two scenarios (NPHs, RDHs), the country also reduces its electricity net exports to neighboring countries to even higher levels than the current ones in the NPLs, RDLs. The government also assists Kenya in achieving universal electricity access. Hydropower and solar are the dominant fuels in Ethiopia, Kenya, Sudan, Tanzania and Uganda by 2030. Also, as electricity demand increases (NPHs, RDHs) in Tanzania, the government further exploits its domestic coal reserves to increase its coal-based electricity generation from 2022 onwards and decrease its net imports cumulatively by 30% (2015-2030). In the opposite case, under higher electricity demand levels (NPHs, RDHs), Rwanda increased its electricity generation by increasing its gas-based electricity generation from 2021 to increase its electricity exports, primarily to Tanzania and Uganda. However, this energy transition comes at the cost of increasing its carbon dioxide emissions (**Paper-IV**).

Some exporting countries assist importing countries in decreasing their fossil-fuel dependency in the decarbonization scenarios. Zimbabwe is one of the countries that transformed itself from a net exporter in the Reference scenario to a net importer in the decarbonization scenarios to reduce its fossil fuel-based generation capacity, importing on average 14 TWh of electricity annually. Also, the importing countries use imports to decrease their electricity supply costs (e.g., Kenya). Some net electricity importing countries (e.g., Congo) decrease fossil-fuel dependency and reduce water consumption levels (**Paper-III**).

A notable finding of **Paper-III** is identifying some countries as transit traders, including Egypt, Sudan, South Africa and Tanzania (**Figure 18**). Indicatively, under the Reference scenario, Egypt imports 659TWh (94%) of its cumulative electricity imports from Sudan, and also exports approximately 1194TWh (96%) of its cumulative electricity exports (2015-

2065) to Asia. In parallel, 64TWh or 15% of Sudan's total electricity exports are derived from imports of electricity generated in Ethiopia.

These results highlight the importance of an enhanced electricity trading scheme on the continent to reduce greenhouse gas emissions and system costs. Nevertheless, this could come at the expense of increasing water withdrawal and consumption in the main electricity exporter countries in the Reference scenario, particularly Ethiopia, Guinea, South Africa and Zimbabwe, which has consequences for managing their national water. However, countries such as Congo, which increase their electricity net imports in all scenarios, experience a concurrent decrease in water consumption.

In addition, specific gas pipeline projects (e.g., West African, Trans-Saharan) could change the role of certain countries (Algeria, Mozambique, Nigeria) as energy exporters, assisting neighboring countries in transforming their energy sector.

In WAPP, gas is the dominant fuel in the region primarily due to investments in Cote D Ivoire, Ghana and Nigeria by 2030, with an increased share of hydropower in Nigeria, Cote D Ivoire and Guinea, and solar off-grid and mini-grid technologies. As electricity demand rises among the scenarios, Nigeria is estimated to increase its coal-based power generation in 2022. However, the country decreases its net exports between 2015-2030 to satisfy the high increase in its domestic electricity consumption leading the electricity importers Benin and Niger to increase their gas-based and hydropower generation in the future (**Paper-IV**).

In CAPP, as electricity demand levels increase between the scenarios, DRC, except for covering part of its domestic electricity consumption from coal-based power plants and solar hybrid mini-grid systems, imports more electricity from Angola, Congo, Rwanda, and Zambia to maintain its electricity exports at similar levels (cumulatively around 108PJ) (**Paper-IV**).

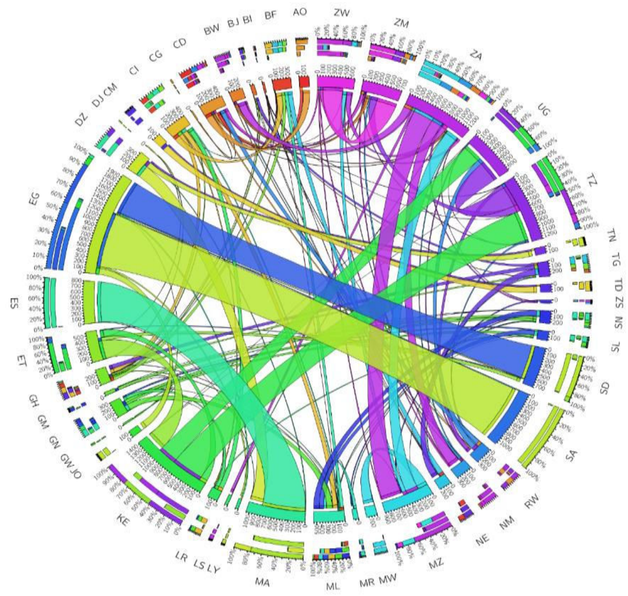


Figure 18. *Cumulative electricity trade (2015-2065) among the African countries in the Reference scenario (in TWh) (Paper-III).*

*The outer circle represents the ISO 3166-1 alpha-2[198] country code of each African country. The three bars (percentage mix), starting from the outlying to the innermost bar, refer to i) exported electricity, ii) imported electricity, iii) the difference between the exported and imported electricity. The colour of the bar (arc), on the inner circle, is specific to the country where electricity is exported or imported from and the scale indicates the absolute values of electricity trade in TWh. Flow bands present the traded electricity among the countries. Flow bands attached to a country's inner circle represent exports from that country and vice-versa. Country codes can be found in **Table 6** (ES: Spain, JO: Jordan, SA: Saudi Arabia). The cumulative electricity trade among the African countries in the 2.0°C and 1.5°C scenarios can be found in Paper III.*

4.4 The influence of water availability in achieving energy security and electricity access in Africa

The earlier results have shown that one of the benefits of renewable technologies, specifically large hydropower projects, is decreasing carbon dioxide emissions and lower water-intensive compared to fossil-fuel technologies. In this section, I discuss the trade-off between energy security, emissions and water use through the availability of water for the purposes of cooling thermal power plants and the operation of hydropower.

In **Section 4.2**, water withdrawals in Africa increase by 2065 as fossil fuels gradually penetrate the power system in the Reference scenario. In the decarbonization scenarios, water withdrawals are lower due to the higher penetration of RET and hydropower. Aside from further increasing evaporative losses in the mitigation scenarios, hydropower creates new opportunities as it is an enabling infrastructure for effective water resources management.

Under limited hydropower-based generation (Dry scenario), higher water withdrawals and consumption are required in Africa due to the higher penetration of fossil fuel technologies. On the contrary, water consumption also reduces in the reference and mitigation scenarios under decreased water withdrawals for cooling purposes. In the Reference scenario, more renewables are required, while in the mitigation scenarios, more nuclear investments.

The three scenarios examined in **Paper-III** that address the influence of water availability in the power system of Africa are presented in ***Table 3***. Specifically, according to a dry and wet scenario, country-specific capacity factors for hydropower plants are considered. Various options are considered for thermal plants with cooling systems with decreased water withdrawal.

In the Reference scenario, by 2065 changes in water availability for hydropower plants result in higher water withdrawal (7%) and consumption (25%) under a Dry scenario, while under a Wet scenario, it results in lower withdrawals (1%) and higher consumption (2%). Compared to the Reference scenario, in 2065, the continental installed capacity under the Dry scenario is higher (1%) and under the Wet scenario it is lower (3%). Under the Dry scenario, the lower hydropower capacity factors mean that coal is more economically competitive, despite increasing water consumption and withdrawal. In the Dry scenario, the lower capacity of hydropower plants (62%) results in a higher capacity of coal power plants (18%) and other renewables (5%) by 2065. On the contrary, higher capacity factors in hydropower plants lead to electricity generation higher in the Wet scenario than in the Reference base scenario. However, to meet the peak demand in 2065, the installed capacity of hydropower plants is lower (17%), while in gas power plants, it is higher (6%).

The levels of electricity trade are estimated to be lower in the Dry scenario and higher in the Wet scenario compared to the Reference scenario due to lower costs of generating electricity on the continent. CAPP is transformed from an exporter in the Reference base scenario to an importer in the Dry scenario, while SAPP from an importer in the Reference base scenario to an exporter in the Dry and Wet scenario due to its coal-based power generation. Due to its hydro and coal-based generation, SAPP increases its exports under the Wet scenario.

Lastly, the changes in water availability affect the costs of generating electricity, with the Reference (Dry) scenario presenting the highest ones and vice-versa. The total system costs related to the power sector are accordingly higher in the Dry scenario (1.4%) compared to the Reference scenario, while in the Wet scenario, it is lower (<1%) during the period 2015-2065.

The 2.0°C (Dry) and 1.5°C (Dry) scenarios correspond to higher water withdrawals and consumptions in the mitigation scenarios. In comparison, wetter ones lead to withdrawals and consumption lower than the respective 2.0°C and 1.5°C base scenarios. To further decarbonize the energy system (1.5°C), higher water withdrawals are required under 1.5°C (Dry) and 1.5°C (Wet) scenarios compared to the 2.0°C scenario combination, respectively. This is due to the higher penetration of nuclear and biomass technologies. However, in the 1.5°C scenario, less water consumption is needed in Dry and Wet scenario compared to the 2.0°C scenario.

As presented in previous sections, the power mix of Ethiopia is primarily based on hydropower in 2015 and by 2065, solar power will be the leading technology, followed by hydropower and gas. Under a dry scenario for the operation of hydropower, the total capacity increases more (by 5GW) than the Reference scenario (86GW) by 2065, while the electricity generation is less due to a higher penetration of gas capacity leading to higher generation costs and water withdrawals. The country remains an electricity exporter in both scenarios. However, the cumulative electricity exports decreased by 50% between the Dry and Reference scenario between 2015-2065. The wet scenario presents results opposite to the Dry scenario, presenting an increase in hydropower, less gas capacity, lower water withdrawals and emissions compared to the Reference scenario, as well as increased cumulative electricity exports of around 50%. Since the power system is primarily based on non-thermal technologies, less water availability for cooling purposes does not significantly affect the evolution of the power mix.

Concluding, water availability can affect the nation´s energy security and electricity access by decreasing hydropower-based generation under a dry scenario in the long-term and less penetration of thermal power plants indicating other RET penetration essential.

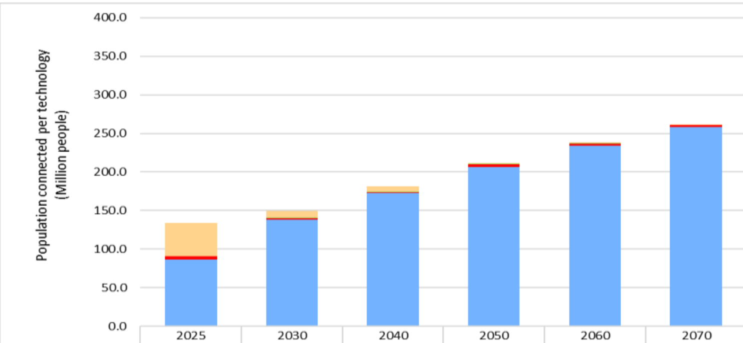
4.5 The role of centralized and decentralized systems in achieving energy security and electricity access in Africa

Hydropower and other large-scale power generation technologies (e.g., natural gas, coal, solar CSP) are grid-connected technologies. Thus, expanding the grid infrastructure is difficult, especially in remote rural areas where infrastructure may not exist to achieve electricity access and socio-economic development in a country. Investments in mini-grid and off-grid systems could overcome this challenge. Distributed generation technologies, off-grid and mini-grid technologies can provide electricity access at a faster rate and lower cost than conventional grid connections enhancing energy security in the country. Also, if the losses in the country's transmission and distribution (T&D) network are quite high (e.g., Ethiopia), investing in non-grid connected technologies and further improving the T&D network may be costly. Lastly, water availability may have less impact on power generation depending on the technology choice.

4.5.1 Ethiopia

Paper-II and **Paper-IV** provide policy insights and electrification split into residential areas in Ethiopia and forty-eight African nations currently un-electrified and total system costs.

In Ethiopia (**Paper-II**), in achieving electricity access in 2025 and continuing to electrify future connected residential areas, the grid-connected technologies cover most of the population in the New Policies scenario (***Figure 19***). Conversely, in the Big Business scenario, under higher electricity demand levels and lower discount rates compared to the New Policies, universal access is achieved in 2042, where we see a higher penetration of mini-grid and stand-alone technologies. In the opposite case, in the Slow Down scenario, there are lower electricity demand levels and higher discount rates than the New Policies, with universal access achieved in 2042, which leads investments in stand-alone solar PV technologies to play a more significant role. Thus, to increase the electrification rates, the penetration of distributed generation technologies in the future power mix is required. A more detailed analysis of the electrification split among the scenarios can be found in Paper-II.

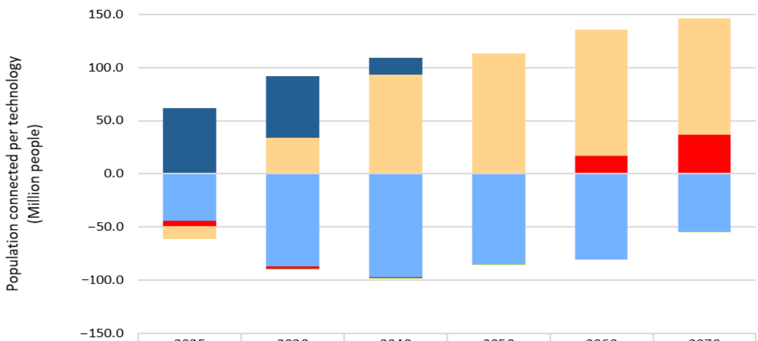


	2025	2030	2040	2050	2060	2070
Stand-alone PV	43.1	9.1	7.0	1.0	0.4	0.3
Hydro Mini-grid	0.3	0.3	0.6	0.9	0.7	0.1
Wind Mini-grid	0.0	0.0	0.0	0.0	0.0	0.0
PV Mini-grid	4.6	2.2	1.2	3.5	2.4	2.6
Grid-connection	86.2	138.1	172.5	206.2	234.3	258.1

Figure 19. *Population (million people) connected per technology (grid, mini-grid, stand-alone) in the New Policy scenario.*

In the Slow Down scenario, the residential electricity demand and the reliance on grid connection are significantly lower than in the New Policies scenario. The considerably lower electricity demand in the Slow Down scenario has a high impact on technology choice. Grid-connection follows a much slower pace, replaced to a large part by stand-alone PV. Furthermore, solar PV mini-grids supply electricity after 2040 as electricity demand increases in more remote areas. A significant share of the population will still have only Tier 1 level electricity demand (5–19 kWh) with an increasing share of Tier 2 (180–230 kWh) and Tier 4 (1870–1910 kWh) electricity demand from 2040 onwards. Therefore, stand-alone solar PV systems would still be the least-cost solution for a large share of the population even by the end of the analysis. Similar to the New Policies scenario, Slow Down shows most of the population with high electricity demand served by the grid (***Figure 20***).

The electricity demand levels, access rates, and future connected population´s distance from the main grid affect the penetration of decentralized technologies in the power mix and, consequently, the nation´s socio-economic development and security of energy supply throughout the years.



	2025	2030	2040	2050	2060	2070
Unelectrified	61.8	57.8	15.4	0.0	0.0	0.0
Stand-alone PV	-12.5	34.2	93.5	113.1	118.3	109.5
Hydro Mini-grid	-0.3	-0.3	-0.6	-0.9	0.6	-0.1
Wind Mini-grid	0.0	0.0	0.0	0.0	0.0	0.0
PV Mini-grid	-4.6	-2.2	-0.4	-0.1	16.7	36.6
Grid-connection	-44.2	-87.0	-97.4	-85.0	-80.3	-54.2

Figure 20. *Newly connected population (million people) per technology (grid, mini-grid, stand-alone) in residential areas in the Slow Down vs New Policy scenario.*

In the Big Business scenario, the residential electricity demand increases slower than in the New Policies scenario, mainly due to a slower electrification rate, but reaches the same level during later years. Between

2025 and 2040, a large share of the population is served by mini-grid (14% in 2040) and stand-alone PV (27% in 2040) technologies, as the grid is focused on supplying the industrial demand over new residential connections in this scenario. A significant increase in grid connections takes place between 2040 and 2050. From 2050 onwards, most of the population will be grid-connected at the lowest cost, and mini-grids will supply remote locations.

The differences in technology split for the three scenarios between 2025 and 2070, between grid-connected, mini-grid and stand-alone technologies are presented in the electrification maps below (***Figure 21***). Corresponding maps for each of the scenarios for intermediate years can be found in **Paper-II**. As electricity demand increases in the New Policies scenario, in the early years, the population supplied by stand-alone technologies had a significantly lower demand per capita. So their share of demand is much smaller than their percentage of the electrified population. However, it is more cost-optimal for the people to connect to the grid as it expands in the long term, as shown in the Figure below. Besides, the high residential demand areas are mostly found close to the existing network. Thus, a small number of mini-grids will be interconnected to the grid in this scenario, especially those that are deployed between 5 km and 25 km grid distance by 2025 to meet the demand in the short term.

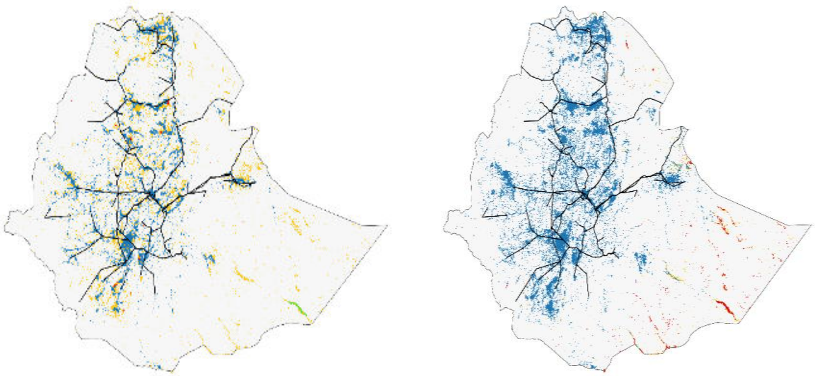


Figure 21. *Technology split in 2025 (left map) and 2070 (right map) in the New Policies scenario. Blue areas are national grid-connected, red ones by mini grids, green by hydro mini grids and yellow by stand-alone PV.*

4.5.2 Africa

Moving from achieving electricity access on a national scale to a continental one (**Paper-IV**) can provide insights into the role of decentralized and centralized technologies considering different countries' energy resources. I show that achieving universal electricity access in Africa and covering the future energy needs of the continent, more fossil fuel-based generation is needed as electricity demand increases at higher levels (NPH, RDH), but lower levels are needed as RET costs decrease by 2030. Natural gas is estimated to be the primary fossil fuel in the continent over the next decade. In the opposite case, hydropower was the dominant renewable power source in 2015. It remains so by 2030 in the low demand scenarios (NPL, RDL), while in the high demand scenarios (NPH, RDH), solar power is the dominant power source (**Figure 22**).

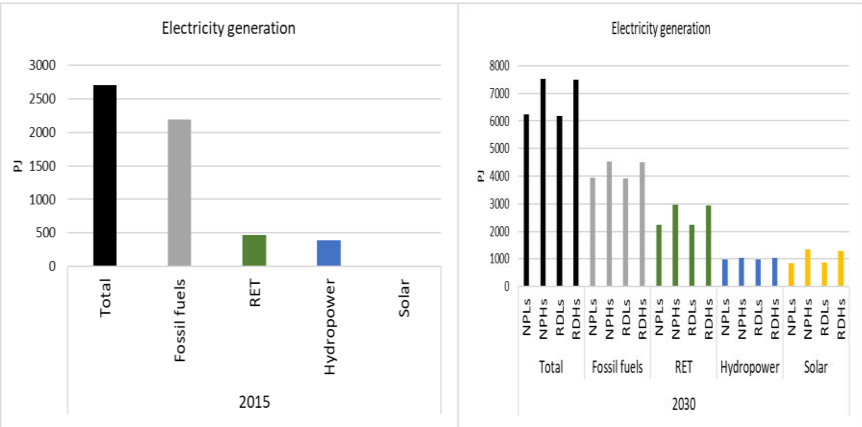


Figure 22. *Electricity generation mix in Africa in each scenario in 2015 and 2030.*

Specifically, solar off-grid and solar hybrid mini-grid are key components in the electrification of the current un-electrified settlements in residential areas. Grid-connected technologies supply most of the total electricity generated in Africa in 2030, depending on the scenario, followed by stand-alone and mini-grid technologies. As the costs of renewables decrease in the Renewable Development scenarios, higher penetration of stand-alone solar technologies is expected by 2030 (**Figure 23**).

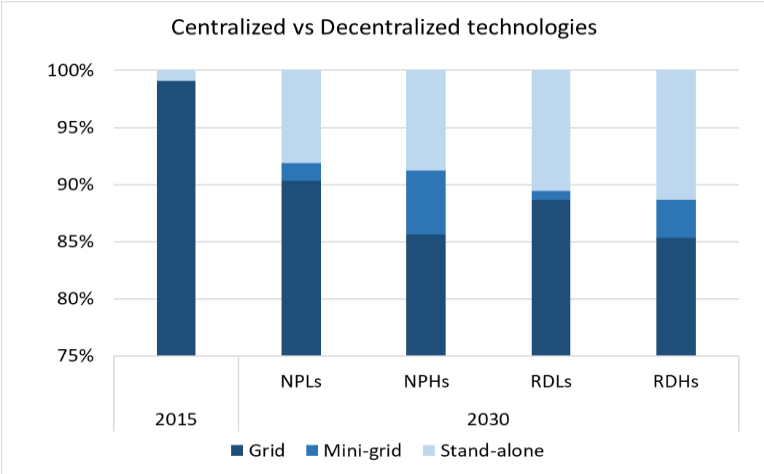


Figure 23. *Share of grid-connected, mini-grid and stand-alone technologies in Africa in each scenario in 2015 and 2030.*

Fossil-fuel-based generation increases among the scenarios in all power pools as electricity demand increases, but the share decreases between 2015-2030. Stand-alone and mini-grid technologies gradually penetrate the power system in each country to achieve universal electricity access by 2030 (**Figure 24**, **Figure 25**, **Figure 26**).

The evolution of electricity generation and electrification mix varies among the power pools since the electricity access levels by country are different (**Figure 27**). Also, the location-distance of the un-electrified population from the grid is different among countries leading to different penetration levels of centralized and decentralized technologies in a cost-optimal way. In WAPP, the small changes in the fossil-fuel share have to do with the electricity trades with the neighboring countries. Also, the stand-alone solar technologies represent 6%-11% of the total generation accordingly to the scenario, while mini-grid technologies up this to 7%. The lower RET costs result in the higher penetration of stand-alone rather than mini-grid technologies. In NAPP, grid-connected technologies decreased from almost 100% in 2015 to approximately 87% in 2030 as stand-alone technologies primarily penetrate the power mix. Only Mauritania is not fully electrified in NAPP. Stand-alone solar technologies play an important role in the country´s energy transition, representing approximately 17%-21%. The lower cost of renewables leads to more grid-connected technologies to supply electricity. In EAPP, stand-alone technologies from 9% in the New Policies scenarios increase up to an average of 12% in the Renewable Development scenarios by 2030. Mini-grid technologies also represent a small amount of the power mix, ranging from 2% to 7%, depending on the scenario. In CAPP, the penetration of coal technologies in the power mix of the Democratic Republic of Congo increased the fossil-fuel share from 38% in 2015 to a range of 34%-45%, according to each scenario by 2030. Solar hybrid mini-grid technologies in this power pool constitute more of the power mix than in other power pools. As renewable costs decrease, stand-alone technologies increase their share from 3% in New Policies to 10% by 2030. In SAPP, grid-connected technologies reduced from almost 100% to 91%-95%, depending on the scenario. Stand-alone solar technologies gradually penetrate the power system in SAPP, reaching from 4% (NPLs) to 8% (RDHs) in 2030 to achieve universal electricity access. The power pool has the highest share of fossil fuel technologies in Africa, primarily due to coal in South Africa and natural gas in Mozambique and Angola.

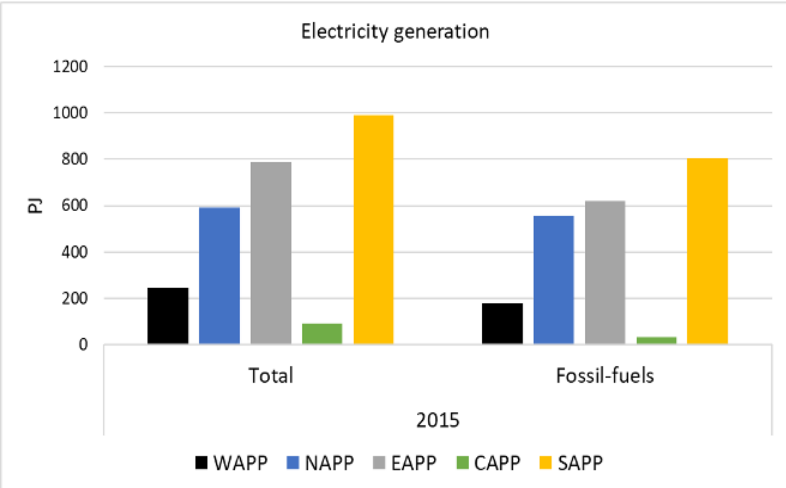


Figure 24. *Electricity generation by power pool in Africa in 2015.*

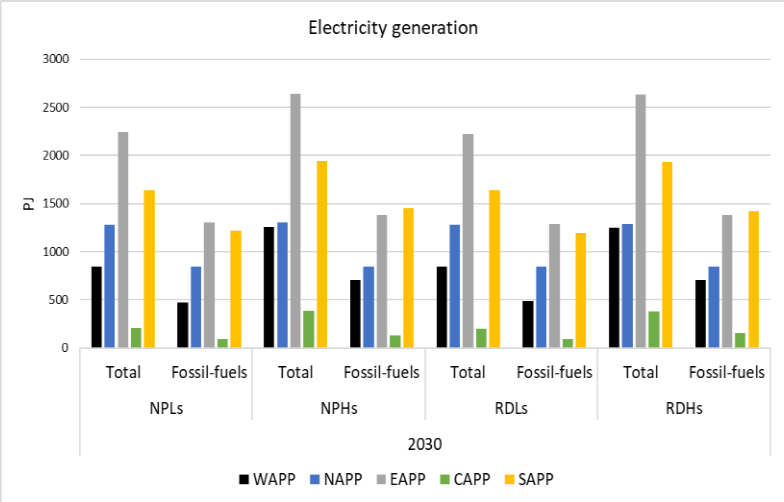


Figure 25. *Electricity generation by power pool and scenario in Africa in 2030.*

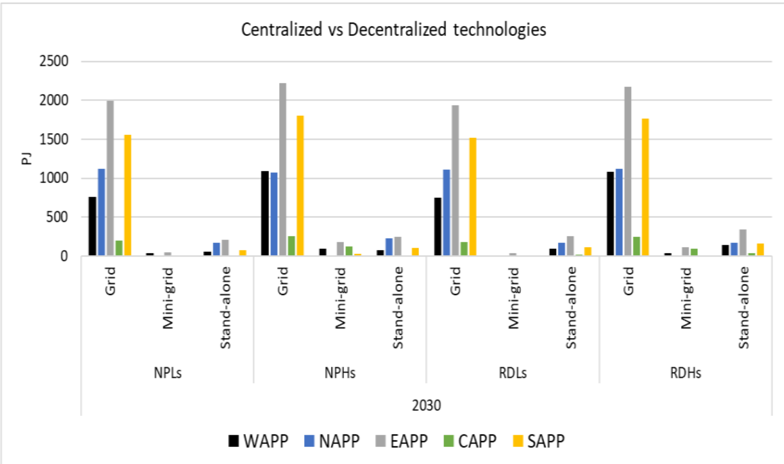


Figure 26. *Electricity generation mix (Centralized vs Decentralized technologies) by power pool and scenario in Africa in 2030.*

Achieving universal electricity access in Africa by 2030 will be expensive. The penetration of solar stand-alone and mini-grid technologies in the future power mix, compared with grid-connected technologies, may be more costly but enhance the energy supply's security if their operation does not depend on the availability of weather. However, their installation does not need investments in expanding the transmission and distribution network and their operational fuel costs are much lower than the fossil-fuel-based technologies.

Financial implications

The minimum total system costs required to fully electrify Africa and cover the future electricity needs in the continent from 2020 to 2030 amount to 3,000BUSD at the Renewable Development Low scenario (lowest electrification level). In the opposite case, the maximum total system costs correspond to 3,500BUSD at the Renewable Development High scenario at the same period. At the New Policies Low and High scenarios, the total system costs are 3,000BUSD and 3,500BUSD, respectively, for 2020-2030. Most of the overall system costs are constituted by the operating fuel ranging from 58%-66% depending on the scenario, as the share of fossil fuels decreases between the Renewable Development and New Policies scenarios. The operation and maintenance costs account for approximately 5% of the total system costs, while the capital costs for transmission and distribution are an average of 9% for the period 2020-2030. As a result, the higher penetration of off-grid technologies in the Renewable Development scenarios leads to lower investments in the T&D network than in the New Policies scenarios. Higher electricity demand levels and lower renewable technology costs lead to higher capital investments in off-grid technologies during 2020-2030. However, higher capital investments in grid-connected technologies are needed in the Renewable Development High scenario. The relatively high costs of the gradual penetration of off-grid systems in the power system of Africa in the Renewable Development scenarios are offset by the lower operating fuel costs and the lower T&D costs (lead by high losses in the T&D network).

Based on the future energy investments of each nation, achieving SDG7 in an African country may have collective implications for several factors (e.g., RET share, CO_2 emissions, energy intensity, the lifetime of fossil fuel resources, import dependency) and achieving one target may have objectives that conflict with others on a local level but also a regional one. Specifically, Benin, Cote D Ivoire, Equatorial Guinea and Ghana are some countries that achieve electricity access and their renewable energy targets by 2030. Nevertheless, this energy transition consumes most of their fossil fuel reserves to cover their future energy needs as electricity demand increases at higher levels. Also, if investments in hydropower are limited to balance the peak demand, other thermal technologies are needed, negatively affecting their net import dependency and energy security in the future. The insights for achieving SDG7 targets and its sub-targets for each country informing the factors mentioned above are presented in **Paper-IV**.

5 Conclusions, future research and impact

5.1 Conclusions

In this thesis, I examine the challenges associated with the energy transition of low-middle-income countries, considering national and global policies. Three research questions were identified, across four papers (**Paper-I – Paper-IV**), to better understand the tensions and trade-offs among the investment decisions in low-carbon technology portfolios for sustainable development. The insights can formulate energy policies and show how energy-systems models by evaluating possible transition pathways could assist in expanding the energy system. The outcomes of this Thesis can support governments in strategic energy planning to identify future renewable energy projects and ensure their financial viability. Data, energy systems models, financing mechanisms, appropriate policies, and an integrated energy-water nexus analysis considering climate change are critical to understanding an energy system's complex interactions for sustainable development.

The energy transition is complex and there are trade-offs associated with new investments in low-carbon technology portfolios for achieving sustainability, addressed in the following research questions.

Research question 1, *"What role do low-carbon technologies and energy trade-links play in achieving energy security and universal electricity access goals in low-middle income countries?"* is addressed in all papers.

The results highlight hydropower and solar PV as key technologies for supporting energy security and energy access goals while remaining consistent with climate change targets.

Hydropower and other renewable electricity can be exported to bolster energy security for the exporting country, although export revenues are eroded by local demand growth and low export prices. The benefits of low-cost electricity provided by cross-border hydropower should be balanced against energy security concerns for the importing country. The research demonstrates the benefits of regional coordination, with trade enabling renewable resources to be harnessed and the electricity transmitted to demand centres. Besides enhancing energy security and achieving electricity access, trade links lower total system costs, transforming countries into key net exporters and transit hubs.

The use of renewable energy technology supports energy access, but the mix of technologies that meet demand evolves and there is a shift from distributed to centralized generation as final energy demand increases (see ***RQ3***).

Hydropower is fully exploited in the long term to enhance energy supply security and achieve energy access goals. However, if electricity storage options are not available, investments in fossil-fuel technologies are needed to provide resilient power grids increasing carbon dioxide emissions.

Research question 2, *"What are the implications of climate change mitigation strategies for energy security and the use of water in energy systems in low-middle income countries*?" is addressed in **Paper III**.

The results highlight higher penetration of hydropower, solar PV, nuclear and carbon capture and storage technologies to achieve deep decarbonization (1.5°C) and security of energy supply in the long term. Although RET decreases carbon dioxide emissions and water use compared to fossil-fuel plants, they require high up-front capital costs offset by the lower operating fuel costs in the long term. Thus, increasing the ambition of climate targets while achieving electricity access results in lower cumulative costs. Besides, a more aggressive energy sector decarbonization (1.5°C) leads to higher water withdrawals but lower water consumption levels than the 2.0°C scenario under lower energy demand levels. As explored in ***RQ1***, countries with large hydropower potential can provide affordable electricity domestically and in neighboring countries with the lowest carbon and water footprint, but this would come at the cost of their domestic available water resources. Investment decisions in large hydroelectricity generation projects cannot be separated from water resource management and electricity trade and require regional coordination across countries, tailored to the local geopolitical and hydrological realities. Although hydropower and RET build climate resilience, hydropower operation depends on climate variability affecting energy security. Thus, mitigation strategies should consider the associated challenges of climate change in hydropower investments. Under conditions of limited water availability, domestic electricity supply and export revenues linked to hydropower generation are reduced, affecting energy security and leading to higher penetration of fossil fuel technologies. Under decreased availability for water withdrawals for cooling power plants, water consumption of the energy transition reduces due to higher investments in RET, increasing overall capacity. Thus, the RET resource-based nations assist other fossil-fuel-based countries in covering their future electricity needs through trade links decreasing overall electricity trade in an interconnected trading scheme.

Research question 3 *"How can centralized and decentralized systems assist in achieving energy security, energy access and job creation in low-middle income countries?"* is addressed in **Paper-II** and **Paper-IV**.

I show that off-grid and mini-grid systems are key complements to national-grid expansion when pushing for universal energy access. Distributed generation technologies, off-grid and mini-grid technologies can provide electricity access at a faster rate and lower cost than conventional grid connections enhancing energy security, energy access and socio-economic development in the country. Higher electricity demand levels lead to higher penetration of off-grid and mini-grid power systems in the short term, while lower renewable costs still lead to higher penetration of these systems by 2030 in Africa. The penetration of solar off-grid and mini-grid power decreases overall investments in the transmission and distribution network and reduces operating fuel costs towards achieving energy access. Hydropower and other RET are grid-connected technologies. Thus, it is not cost-optimal in some cases to expand the T&D network to supply electricity to the un-electrified settlements in the residential areas using RET-centralized based instead of investing in decentralized technologies. The penetration of renewables in the power mix of a nation except providing low-cost electricity (depending on the technology) than the fossil fuel technologies (see ***RQ1***), being less carbon and water-intensive (see ***RQ2***), also has socio-economic benefits by creating more jobs. Potentially achieving climate change targets in the future (e.g., 2.0^{o}C, 1.5^{o}C), more jobs could be created in Africa, meaning that more jobs can ensure political and societal stability.

Concluding, energy systems in their transition need to be affordable, reliable and sustainable (e.g., energy secured, combat climate change) by being climate-resilient. The thesis findings demonstrate that nations need integrated energy planning, accounting for the geospatial characteristics of energy technologies, and water resources management to achieve SDG7 and build climate-resilient (SDG13). A broad portfolio of renewable technologies, interconnectors and a decentralized power generation system providing electricity closer to the end-user demand is needed to enhance energy security, decrease environmental pressures and provide affordable electricity for a nation. Decision-makers must consider the financial viability of the economic potential of investing in a large hydropower project, policies for resettlements, hydrological uncertainties, as well as geopolitical challenges. Governments need to invest rapidly in a broad portfolio of zero-carbon technologies to limit global warming, address the associated aspects of decarbonizing their energy system and not lock in into needless and costly infrastructure in the long term. Also, government policies are a core aspect of sustainable development and are required to promote sustainable development and global connectivity among stakeholders, government officials, research analysts and the scientific community. Partnerships and cross-sector collaboration are required to transition to a low-carbon economy. The outcomes of this thesis can be used to inform SDG2, SDG3, SDG6, SDG8, the National Determined Contributions (NDCs) for development and Africa´s Agenda for strategic framework [13], [102], [133].

5.2 Thesis contributions

In **Table 5**, this thesis's contributions to the scientific community are presented and categorized in terms of methodological and applied analytical advances, new data, insights, and impacts.

Table 5. *Thesis contributions.*

Methodological and applied analytical advances
• The first open-source, bottom-up cost-optimization study for Paraguay using a long-term energy planning tool, soft-linked with an accounting project finance model in academic literature.
• The first open-source, bottom-up study for energy planning for Ethiopia soft-linking a cost-optimization long-term energy planning tool with geospatial analysis in academic literature.
• The first open-source, bottom-up energy system model for Africa which contains the energy supply system, focusing on the power sector, of 48 countries interconnected with electricity and gas trade links to combat climate change (SDG13). ➢ Results are provided on a national and continental level on an annual basis (2015-2065): Water withdrawal and consumption, energy supply, CO_2 emissions and financial requirements. ➢ Detailed results are provided for climate change mitigation measures for the energy system of 48 African countries. ➢ Four cooling types for thermal power generation technologies are included in the analysis ➢ Water factors are accounted for in the energy system model for the fuel processing and cooling purposes of estimating water withdrawal and consumption ➢ The fuel demands of all sectors are included in the analysis.
• The first open-source, bottom-up energy system model for Africa which contains the energy supply system, focusing on the power sector, of 48 countries interconnected with electricity and gas trade links to achieve universal electricity access (SDG7).

➢ Results are provided on a national and continental level on an annual basis (2015-2030) regarding energy supply, CO_2 emissions and financial requirements focusing on achieving universal access ➢ A geospatial electrification outlook considering the location and size-specific characteristics for power generation technologies is included ➢ Over twenty centralized and decentralized generation options are addressed ➢ Job creation potential of achieving universal access is estimated ➢ SDG7 and its sub-targets are informed
• Methodology to develop an OSeMOSYS model, specifically for large input data-modelling assumptions, using a Microsoft Excel-based interface and Python programing techniques.
New data and insights
• Estimated national revenues for Paraguay through electricity exports from the Itaipu Dam to Brazil and assessment of the security of energy exports.
• Insights into decentralized and on-grid technologies to achieve electricity access by considering energy modelling together with geospatial analysis to support electrification pathways in Ethiopia and Africa.
• Insights into the effects of climate change mitigation strategies on the energy system of Africa and its associated water footprint.
• Insights into technology options for achieving low-cost universal electricity access in Africa (SDG7)
• Estimated energy indicators for sustainable development (energy security, environmental sustainability, cost of generating electricity) for each African country.
• Estimated the annual energy requirements of 48 African countries over mitigation scenarios for the period 2015-2065.
• Estimated the annual water withdrawal of 48 African countries over mitigation scenarios for the period 2015-2065.
• Estimated the annual water consumption for 48 African countries over mitigation scenarios for the period 2015-2065.
• Insights into achieving universal access in Africa under different electricity demand and techno-economic parameters.
• Open-source datasets for the energy supply system of each African country and Paraguay.
• Open-source datasets for the different cooling types of thermal power plants in Africa.
Impacts

• The Africa model formed the technical report "Energy projections for African countries" for the Joint Research Center of the European Commission.
• The model developed for Paraguay (Paper-I) used in capacity-building activities, in partnership with the UN, to train analysts and policymakers on the use of open-source tools for energy systems planning.
• The open-source model developed for Ethiopia (Paper-II) enhanced the modelling and analytical capacity of academic and research institutions, and government institutions such as the Ministry of Energy, Water and Irrigation (MoWIE) and development organizations.
• The model developed for Africa (Paper-III) assisted in expanding the knowledge in energy planning through the use of open-source modelling tools (Osemosys) to groups of policymakers, researchers, and practitioners involved in policy and decision making through capacity building activities (CLEWs summer schools 2017, 2018; UNECA workshop; EMP-A 2019)
• The open-source datasets assisted in developing future energy models for each African country (lack of data in this field)

5.3 Limitations and Future work

Beyond the scope of this thesis, there are some limitations and further work associated with each research study that could be further examined in the future.

Such as, there are challenges associated with the uptake of RET in the future power mix, and storage is one of them as an enabler of their penetration. Solar, wind, and other RET, alongside the need for storage technologies, are expected to increase the demand for rare minerals required to produce them, like lithium, cobalt, nickel, and many more. This demand for rare minerals may cause geopolitics in the future since the Democratic Republic of Congo is the biggest cobalt supplier globally and Zimbabwe is a global producer of lithium and copper. This type of analysis is not conducted in this Thesis, but the modelling results of **Paper-I** and **IV** can be used as inputs to conduct it in the future.

In **Paper-I** (Paraguay), other sectors except for electricity, such as transport and residential, could be explicitly modelled to provide more insights into the nation's energy transition. Trade links with other neighboring countries, demand-side management, energy efficiency measures and consumer behaviour could also be considered. Furthermore, analyzing the demand drivers can provide insights into the evolution of electricity demand. In **Paper-II** and **Paper-IV**, the penetration of decentralized technologies into the country's power system will play a complex role that needs to be examined in greater detail [199]. Trade-offs exist, for example, with potable, industrial and agricultural uses of water [42], [59], but also with climate variability. In **Paper-III**, combining agricultural and municipal water withdrawals [200] for each African nation with our results would show the impact of the scenarios upon levels of water-stress [201]. Linking a water-systems model to the energy-system model of this study would provide insights into the resilience of the African continent in terms of water and energy under climate change which could also inform the study conducted in **Paper-II**. The study does not consider the influence of water temperatures on water availability for power plant operation. Better data (e.g., country available information on future power plant investments, cooling types) and spatial techniques (e.g., soft-link with GIS) could help identify and allocate the individual cooling technologies for future thermal power plants. Also, by incorporating country-specific reserve margins rather than using an average, the power sector projections would improve the representation of national energy systems (also in **Paper-IV**). Lastly, the costs of energy efficiency measures and reduction in energy service provision are not endogenously accounted for in the model. In **Paper-IV**, limitations include country-specific hydro capacity factors and represent hydropower plants individually instead of aggregating them per size. Better data and spatial techniques could enhance the modelling results. Disaggregate the final energy demand in sectors and exogenous assumptions around fuel switching and efficiency improvements. Including oil and coal export analysis is currently excluded from this and **Paper-III**´s analysis. Another limitation in this thesis is the climate change mitigation scenarios developed in **Paper-III** are modelled as emission reduction targets limits on a regional and not country level due to lack of data.

In all papers, the sub-annual time resolution could be further increased to better capture the variability in the electricity generated by renewable technologies. However, this is prevented due to the limitation of other input data associated with the model. Battery storage for solar PV and pumped hydropower storage are only implicitly modelled. The broader social and environmental effects of hydropower and nuclear power should be further examined to better understand the implications of those technologies. Also, the COVID-19 pandemic represents an uncertainty that impacted not only the energy system but also the economy of African countries [202], [203].

The models used in this thesis are deterministic and the uncertainty surrounding future electricity demand, fuel prices, and technology costs projections could be further examined through a sensitivity analysis to quantify and gain a formal understanding of the implications in the electricity supply system. The soft-linking with other energy and socio-economic modelling tools can provide further policy insights in this analysis and capture various aspects of the energy and socio-economic transition. Future work could also include some detailed discussions on sensitivity to discount rates. There is always a debate in the scientific community on the discount rate used when modelling resource systems. A sensitivity analysis will shed some light on this aspect.

Dagnachew, A., (2017, 2021) [120], [204] conducted a sensitivity analysis for the cost of diesel fuel and transmission and distribution network to examine how these parameters affect the model results of achieving universal access in Africa since projections vary among studies. He pointed out that the cost of diesel has very little impact on the share of decentralized and centralized electrification systems for all levels of electricity consumption. However, the costs of the network components have a visible effect on the share of the electrification systems at low consumption levels and a relatively minor impact at higher levels of consumption. **Paper-IV** does not analyze these aspects, which could better understand the parameters affecting decentralized technologies' penetration to achieve universal access in Africa. Examining the influence of diesel costs and the costs of the network components in power system expansion could also provide further insights into job creation potential in Africa. Furthemore, **Rocco et al. (2021)** [205] investigated four exogenous model parameters affecting the achievement of universal electricity access in Tanzania: electricity demand, discount rate, grid rate and the evolution of the domestic price for natural gas. Grid rate indicator is defined as the yearly electricity ratio, centrally generated or imported, and the total electricity produced within the country. However, a sensitivity analysis showed that the share of the population connected via stand-alone systems increases when considering stand-alone systems of larger size and lower costs. The electricity demand assumptions significantly affect the average specific investment costs with relative changes depending on the scenario. More is needed with less penetration of stand-alone systems in that scenario. The insights of the influence of the electricity demand assumptions in the average cost of generating electricity and power mix are similar to those in **Paper-IV**. The discount rate affects investment costs and emissions for all the scenarios. Lower discount rates correspond to higher investment cost per unit of electricity generated, and this strongly affects the technology mix, leading to low carbon-intensive technologies in all scenarios. The grid rate parameter has a relatively smaller effect on specific investment costs compared to other parameters and modifies CO_2 emissions significantly. Low grid rates indicate higher penetration of off-grid technologies and reduce carbon dioxide emissions. This outcome is also shown in **Paper-IV**. High projections for the domestic price of natural gas result in lower CO_2 emissions in the environmental policy scenario.

Otherwise, Tanzania's gas-fired-based power system is not considerably affected by a fluctuation in gas prices. This analysis could complement the studies conducted in **Paper-III** and **Paper-IV**, specifically for gas-based nations, to show how changes in gas prices and discount rates could affect decarbonization and achieve universal access in Africa. **Mosknes**, **N. (2017)** [173] conducted a similar study only for Kenya and did a sensitivity analysis of discount rate and grid cost. She concluded that an increased discount rate would favor technologies with a low capital cost, such as natural gas and coal, while in the opposite case, geothermal and solar utility. Also, the grid cost affects the share of settlements that will get connected to the grid. A lower grid cost increases the grid-connected population and depending on each technology´s generation cost, the power mix changes. Nevertheless, in **Paper-IV**, we show that although the grid cost may be lower in the Renewable Deployment scenario, a lower capital cost of renewable technologies leads to higher penetration of stand-alone technologies (e.g., solar).

Lastly, all the studies are open source (data, model, code, results). The input data could be updated in the future to improve the accuracy of the modelling results further, assisting in transparency and freely reproducibility of the research. The reliability of more technologies than the ones examined in this thesis, such as green hydrogen and smart-grids could be investigated to examine their impact on achieving sustainable development. Also, more sectors could be modelled in detail, such as the transport sector and residential water heating and cooking appliances to include all end-users services demands. Carbon tax budgets may also be an option to assist sustainable development in Africa but the low emissions and the imposed RET targets in the continent prevent this option. Lastly, energy justice needs to be considered in the future transformation of energy systems [206].

5.4 Impact of the thesis

The study conducted for Paraguay (**Paper-I**) was developed in collaboration with the United Nations Division of Economic and Social Affairs (UNDESA) and the government of Paraguay to form the first-open source least-cost power system expansion model for the country. The model is also used in capacity-building activities, in partnership with the UN, to train analysts and policymakers on using open-source tools for energy systems planning to enhance the in-country knowledge in energy planning.

The open-source energy system model developed for Ethiopia (**Paper-II**) enhanced the modelling and analytical capacity of academic and research institutions, government institutions such as the Ministry of Energy, Water and Irrigation (MoWIE) and development organizations in Ethiopia. The model was also transferred to local authorities (University of Addis Ababa Institute of Technology, MoWIE) to be used for future studies.

The open-source Africa model developed in **Paper-III** formed the technical report "Energy projections for African countries" for the Joint Research Centre of the European Commission. It also enhanced human capacity and institutional development towards a sustainable energy future since the model was used to train groups of policymakers, researchers and government analysts from Africa in summer schools (2017, 2018, 2019) at the International Centre for Theoretical Physics (ICTP) in Trieste, Italy[3] and the Energy Modelling Platform for Africa (2019)[4] in Cape Town, in collaboration with UN agencies and the World Bank, by extracting country-specific starter models.

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7 Appendix

The following table presents the list of African countries of which the energy supply system is modelled in **Paper-III** and **Paper-IV**.

Table 6. *List of African countries per power pool considered in Paper-III and IV (with the ISO 3166-1 alpha-2 and alpha-3 accordingly [198] country code in brackets).*

Central Africa (CAPP)	**Eastern Africa (EAPP)**	**Northern Africa (NAPP)**	**Southern Africa (SAPP)**	**Western Africa (WAPP)**
Cameroon (CM)	Burundi (BI)	Algeria (DZ)	Angola (AO)	Benin (BJ)
Central African Rep. (CF)	Djibouti (DJ)	Libya (LY)	Botswana (BW)	Burkina Faso (BF)
Chad (TD)	Eritrea (ER)	Mauritania (MR)	Lesotho (LS)	Côte d'Ivoire (CI)
Congo (CG)	Ethiopia (ET)	Morocco (MA)	Malawi (MW)	Gambia (GM)
Democratic Rep. of Congo (CD)	Kenya (KE)	Tunisia (TN)	Mozambique (MZ)	Ghana (GH)
Equatorial Guinea (GQ)	Rwanda (RW)		Namibia (NM)	Guinea (GN)
Gabon (GA)	Somalia (SO)		South Africa (ZA)	Guinea Bissau (GW)
	Sudan (SD)		Swaziland (SZ)	Liberia (LR)
	South Sudan (SS)		Zambia (ZM)	Mali (ML)
	Tanzania (TZ)		Zimbabwe (ZW)	Niger (NE)
	Uganda (UG)			Nigeria (NG)
	Egypt (EG)			Senegal (SN)
				Sierra Leone (SL)
				Togo (TG)

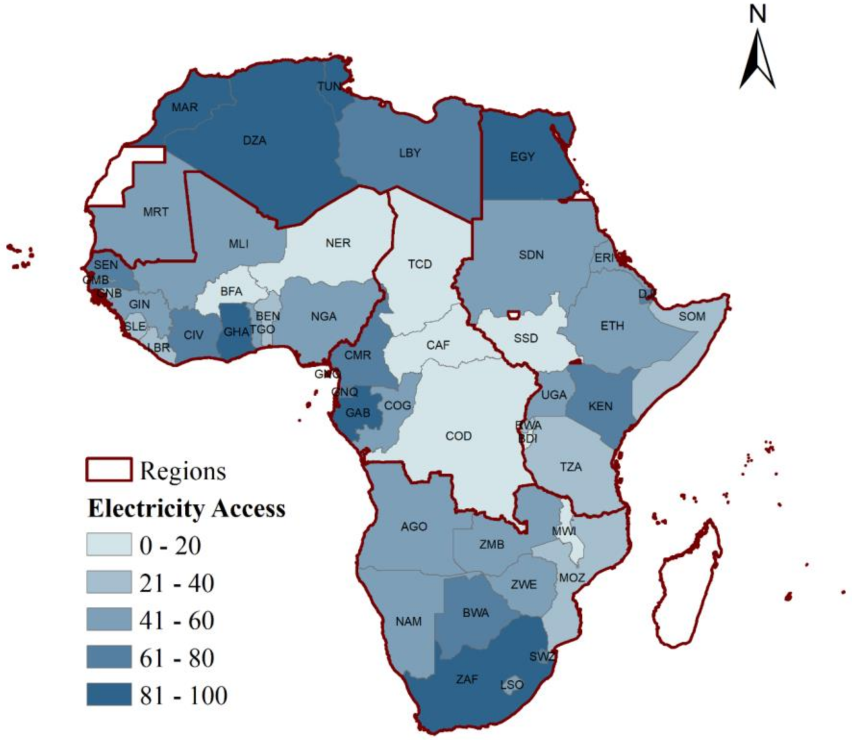

Figure 27. *Electricity access levels by country in 2019 [215] (Note: The detailed list of African countries per power pool included in the analysis is presented in Table 6*