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Creation of a pan-African energy planning model for development of long-term strategies

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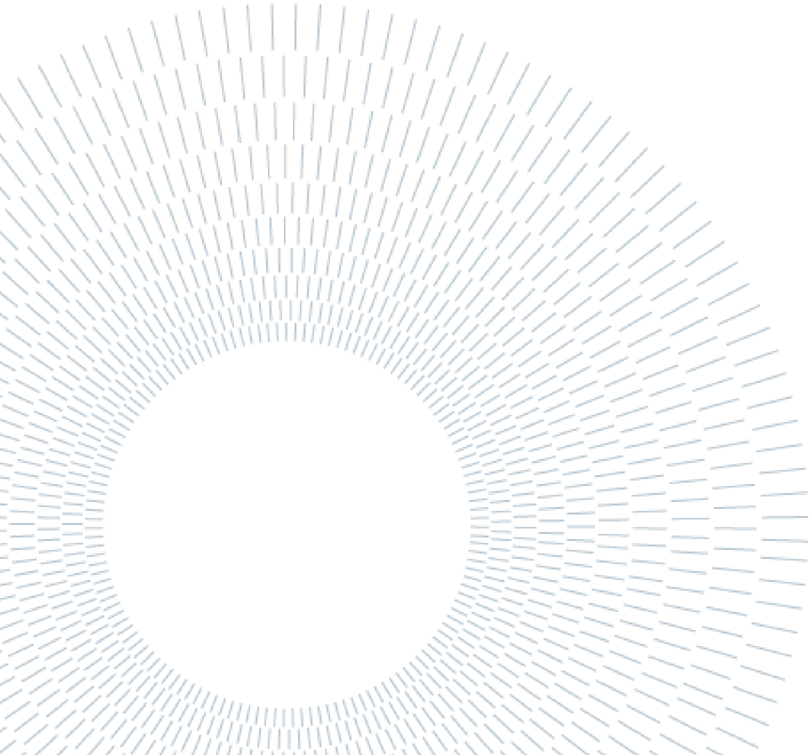


Abstract

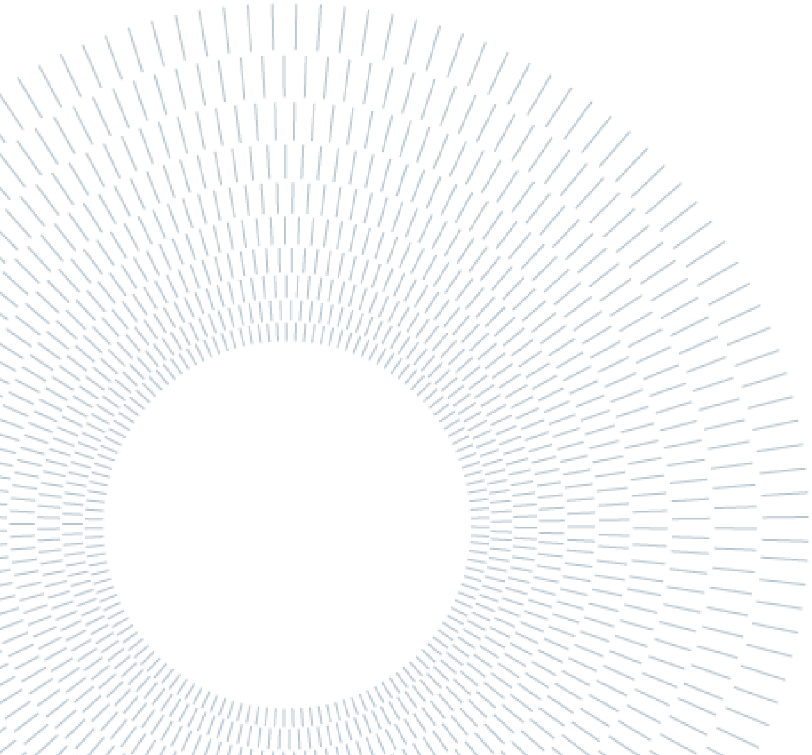
Africa power sector is still underdeveloped and the continent suffers of limited electricity supply and access to electricity. Nevertheless, Africa has been experiencing substantial economic and demographic growth over the last years, which have been accompanied by increasing electrification rates and expansion of power systems. In a context where climate change has become one of global fundamental concerns, the path that the continent will choose to meet its growing electricity demand will affect the entire world. Energy policy can have an essential impact on the evolution that the electricity sector will undergo, but it should always rely on technical findings. Energy planning based on results from accurate energy models can give a valuable support in designing effective energy policies. In this project, a new energy model, named CalAMo (Calliope Africa Model), is created to describe the existing Africa power system and to optimize its expansion under a set of different scenarios. CalAMo is a multi-nodal dynamic bottom-up energy model created in the Calliope environment. Calliope offers great flexibility since it allows to customize technologies and problem constraints and can be used in operational mode, which optimizes the operation of the existing power system, and in planning mode, which, besides operating it, installs new capacity of most suitable technologies to meet imposed constraints. Particular attention is dedicated to VREs. Every on-grid VRE power station in Africa is modelled in its actual location, considering its specifications and local availability of the utilized resource. The model is validated by comparing its results for the existing power system with data from IEA, to verify that they are representative of the real energy system. Findings show results are descriptive of the actual system, with minor variations mainly because of differences in climatic years. CalAMo is then used to study scenarios for 2040 based on different demand projections from IEA's Africa Energy Outlook. Further scenarios are analysed imposing a CO_2 cap that complies with a 1.5 °C increase of global temperature. Investment costs resulting from scenarios with an emission cap result significantly higher than in unconstrained scenarios, while total costs are only marginally higher in most regions. This suggests that constraining expansion of the power system with an emission cap does not result in significant costs increase, but policies to stimulate investments in low-emitting technologies could be required.

Keywords: Energy Planning in Developing Countries, Energy transition, Energy modelling in Africa, Optimal Electrification Strategies, Electric Grid Expansion.

Abstract in italiano

Il settore energetico africano è ancora sottosviluppato e il continente soffre pesanti limitazioni in termini di fornitura elettrica e accesso all'elettricità. Tuttavia, negli ultimi anni l'Africa ha registrato una notevole crescita economica e demografica, accompagnata da un aumento dei tassi di elettrificazione e dall'espansione dei sistemi energetici. In un contesto in cui il cambiamento climatico è diventato uno delle principali preoccupazioni a livello globale, il percorso che il continente sceglierà per soddisfare la sua crescente domanda elettrica influenzerà il mondo intero. Le politiche energetiche possono avere un impatto importante sull'evoluzione che subirà il settore dell'elettricità, ma queste dovrebbero sempre essere basate su risultati tecnici. La pianificazione energetica basata su risultati di accurati modelli energetici può fornire un valido supporto nella creazione di politiche energetiche efficaci. In questo progetto, viene creato un nuovo modello energetico, denominato CalAMo (Calliope Africa Model), per descrivere il sistema energetico africano esistente e ottimizzare la sua espansione sotto una serie di diversi scenari. CalAMo è un modello energetico bottom-up dinamico multi-nodale creato nell'ambiente Calliope. Calliope offre una grande flessibilità in quanto consente di personalizzare le tecnologie e i vincoli del problema e può essere utilizzato in modalità operativa, che ottimizza il funzionamento del sistema energetico esistente, e in modalità di pianificazione, che installa nuove capacità delle tecnologie più idonee a soddisfare i vincoli imposti. Particolare attenzione è dedicata alle energie rinnovabili variabili. Ogni impianto rinnovabile collegato alla rete africana è modellato nella sua posizione reale, considerando le sue specifiche e la disponibilità locale della risorsa utilizzata. Il modello viene convalidato confrontando i risultati ottenuti per il sistema energetico esistente con i dati della IEA, per verificare che siano rappresentativi del sistema reale. La descrizione data dal modello risulta essere rassomigliante alla situazione reale, con differenze minori dovute principalmente a differenze tra anni climatici. CalAMo viene quindi utilizzato per studiare scenari per il 2040 sulla base di diverse proiezioni della domanda derivate dall'Africa Energy Outlook della IEA. Vengono analizzati ulteriori scenari che impongono un limite sulle emissioni di CO_2 conforme ad un aumento della temperatura globale di 1,5 °C. I costi di investimento derivanti da scenari con un limite sulle emissioni risultano significativamente più elevati rispetto a quelli negli scenari non vincolati, mentre i costi totali sono solo leggermente più elevati nella maggior parte delle regioni. Ciò suggerisce che limitare l'espansione del sistema energetico con una soglia sulle emissioni non comporta un aumento significativo dei costi, ma politiche per stimolare gli investimenti in tecnologie a basse emissioni potrebbero essere necessarie.

Parole chiave: Pianificazione Energetica in Paesi in via di Sviluppo, Transizione Energetica, Modellazione Energetica in Africa, Strategie Ottimali di Elettrificazione, Espansione della Rete Elettrica.



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1 Introduction

In a global context of increasing population, fast economic growth in developing countries and rising concerns about the impact on environment of human activities, energy transition has become one of the most urgent focuses of political programs. In 2015 the UN released its 2030 Agenda, a plan that aims to end poverty and hunger, to reach widespread prosperity and safeguard the environment. [1] The Agenda includes 17 Sustainable Development Goals (SDGs), among which the SDG7 is dedicated to energy and it states the ambition to "ensure access to affordable, reliable, sustainable and modern energy for all". [2] In its targets it is highlighted the importance to "increase substantially the share of renewable energy in the global energy mix" (Target 7.2) and "expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries " (Target 7.b). [2]

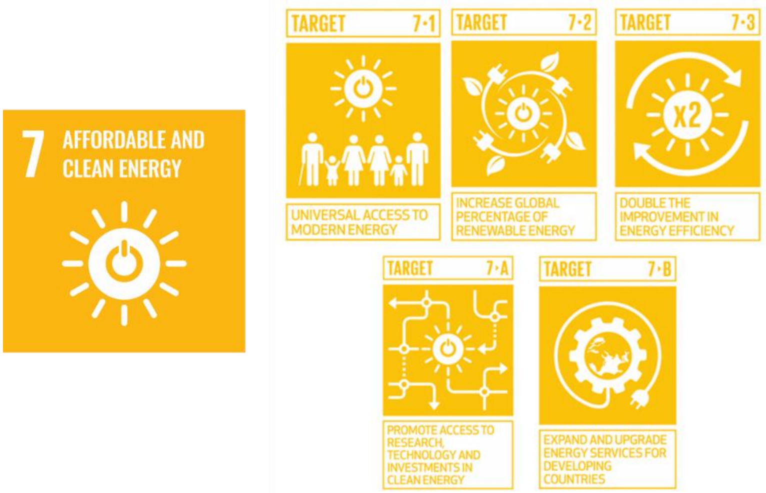

Figure 1.1: SDG7 and its related targets. [2]

Anyhow, this process presents many challenges, that could slow down energy transition and hinder to reach other SDGs, as the availability of sustainable and reliable energy supports all sectors, from agriculture to education. [3] Adequate instruments are therefore required to fulfil SDG7 and implement energy transition efficiently, also creating opportunities for economic growth and employment. [4]

1.1. Main challenges in the energy sector

The energy sector is a major contributor to climate change as its emissions amount to more than two thirds of global greenhouse gas emissions. [5] It is agreed that to avoid the worst effects of climate change, global temperature should not rise more than 1.5°C with respect to preindustrial levels. [6] The IPCC stated that to achieve this goal, greenhouse gas emissions should peak before 2025 and should be reduced by 43 % by 2030. [7] These premises underline the importance to switch towards energy systems based on low-carbon technologies as fast as possible, anyhow various challenges could impede to reach this achievement. Though investment in sustainable generation technologies is of vital importance to be able to comply with environmental targets, for many developing countries "affordable energy access remains a key priority as does the need to power economic growth". [8] According to IEA, in 2021 770 million people still did not have access to electricity, the 77 % of them living in Sub-Saharan Africa. [9] Moreover, it is estimated that approximately 100 million people could not afford to pay electricity bills due to the impact of the COVID-19 pandemic. [8] It is therefore important for new sustainable technologies to be deployed on a large scale to not impose further costs on poor consumers who cannot afford to pay for them. [8] In the decade 2010-2020 the cost of renewable generation technologies (excluding hydro and geothermal) fell abruptly. In particular the cost of utility-scale PV plants dropped by 85 %, while the cost of onshore wind diminished by 56 %, both becoming cheaper than the cheapest fossil fuel power station. [10]

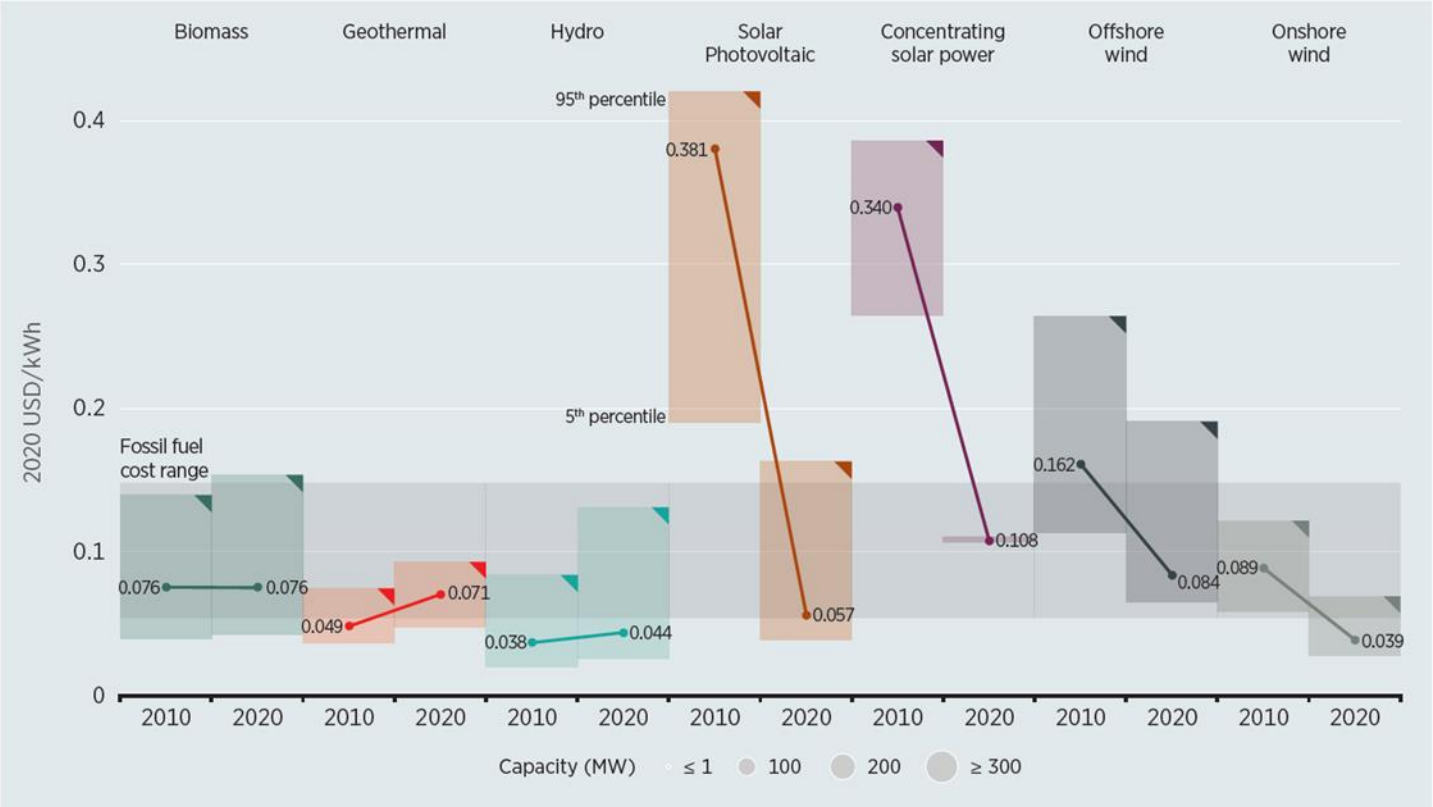

Figure 1.2: Trend of LCOEs for utility-scale renewable technologies from 2010 to 2020. [10]

In most cases developing countries do not have enough money to implement adaptation strategies to climate change. That is why cooperation between developed and developing countries remains a theme of paramount importance. Though pledges were made already in 2009 by developed countries to give as much as 100 billion USD a year by 2020 to help developing countries to face challenges deriving from climate change, this threshold has not been met. [11] Moreover, this amount is not considered to be enough to face necessary expenses to adapt to climate change and by 2018 three-quarters of governmental help was given in the form of loans, creating a further problem for many heavily indebted countries. [11] For these reasons, this theme was one of the main concerns at COP26, held in Glasgow in 2021. But even though the initial objective of developing countries at the conference was to urge developed countries to double their help by 2025 (with respect to 2019 levels) and reach 1 trillion USD a year by 2030, at the end only a vague "increase" was pledged. [11]

In the meanwhile, energy demand is growing so fast that even though current policies are stimulating a fast growth of electricity generation from renewables (8 % growth in 2021, more than 6% in 2022), it is still not sufficient to cover new demand. In 2021, 45 % of additional demand was covered through fossil fuel generation and this share is set to be 40 % in 2022. [12]

A substantial part of required investment to create sustainable energy systems is intended to the expansion or creation of electric grids that adapt to decentralized and intermittent renewable generation technologies. [8] Another important focus to allow increased renewable penetration is energy storage, which is needed to stabilize the grid and meet electricity demand even when variable renewable energy sources are not available. Though many technologies are still in the development phase, costs have been decreasing drastically (for example Li-ion batteries cost decreased by 60 % between 2014 and 2017), while performances have been improving over the last years. It is estimated that by 2030 175 GW of batteries and 235 GW of pumped hydro should be installed. [13], [14]

Another fundamental theme in the framework of energy transition is energy security. Energy security can be defined in various ways, for example it is described by IEA as "the uninterrupted availability of energy sources at an affordable price", while the US Department of State identifies it as the "access to diversified energy sources, routes, suppliers [to limit] the influence of a single dominant buyer, seller, or investor and guards against those who would use energy for coercive ends". [15] The main threats to energy security are due to natural disasters, geopolitical issues, effects of climate change, fuel price fluctuations and limits related to generation and transmission technologies. [15] Renewable technologies present in this case some opportunities, as they allow to differentiate the generation mix, to reduce the dependence on fossil-fuel exporting countries and to stabilize the price of energy, as they are not subject to fossil fuels price fluctuations due to market and geopolitical instability. [15] Furthermore, a decentralized energy system is more resilient to threats as a modular system is easier to repair and allows islanding, that is the possibility to isolate a distributed power source to continue to provide power locally, even in the case of main grid disruption. [15] Anyhow, even in this context some challenges must be faced, as reliance on variable energy sources imposes to have an adequate storage and/or backup system in place to grant adequate energy supply in any moment. [15] Another issue is the control over supply chains of low-carbon and renewable technologies to avoid excessive dependence on single countries. For example, by 2019 China was responsible of about 60 % of production and nearly 90 % of refining of rare earths, which are essential for example for permanent magnets in wind turbines. [8], [16]

1.2. Energy planning

Considering the complexity and urgency of all the challenges introduced in the previous section, coordinated measures must be undertaken to allow a quick and efficient energy transition. Since energy is used in every area of the economy, it influences the costs to which industries, transportation, commercial activities and final customers are subject. [17] Consumers choose the best technology to cover their energy needs basing primarily on technical and economic feasibility, but they are as well heavily influenced by policies in place. [18] Public opinion plays an important role too and according to the UNDP's The Peoples' Climate Vote survey, covering about 56 % of world's population, 53 % of the respondents supported urgent climate policies about increasing reliance on renewable energy sources. [19] To meet the ambitious objectives regarding the energy sector technical support is essential when creating new policies, which should always derive from a process of energy planning.

Energy planning can be defined as the process aiming to determine the optimal energy sources to meet a forecasted demand, taking into account technical, economic, social, political and environmental factors. It should be based as well on existing historical energy data for the location under study. Energy planning should foster diversification of energy generation and energy security and, most importantly, it should always aspire to sustainable development. [20]–[23]

The main purpose of energy planning is to support decision-makers on short and long-term energy strategies through the generation of scenarios and to discuss on the best ways to develop energy systems. [24]

1.3. Energy modeling to support energy planning

For energy planning to be effective, it must be based on scenarios and optimizations realized using energy modeling tools with the adequate characteristics, starting from reliable data describing the energy situation as is. Energy models can vary their features according to their purpose, to their temporal and spatial scale, to the focus on specific sectors or technologies. [25]

As a first distinction, energy models can be divided into top-down and bottom-up models. Top-down models are characterized by a low-detail representation of the various components of an energy system, as their focus is the interaction of energy systems as whole with other macroeconomic sectors to determine the social and economic effect of new policies on the society. Usually, this typology of model is used by economists or public administrations, but it results inadequate to support policies addressing specific technologies or sectors. [25] On the other hand, bottom-up models describe technologies much more accurately and can be used to determine the optimal mix to meet a certain demand, taking into account techno-economic constraints and the environmental impact of each technology. Anyhow, though they can be used to support sector-specific decision-making, bottom-up models miss the link between the energy sectors and other macroeconomic sectors. [25] Some recent models attempted as well to combine the two categories of model.

Bottom-up models can be long-term models, that describe the evolution to reach the configuration of the energy system in a target year starting from the system as is, or short-term models, which evaluate the possible alternative configurations of the energy systems in the target year, regardless of the process to get there. [25]

Thanks to increasing computational power availability, energy models have been increasing in number and complexity over the last 20 years. Still many challenges remain to this day, especially considering that energy systems have become more complex to describe, due to new technologies such as variable renewable energy sources and storage technologies. An accurate energy model requires acceptable spatial resolution (from single to multi-node approaches), satisfactory temporal resolution (integral, dynamic and semi-dynamic methods), detailed description of the technologies, focus on individual sectors and introduction of behavioral economics. Moreover, in most of the cases energy models are deterministic and do not account for uncertainty, since this would require very high computational power, though this can be very high in a complex context such as the one of energy. Another essential feature for energy models is transparency, as scientists and technical experts should be allowed to assess how each challenge was addressed and to evaluate the solidity of the model. [25]

1.4. The importance of energy planning in Africa

Though Africa accounted for only 3.81 % of global CO_2 emissions in 2020, it plays a key role in the process of energy transition. [26] As stated in section 1.1, Africa has the lowest electricity access rate in the world, anyhow a fast economic growth is involving the continent (Sub-Saharan Africa GDP experienced a 125 % increase in the period 2000-2020) and access to electricity and electricity demand are rapidly increasing. [27] Africa population is dramatically growing as well and it is projected to pass from 1.3 billion people in 2020 to approximately 2.5 in 2050, accounting for more than a quarter of 2050 world's population. [28], [29] Electrification of Africa in accordance with the standards of sustainable development and energy transition is therefore of vital importance, but it requires massive investments to build new infrastructure. [30] However, in 2021 just 4 % of power supply investments were in Africa, due to the high risks perceived by potential financers, including political instability, unfavorable regulatory framework, commercial risks (due to consumers' inability to pay the bills) and lack of coordination of governments and utilities. [31]

Among all these criticalities, energy planning can provide an effective support to create a favorable environment for investment. Modeling accurate scenarios can give precious information over which technologies fit the best each context and can reach financial viability. Optimization of energy system expansion can also allow governments to create policies that favor the deployment of the best technologies and create long-term strategies for sustainable development.

2 Energy modeling in Africa

Since the objective of this project is the realization of a pan-African energy planning model to favor electrification and energy transition, it is necessary to know the framework from which this project starts to highlight its relevance. In this chapter some noteworthy existing energy models describing the African continent will be examined and their differences underlined. Then it will be presented a brief overview of the unique features characterizing the Calliope Africa Model (CalAMo), created in this project. A more detailed explanation of Calliope environment and of how CalAMo was built will be provided in chapters 4 and 5.

2.1. Notable existing models

2.1.1. TEMBA (The Electricity Model Base for Africa)

Temba is a model realized by KTH Royal Institute of Technology and United Nations Economic Commission for Africa researchers that describes supply and demand for 47 African countries, as well as the links connecting them. TEMBA is built on OSeMOSYS (Open Source energy Modelling System), which is a bottom-up long-term optimization tool based on linear programming. The model gives as a result the optimal energy mix and investment strategy in order to meet electricity demand, which is given as an input. [30] TEMBA uses a database to define supply, while demand is based on projections. The model can be constrained by policies or other requirements and focuses on three sectors: heavy industry, urban residential and commercial, rural residential. Its spatial resolution is of 45 individually modelled nodes, while its temporal resolution is of 4 periods per year, which are 1 day and 1 night for 2 considered seasons. [30] In the reference study, TEMBA is used to model two scenarios, the Reference Trade scenario and the Enhanced Trade scenario, for the period spanning from 2010 to 2040. Since OSeMOSYS is a long-term model, it simulates each single year (see section 1.3). The Reference Trade scenario focuses on which generation plants are financially viable in a context where the continental transmission grid is not going to be expanded. In this case only existing and committed interconnections are considered. The Enhanced Trade scenario instead considers as well planned transmission lines and allows further expansion of the grid since 2025. [30]

2.1.2. The Dispa-SET Africa model

The Dispa-SET Africa is a pan-African energy model created in 2021 by a group of scientists from KU Leuven and the Joint Research Center of the European Commission mainly to investigate the water-energy nexus, but as well to improve the representation of the continental energy system given by already existing models (such as the TEMBA, presented in section 2.1.1) and analyze the present electricity situation in Africa and its possible future developments. [32] The model uses an hourly temporal resolution and a spatial resolution of one node for each country. The model relies mainly on data from publicly available datasets, which are complemented with assumptions or using various tools, such as LISFLOOD and a cooling system selection matrix that depends on geography and generation technology. The model utilizes LISFLOOD model to generate hydrological profiles for various years which are used to compute the water inflows for hydroelectric power plants in m^3/s. Since resulting inflows tend to be much higher than historical data, capacity and availability factors are introduced as a correction. [32] Input data from databases and profiles from the LISFLOOD model are then pre-processed passing them to the Dispa-SET Side Tools package, which calibrates and translates the data to create a Dispa-SET database, that is subsequently used as an input by the main model. The optimization procedure utilizes the Dispa-SET MTS (Mid-Term hydro-thermal Scheduling) to pre-allocate the production of large hydro power plants on a one-year horizon, so the MTS results and the Dispa-SET database are utilized by the Dispa-SET UCM (Unit Commitment and power dispatch) model to optimize power dispatch and energy flows on a four-day horizon. The model includes various generation technologies, which are modelled including features such as minimum and maximum plant production, ramping rates and fixed and variable costs. [32] A flow chart displaying how the model is organized can be observed in Figure 2.1. In the reference study the model is utilized to study two scenarios on 39 different climatic years. The Baseline scenario considers the electricity grid as it was in 2018, while the High Interconnections scenario considers grid-expansion progresses for the year 2025. In the study costs related to the expansion of the grid are not considered, while the assessment of new potential interconnections between different Power Pools are judged to be out of the scope of the investigation. Though results are presented grouped by Power Pool, simulations were run individually for each country. [32]

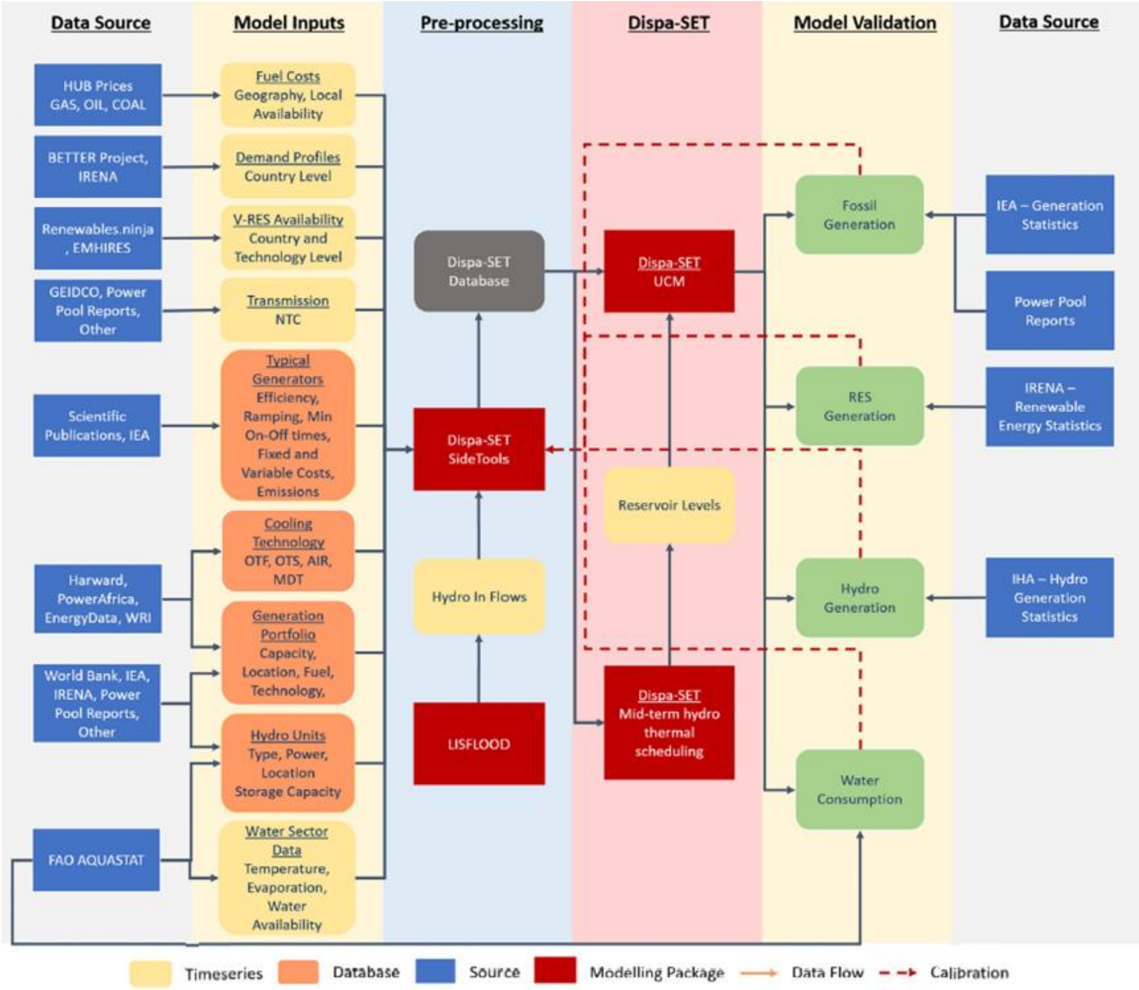

Figure 2.1: Dispa-SET Africa model structure. [32]

2.1.3. Lighting the world

The Lighting the world project is the application of a newly created optimization tool, OnSSET (Open-Source Spatial Electrification Tool) on Sub-Saharan Africa, to derive the least-cost electrification strategies for 44 countries. [33] OnSSET is based on GIS (Geospatial Information Systems), which are datasets based on maps and satellite records, that allow to consider the spatial dimension and topography implications in the electrification process. [34]

The model relies on datasets and parameters calculated with simplified procedures to give as a result continental grid composed by 1 km × 1 km cells. For each one cost and best strategy for electrification are determined for a variety of scenarios. The model allows three electrification technologies, stand-alone systems (with the possibility to choose between PV or Diesel generator), mini-grids (Diesel generator, PV, wind turbine or small hydro) and main grid expansion, and takes into account many factors, such as population density, resource availability, local cost of technologies, distance from the main grid, cost of electricity in the national grid and topography. [33]

This effort is based on already existing GIS models but implements original features like the use of Open Street Map to determine the position of transmission lines and power stations. Data about distribution of population, transmission grid maps and nighttime light databases were used to determine which cells in the continental grid are already electrified. Renewable resources potentials for each cell were computed using Global Wind and Solar Atlases for wind and sun. Hydro potential was instead calculated utilizing elevation maps and databases on river networks, determining the flow accumulation for each GIS cell and combining it with historical mean water runoff data, to obtain average discharge in m^3/s. After deriving other relevant parameters, such as the available head, small hydro potential could be computed for each cell. [33]

In the study 10 scenarios are considered for 2030, varying for two alternative low and high price of Diesel and five tiers of electrification. The model considers a projected population for 2030 and applies the selected tier homogenously on the continent, even though this is a significant simplification due to the presence of great income inequality. The model gives as a result the best technology for every cell in each scenario and necessary investment costs. [33] A map resulting from OnSSET optimization is shown in Figure 2.2.

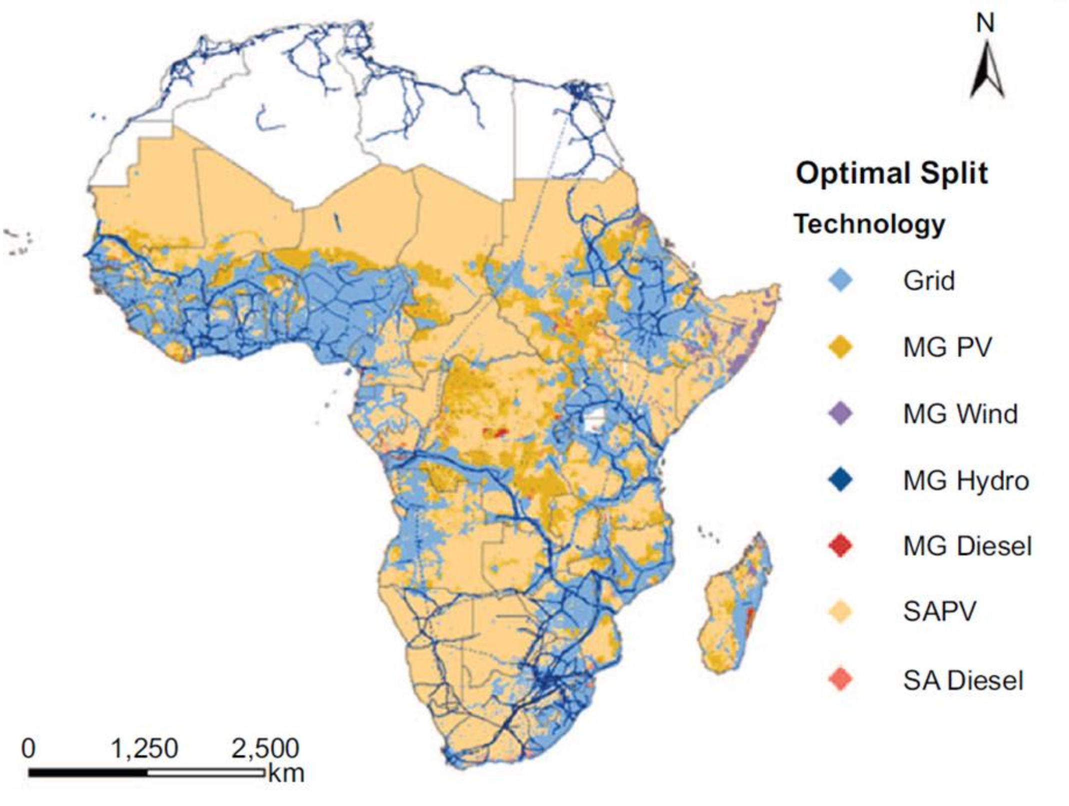

Figure 2.2: Example of a map resulting from a GIS optimization using OnSSET. [33]

2.1.4. "The effects of climate change mitigation strategies on the energy system of Africa" study by Pappis et al.

This study was realized as an expansion of the TEMBA model presented in section 2.1.1, so it is as well based on OSeMOSYS and utilizes a temporal resolution of 4 time periods per year. [35] Some features were added to the original model to consider the effect of water scarcity on the optimization of the energy system in various scenarios. The influence of water availability on the energy system is considered through capacity factors applied to hydroelectric power plants, distinguishing between dry and wet years, and taking in account the water withdrawal for the cooling of thermal power stations. Five cooling types were considered, each one with a different water requirement. [35] The model is used to study three different scenarios for the period 2015-2065. The first modelled scenario is called the Reference scenario and is created considering environmental policies stated by 2017. The other two refer to mitigation of environmental risks through emission reduction to reach the objectives of, respectively, 1.5 °C and 2 °C increase of global temperature by 2100. Emission limits are applied in the model on a regional level. [35]

2.2. The Calliope Africa Model (CalAMo)

The Calliope Africa Model, or CalAMo, is a new model created for this project to describe the African energy system. CalAMo is a bottom-up multi-node model created in the Calliope environment to optimize the functioning of the continental grid with the objective to minimize system total costs.

A large part of the project consisted in data gathering since the model is entirely based on data deriving from public databases and reports. In the vast majority of cases only very partial or imprecise information could be found and many datasets from reliable sources were uncoherent with one another. Therefore, a massive number of sources had to be compared between them and with aggregated data on total installed capacity and electricity production (in particular IRENASTAT by IRENA, UNdata by U.N. Statistics Division and IEA data) to obtain the most reliable and complete database. Due to limited local data availability, the continent was divided into 55 nodes, one for each country except for Mozambique (2 nodes), Kenya (4 nodes) and Nigeria (4 nodes).

The model focuses only on the on-grid supply system and can optimize the operation of power stations and transmission grids considering the whole continent or single power pools.

Even if CalAMo is not a GIS-based model (see section 2.1.3) it considers with simplified methods space-dependent parameters of some technologies. Transmission interconnections for instance are modelled through per-distance efficiencies. Maps and satellite data were used to calculate the approximate lengths of transmission lines. Variable renewable power stations, though contained in the concentrated nodes, receive as an input available resource timeseries computed for the real locations of the plants.

Temporal resolution plays a fundamental role in the description of energy systems, in particular when there is a high penetration of variable renewable sources. Since one of the aims of CalAMo model is to favor the deployment of renewable technologies, including VREs, it utilizes a very high temporal resolution, dividing the year in 8760 one-hour periods, differentiating from the models based on TEMBA (described in sections 2.1.1 and 2.1.4).

Though it uses simpler description of some technologies with respect to the Dispa-SET Africa model to have a lighter model due to computational limitations, CalAMo, on the contrary of Dispa-SET Africa, can be run in planning mode to optimize the transmission and supply system expansion in different scenarios conditions. [36]

Besides monetary costs, the Calliope Africa Model includes CO_2 emissions for each technology, so environmental policies can be implemented in the form of a total emission cap or of a carbon tax that can be included in the objective function.

3 A brief presentation of electricity sector in Africa

In this chapter Africa electricity context and policies in place will be briefly presented.

Africa is home to about 1.3 billion people, but in 2018 more than 595 million still lacked access to electricity. Anyhow, the African electricity sector is rapidly evolving and the number of people with no electricity peaked in 2013, when it was 610 million people. Between 2014 and 2018, 20 million people a year gained access to electricity through connection to the national grid, creation of mini-grids or through home systems. [36] Though these last two technologies have a relevant role in the electrification of the African continent (more than 8.5 million people rely on solar home systems and there are about 1500 mini-grids in Africa), this chapter will describe the continental and regional context for on-grid technologies, since they are the focus of this project. [36], [37]

3.1. Access to electricity

As it can be observed in Figure 3.1, electrification rate can vary a lot between different regions and countries of the continent.

Most of northern Africa countries are middle-income countries with almost universal access to electricity, thanks to large availability of hydrocarbons to support power generation and economies, besides governmental efforts to electrify urban and rural populations. South Africa is another country where the electricity sector is much more advanced than in other regions, reaching an 85 % access rate.

Other Sub-Saharan regions are still lagging behind regarding access to electricity and in 2019 the Sub-Saharan region with the highest access rate was West Africa (53 %), while in Central Africa this was only 32 %. Anyhow, fast improvements are occurring, particularly in East Africa, where yearly increase in electricity access was more than 4 % between 2014 and 2018. It is interesting to underline the high access rates that could be reached by Kenya (75 %) and Ghana (84 %) in regions with lower access to electricity thanks to effective energy policies created in the framework of long-term energy planning. [36], [37]

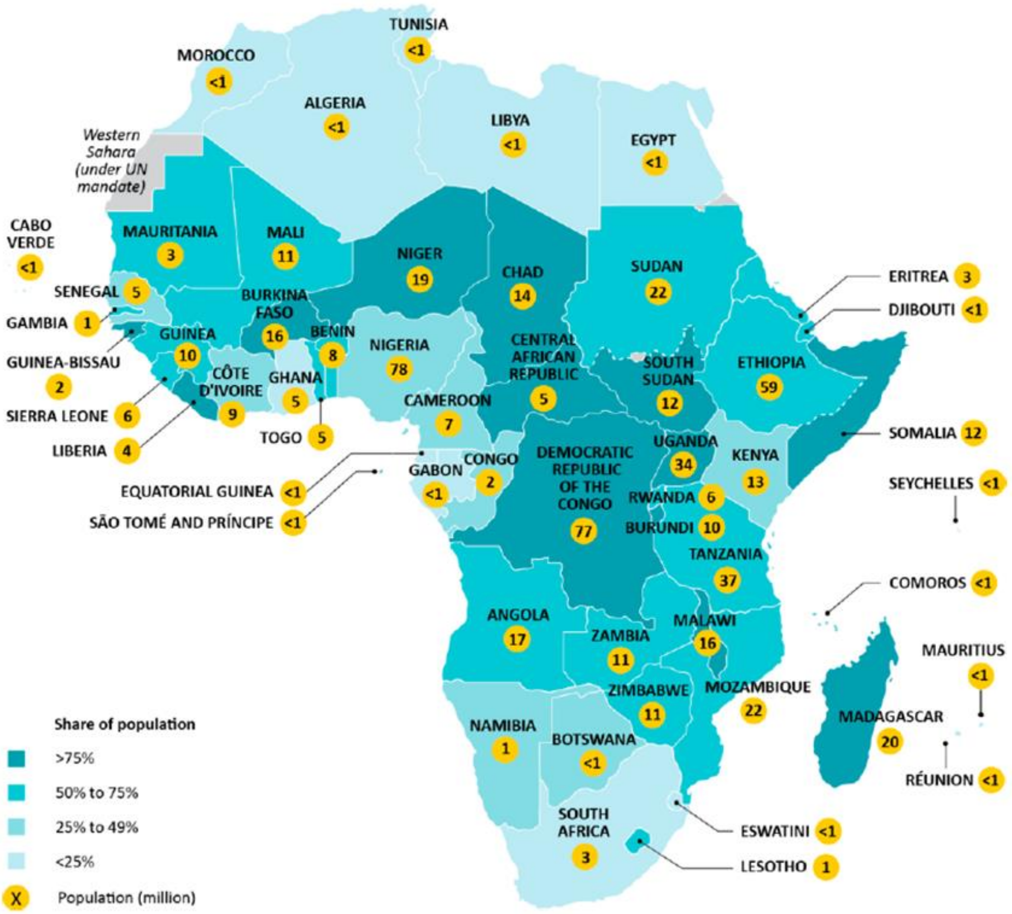

Figure 3.1: Population that lacked access to electricity in Africa in 2018. [36]

3.2. Electricity demand and supply

In 2018 Africa electricity demand was just 3 % of global demand amounting to 705 TWh, while per capita demand was only 370 kWh in Sub-Saharan Africa and 550 kWh considering the whole continent, very far from the 5600 kWh per capita measured in Europe. Furthermore, electricity demand is not homogenously distributed and in 2018 South Africa and Northern Africa countries accounted for 72 % of continental demand. In the meanwhile, 40 % of industry sector electricity demand was concentrated in South Africa. [36]

Electricity generation is rapidly increasing in last years and installed capacity passed from 155 GW in 2010 to 245 GW in 2018. Electricity production is mainly based on thermal power plants and in 2019 the 77 % of generated electricity was from gas, coal and oil. Different technologies are concentrated in different regions and in 2018 85 % of natural gas power plants were in northern Africa countries, while 42.5 GW of coal capacity on 50 GW of the entire continent were in South Africa. This can be attributable to the large availability of fossil fuels in these areas, since northern Africa has approximately 42 trillion cubic meters of recoverable natural gas reserves (100 trillion cubic meter in Africa) and South Africa has 216 billion tons of coal (on a continental recoverable reserve of 300 billion tons), as well as more advanced economies and electricity sectors in these countries. Use of gas-fueled power plants has been increasing in the continent with a rate of 4.2 % between 2011 and 2019, also thanks to new important discoveries of gas reserves in Tanzania, Egypt, Mozambique and Senegal. Oil is as well employed for power generation using Diesel generators and HFO and LFO power plants and large reserves of oil are present in Algeria, Nigeria, Angola and Libya.

The most utilized renewable generation technology in Africa is hydroelectric with almost 34 GW installed as of 2020. Hydropower generation is particularly important in central Africa since in 2020 it constituted 65 % of its electricity mix. Thanks to the large unexploited technical potential of the continent, estimated by Delft University to be around 1753 GW, it could be used to cover even a larger share of the energy mix. As of 2022, summing candidate, planned and committed hydroelectric projects to the already operational power stations, the continental installed capacity would get to 131 GW. Anyhow, risks related to climate change, financing and political disputes (as the ones involving Ethiopia’s 6 GW Great Renaissance Dam with Sudan and Egypt) give some uncertainty over the completion of these projects.

As of 2019, other renewable electricity generation technologies accounted to approximately 4 % of Africa electricity mix. Anyhow, Africa potential for renewables is huge, with a technical potential amounting to about 7900 GW for solar, 461 GW for wind and 15 GW for geothermal (this mostly concentrated in the East Africa Rift System) and deployment of modern renewable power stations has been increasing rapidly over last years. Solar has been increasing with an average Compound Annual Growth Rate (CAGR) of 54 % in the period 2011-2020, while wind has been growing with a CAGR of 22.5 %. Most of both solar and wind generation capacity is installed in South Africa, with around 6 GW of the first (57 % of solar capacity installed in Africa) and 2. 7 GW of the second (41 % of wind capacity installed in Africa). Egypt and Morocco are the following countries for both solar and wind generation and the capacities of these three countries together account for around 80 % of total continental solar and wind capacities. South Africa is the only country in the continent to produce electricity from nuclear, using the 1.94 GW Koeberg power station, while the whole 0.8 GW geothermal capacity is installed in Kenya. Though bioenergy has a very important role for cooking and other uses, its use in electricity generation is not very relevant. [36], [37]

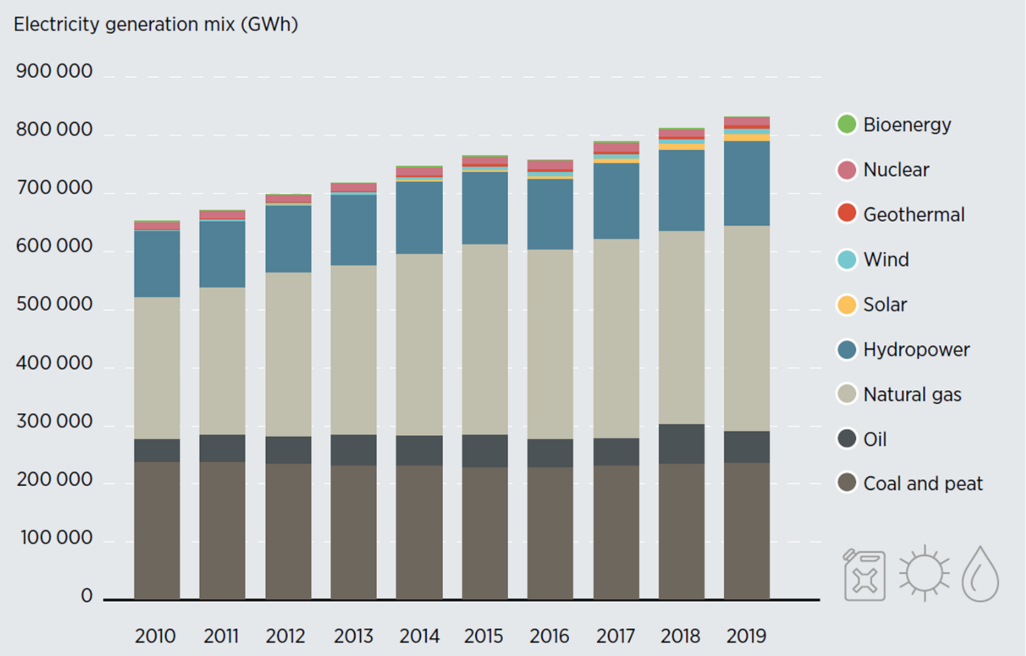

Figure 3.2: Evolution of the electricity generation mix in Africa. [37]

3.3. Trade of electricity

In Africa electricity trade is limited and mostly carried out through bilateral contracts. Five regional power pools were created between 1974 (COMELEC) and 2005 (EAPP) to promote the creation of interconnections between countries and grid development, to increase trade of electricity and to create regional electricity markets. The power pools are:

- **Central African Power Pool** (**CAPP**), including Angola, Burundi, Cameroon, the Central African Republic, Chad, the Democratic Republic of the Congo, the Republic of the Congo, Equatorial Guinea, Gabon and São Tomé and Principe.
- **Eastern Africa Power Pool** (**EAPP**), including Burundi, the Democratic Republic of the Congo, Djibouti, Egypt, Ethiopia, Kenya, Libya, Rwanda, South Sudan, the Sudan, the United Republic of Tanzania and Uganda.
- **Comité Maghrébin de l'Electricité** (**COMELEC**, informally referred to as North Africa Power Pool NAPP), including Algeria, Libya, Mauritania, Morocco and Tunisia.
- **Southern African Power Pool** (**SAPP**), including Angola, Botswana, the Democratic Republic of the Congo, Eswatini, Lesotho, Malawi, Mozambique, Namibia, South Africa, the United Republic of Tanzania, Zambia and Zimbabwe.
- **West African Power Pool** (**WAPP**), including Benin, Burkina Faso, Côte d'Ivoire, the Gambia, Ghana, Guinea-Bissau, Liberia, Mali, Mauritania, Morocco, Nigeria, Senegal, Sierra Leone and Togo.

The SAPP and the COMELEC are the most developed and established organizations. The SAPP runs four different competitive electricity markets, which are the only functioning electricity markets in Sub-Saharan Africa. Though, trade between countries is limited by the low development of transmission interconnections and a significant portion of matched power cannot be traded. In the COMELEC there are sufficient interconnection capacities, but trading is limited due to generation scarcity and lack of regional and market regulation. WAPP has been working to create a regional market, but this is not going to be operational for some years to allow sufficient expansion of the regional grid. EAPP has been creating regional regulations and has been expanding interconnections rapidly to establish a market, but this is still not ready to function. CAPP is the least developed Power Pool, being still on the way to create necessary regulation and institutions for regional grid integration.

Developing more integrated electricity grids and markets can give advantage to African countries in terms of necessary investments in generation to cover the increasing demand and in terms of resilience of national power systems. Interconnections are mostly publicly funded since transmission lines are capital intensive and very high risks are perceived by private funders for this kind of projects in the African continent. Anyhow, in the last years, funds coming from international donors, such as the European Union and the U.S. Agency for International Development through the Power Africa initiative, are accelerating this integration progress.

Projects to unify the five power pools to create a pan-African electricity grid and market have been proposed as well by the African Union. This proposals will be supported through on-going modeling initiatives carried out by IRENA and IAEA and financed by the European Union to create a Continental Systems Master Plan. [36]–[38]

3.4. Electricity sector policy framework

At the 2015 Paris COP21 53 African countries presented Nationally Determined Contributions (NDCs), which are master plans to adapt to risks related to climate change and cut emissions, containing strategies to fulfill environmental targets, besides methods to monitor the progress of these strategies and financing plans. NDCs of 40 African countries included targets on renewable, 28 included renewable rural electrification targets and about half had targets on energy efficiency. Anyhow, all countries have national master plans on energy and electrification which not always are in line with NDCs.

Besides national policies, regional plans to support energy transition were created for every region of the continent. To support the deployment of renewable energy and the improvement of efficiency of power systems, dedicated centers were created in each region. Some examples are the Southern African development community Centre for Renewable Energy and Energy Efficiency (SACREEE) and the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE). Some regions have established as well regional targets for electricity production from renewables. For instance, in accordance with the Pan-Arab Sustainable Energy Strategy, North Africa aims to reach 12.4 % of generation from renewables by 2030, while Western Africa, to be in line with the ECOWAS Renewable Energy Policy (EREP), intends to reach 48 % of renewables in the electricity mix.

There are as well continental initiatives to foster universal access to electricity and high renewable penetration. The Africa Development Bank's New Deal on Energy for Africa is a plan that aims to reach complete urban electrification and 95 % of rural electrification by 2025. African Union's Agenda 2063 is a 50-year plan that defines strategies to reach sustainable development in Africa. In this masterplan aspirations to increase integration of power systems and reliance on renewable generation are included.

South Africa, Nigeria, Angola and other countries still have fossil fuel subsidies which significantly affect governmental budgets and obviously do not favor energy transition. Nevertheless, reforms of subsidies have been announced in the NDCs of many countries, including Egypt and Ethiopia. Anyhow, these reforms should happen gradually not to burden on poor population. In the meanwhile, South Africa has introduced a carbon pricing system to reduce consumption of fossil fuels, anyhow this has not been applied to the electricity sector yet. [37]

4 Overview of Calliope project

Figure 4.1: Calliope logo.

“Calliope is a free and open-source (Apache 2.0 licensed) tool that makes it easy to build energy system models at scales ranging from urban districts to entire continents.” [39]

The following section refers to official Calliope documentation. [40]

4.1. General information and aim

Calliope is an openly developed tool that allows to create energy models of a wide range of power systems, to run them and to analyse the obtained results. Calliope uses a Python toolchain based on Pyomo, xarray and Pandas, anyway the user does not require to access the code to create a model, as data and framework are well separated. Models are built using human and computer readable YAML and CSV files.

Energy modelling can have several aims and a variety of modelling tools are openly available. Anyway, each model is distinguished by its own characteristics and is created to fulfil a peculiar objective. In the case of Calliope, the aim is to support energy policies with accurate and reliable information about power systems to facilitate the transition towards an energy sector in which production from renewable sources prevails. [40] Calliope allows to optimize the operation of existing power systems, verify how different conditions could affect costs and energy balance. Scenarios can be applied to a base model so that future interventions on transmission and supply sides can be optimized.

4.2. Model building

A model is created receiving various inputs that constrain the problem and allow the solver to reach an optimal solution. Here the basic structure and settings are described, anyway Calliope allows to set many more constraints, allowing to adapt the model to each possible situation and reach better solutions.

4.2.1. Model.yaml

A YAML file defines the structure and operation of the model. It starts importing all the YAML and CSV files that contain the data necessary to characterize the model.

A second section contains the configuration of the model. It states some basic information, such as the name of the model, the Calliope version on which the model is intended to run, timeseries directory and date format. In this section it is as well defined the subset of timesteps for which a solution is searched.

The third section configures the run of the model. It must at least include the solver which will be utilized and the mode in which the model will be run. An optimization software is selected to solve the problem and it should be sufficient that this is compatible with Pyomo optimization modelling language. Some examples are GLPK, Gurobi, CPLEX, and CBC.

The mode setting defines how the model will be run. A model can run in operational, planning or SPORES mode. In planning mode capacities are determined by the model, while in operational mode capacities are fixed and the model just operates the system in an optimal way. In SPORES mode the model is first run in planning mode, then it is run many times to find possible alternatives that are comparable from an economic point of view but differ significantly in terms of capacity and location of newly installed technologies. In this section the arguments to be passed to the objective functions, which usually are different classes of costs, and their weights are also reported. Unmet demand to ensure the feasibility of the model can be also allowed in this section using the designated function (unmet demand will appear only if strictly necessary).

4.2.2. Technologies

The various technologies that are included into the model are defined through YAML files. These files include supply and storage technologies, transmission, demand, imports and so on.

For each technology some essential information is specified, such as its name, its parent (e.g. supply), its carrier (e.g. power) and the colour used in graphical representation of the results. Some constraints that characterize the technology are reported in this section. The most common are energy efficiency, lifetime and available resource. In these YAML files, costs and interest rate are stated as well. Costs can be divided in investment costs, fixed and variable O&M and combustible costs. By default, only monetary costs are included, but this section can include other classes of costs, for example CO2 emissions. Constraints and costs can be overwritten in the location constraints section, this allows, for example, to specify individual resource availability for each location. More about single constraints and costs settings in chapter 5, dedicated to the building of CalAMo.

4.2.3. Locations and links

Locations are specified as well using YAML files. Locations in Calliope are modelled as nodes in which various technologies are concentrated. Each location is characterized by its coordinates (optional but used in visualization and to compute distance between two nodes if this is not specified) and the installed technologies. Additional location specific parameters, such as technology capacity or resource availability, can be specified.

The various nodes representing the locations can be connected through transmission links, which are listed in a YAML files. To define a link, it is necessary to identify connected regions and allowed technologies. Link specific constraints, such as transmission line capacity and length, can be specified.

4.2.4. Timeseries

Timeseries are the only input which is given in another format, as in this case CSV files are used. Timeseries are used for parameters that vary in time, for example demand or resource availability for VRE technologies. Demand is given as a negative series of values, while resources are given as a series of positive values. Timeseries use a temporal resolution of one hour.

4.2.5. Overrides

Calliope allows to run different scenarios using YAML files that expand or override the base model. An override is defined by a name and a number of settings that modify the model. A scenario is as well designated by a name and is formed by several overrides.

4.3. Model results

After the run, if the model converges results are obtained. These are given as an xarray dataset and can be saved either in NetCDF or CSV format. Results include timeseries of the capacity factors of the technology of each location, consumed and produced carriers, investment and variable costs, installed capacity, unmet demand and other useful information.

5 Building the CalAMo

The Calliope Africa Model is a bottom-up multi-nodal short-term model which describes the whole continental Africa power system. In the next sections it will be described the methodology followed to build the model, the elements that compose it and the principal assumptions that were adopted.

5.1. Spatial resolution

The CalAMo is composed by five sub-models that can be run independently, each one describing a Power Pool. Some countries belong to multiple Power Pools at the same time, in this case they were arbitrarily included just in one Power Pool. In other cases, some countries do not belong to any Power Pool. Because of this they were included in an adjacent Power Pool. Here are listed the countries included in each Power Pool. Considered locations and territorial divisions within the model are without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

- **North African Power Pool:** Algeria, Libya, Mauritania, Morocco, Tunisia.

- **Eastern Africa Power Pool:** Djibouti, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, South Sudan, Sudan, Uganda and the United Republic of Tanzania.

- **Central African Power Pool:** Angola, Burundi, Cameroon, the Central African Republic, Chad, the Democratic Republic of the Congo, the Republic of the Congo, Equatorial Guinea and Gabon.

- **Southern Africa Power Pool:** Botswana, Eswatini, Lesotho, Malawi, Mozambique, Namibia, South Africa, Zambia and Zimbabwe.

- **West African Power Pool:** Benin, Burkina Faso, Côte d'Ivoire, the Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo.

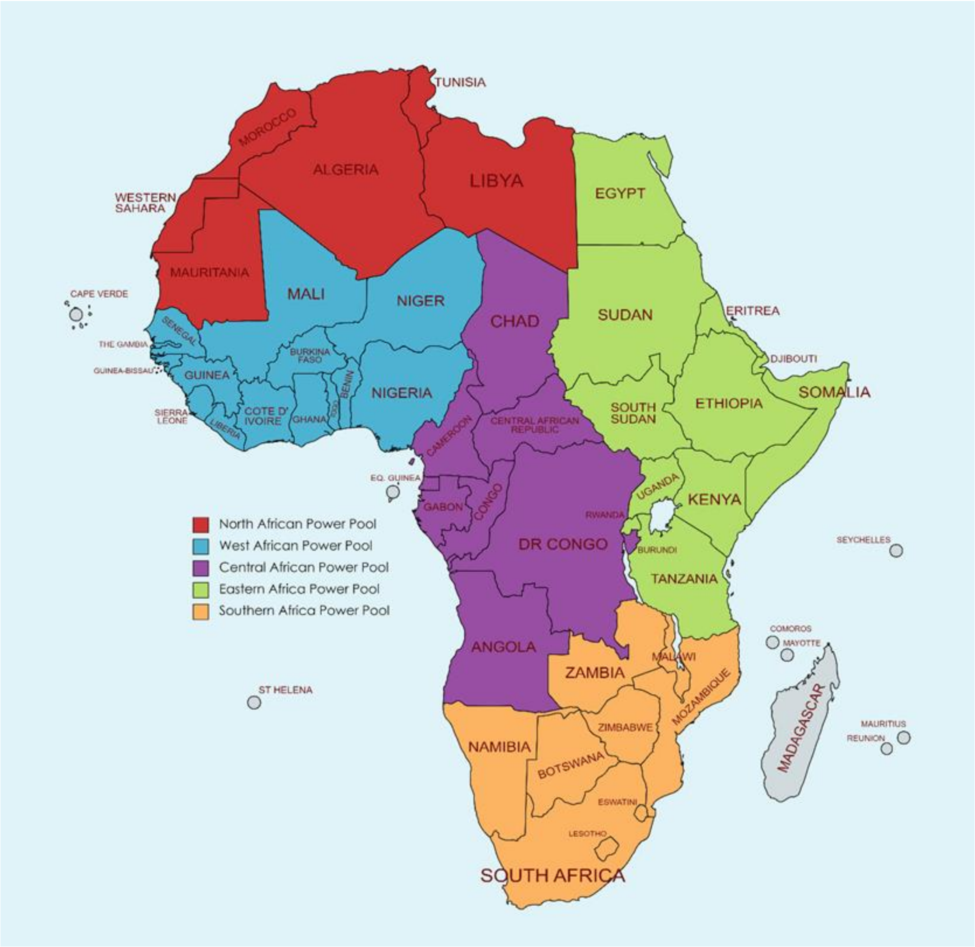

Figure 5.1: Power Pool division considered in CalAMo.

Only continental Africa was considered, so Cape Verde, the Comoros, Madagascar, Mauritius, the Seychelles and São Tomé and Príncipe were excluded from the model, while Equatorial Guinea was counted only in its continental portion.

High spatial resolution is a very important element to obtain an accurate model, as increasing the number of nodes (compatibly with the available computational power) allows to obtain a more precise representation of power flows and resources availability. Anyhow this can be difficult to achieve, as detailed data about power station exact locations, local demand and transmission grids are needed. In the case of African continent only in very few cases it was possible to find subnational data about demand and precise grid configuration. Because of this, most of the countries were modelled as a single node. The countries that could be divided in more nodes are Kenya, Mozambique and Nigeria.

Kenya was divided into four regions, adopting the division that was utilized in the SESAM Calliope-Kenya model. [41] The four territories are Nairobi region, Coast region, Western region and Mount Kenya region. Additionally, there is an “off-grid region” which was excluded from the model. There are two power stations (Garissa PV plant and Lake Turkana wind farm) that are located in the “off-grid region” but are connected to the grid of Mount Kenya region. In this case they were included in the location constraints of Mount Kenya region, even though they were modelled using their actual location.

Mozambique was split into South and North-Center regions as done in SESAM Calliope-Hydro model referring to the Zambesi River basin. [42]

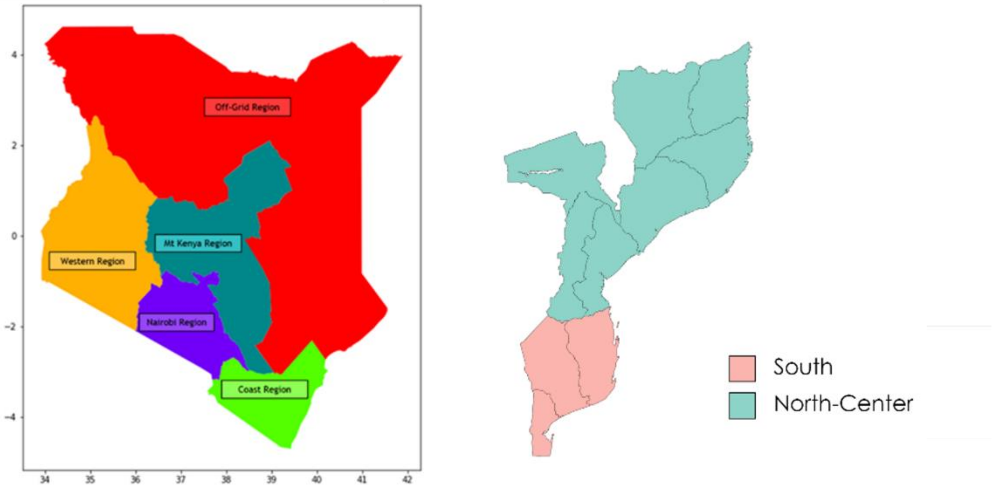

Figure 5.2: Regional division of Kenya and Mozambique in CalAMo.

Nigeria was separated into four regions obtained aggregating in four groups the eleven DisCos, which are the eleven distribution companies of Nigeria, as subnational data are available for DisCos coverage areas. [43] DisCos areas were arbitrarily grouped in four regions to simplify the modelling of transmission links.

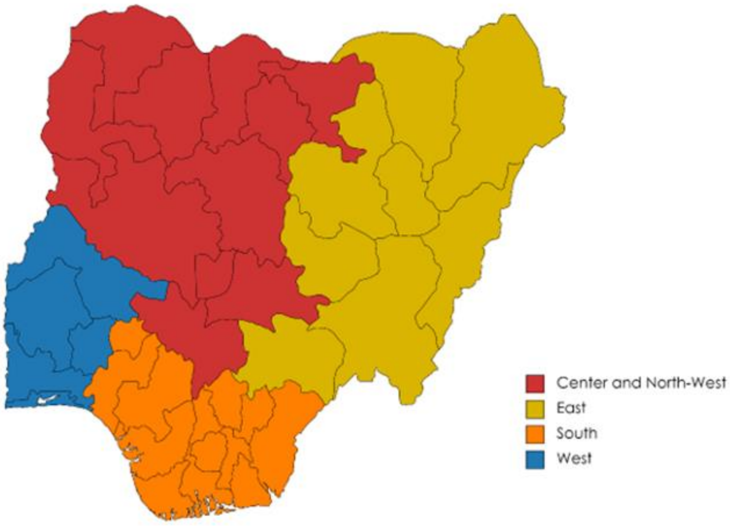

Figure 5.3: Regional division of Nigeria in CalAMo.

While the position of conventional power stations is not very relevant to model them accurately, spatial resolution is of fundamental importance when modelling solar and wind power plants, as resource availability varies drastically with location. Because of this, subject to data availability, more than 98 % of PV, CSP and wind power stations were modelled considering their real coordinates to obtain the timeseries of hourly production and irradiance from Renewables.ninja. [44] The single plants were then inserted in the location constraints of the corresponding national or regional node (e.g., a PV power station in Morocco was included in the location constraints of Morocco national node) to limit the number of nodes, in order to have a "lighter" model. To insert multiple distinct power plants using the same technology in a single node, various technology with the same parameters were defined (for example, PV1, PV2, PV3, …, PVN, all with the same characteristics).

5.2. Generation technologies

The various generation technologies that are present in the Africa power system are defined in the YAML file called Technologies_Generation.yaml. In the following subsections it will be described how the different technologies were modelled, with direct references to the model code.

5.2.1. Fossil fuel technologies

Fossil fuel power stations were modelled as infinite resource technologies. Considered fossil fuel technologies are: Coal power plant, Combined Cycle Gas Turbine (CCGT), Open Cycle Gas Turbine (OCGT) fuelled by different fuels, Gas fuelled steam turbine, HFO power station, Diesel engine, Gas engine and Integrated Solar Combined Cycle (ISCC). In tables 4.1 and 4.2 are reported the parameters that were used to model the various technologies and their sources. Since only already installed capacity was considered only direct CO2 emissions were considered. In any case in the model both direct and lifecycle CO2 emissions are reported and it is possible to select the most appropriate for each application of the model. Some data could not be found from direct sources and were therefore derived from SESAM Calliope Hydro model about Zambesi River basin. [42] Ramp rate, which represents the rate at which a technology can change its output (here expressed as fraction of installed capacity per hour), was included in the modelling for the technologies with the highest start up times.

ISCC technology was modelled assuming lifetime, ramping rate, O&M costs and combustible costs equal to the ones of CCGT. The advantage given by the addition of solar concentration plant is difficult to evaluate, depends on irradiation in each location, fraction of solar plant capacity on total capacity and other factors. A report on Algeria's Hassi R'Mel ISCC performances was utilized as a base to assume the efficiency of this technology. [45] This document states that the plant can reach an efficiency of 67 % in summer periods, anyhow it is not clear how many hours of the year the plant can produce at this level of performance and other installed ISCCs have a lower fraction of solar capacity on total capacity, so should have lower performances. Because of this a 59 % efficiency was conservatively assumed. Investment costs were obtained considering the average fraction of solar capacity on total ISCC capacity and multiplying CSP investment costs for CSP fraction and CCGT investments costs for CCGT fraction.

Table 5.1: Techno-economic parameters of fossil fuel generation technologies included in CalAMo.

	Energy efficiency	Lifetime	Ramping rate	Investment costs	Fixed O&M costs	Variable O&M costs	Combustible costs
	[-]	[years]	[h^{-1}]	[$/kW]	[$/kW]	[$/kWh]	[$/kWh]
Coal	0.41	40	0.15	2200	32.8	0.0043	0.0082
CCGT	0.56	30	0.4	1100	13.90	0.0025	0.0210
Oil fuelled CCGT	0.56	30	0.4	1100	13.90	0.0025	0.0139
OCGT	0.40	30	-	900	11	0.0035	0.0210
Oil fuelled OCGT	0.35	30	-	900	11	0.0035	0.0139
Diesel fuelled OCGT	0.35	30	-	900	11	0.0035	0.0493
HFO	0.35	50	0.3	1350	26.5	0.001	0.0139
Gas fuelled Steam Turbine	0.35	50	0.3	1350	26.5	0.001	0.0210
Diesel Engine	0.35	30	-	708	24	0.003	0.0493
Gas Engine	0.40	30	-	708	24	0.0024	0.0109
ISCC	0.59	30	0.4	1834	13.90	0.0025	0.0210

Table 5.2: CO_2 emissions of fossil fuel generation technologies included in CalAMo.

	CO2 Direct Emissions	**Life cycle CO2 Emissions**
	$[\mathrm{kg}_{CO_2}/\mathrm{kWh}]$	$[\mathrm{kg}_{CO_2}/\mathrm{kWh}]$
Coal	0.760	0.820
CCGT	0.370	0.490
Oil fuelled CCGT	Cons. Assumption: 0.738	Cons. Assumption: 0.778
OCGT	0.528	0.640
Oil fuelled OCGT	Cons. Assumption: 0.738	Cons. Assumption: 0.778
Diesel fuelled OCGT	Cons. Assumption: 0.738	Cons. Assumption: 0.738
HFO	0.738	0.778
Gas fuelled Steam Turbine	Assumption: 0.528	Assumption: 0.640
Diesel	0.651	0.778
Gas Engine	0.565	0.778
ISCC	0.370	0.490

5.2.2. Hydroelectric technologies

Conventional hydropower plants were divided into two categories, which are large power plants (capacity > 10 MW) and small power plants (capacity ≤ 10 MW), as defined by IRENA. [46] Water cannot be treated as an infinite resource, as its availability is limited in many regions and subject to seasonality. This has a heavy effect in limiting hydro power plants yearly energy production. Due to this, plant-specific monthly capacity factor obtained from IRENA's Hydropower Atlas Dataset were imposed. [47] Specific capacity factors are available for most of the power plants. When these were not available, monthly capacity factors of nearby power stations were utilized. If even this approximation was not possible, an annual national capacity factor taken from EU Science Hub's Africa Knowledge Platform was used. [48] Efficiency was assumed equal to be equal to 1, since capacity factors already include its effect. Pumped hydro technology was modelled as a storage technology. Storage losses were assumed to be null as, according to the EU Science Hub's Africa Knowledge Platform, the plant with the highest losses would lose approximately 0.0354 % of basin water per hour. [48] For the other pumped hydro plants losses are considerably lower. As well it was imposed a maximum depth of discharge of basin water of 80 %, to guarantee the maintenance of ecosystems. [49]

Table 5.3: Techno-economic parameters and CO_2 emissions of hydroelectric generation technologies included in CalAMo.

	Energy efficiency	Lifetime	Investment costs	Fixed O&M costs	Variable O&M costs	Direct CO_2 Emissions	Life cycle CO_2 Emissions
	[-]	[years]	[\$/kW]	[\$/kW]	[\$/kWh]	[kg_{CO2}/kWh]	[kg_{CO2}/kWh]
Large Hydro	1	50	4000	60	-	0	0.1265
Small Hydro	1	30	4500	65	-	0	0.00905

Table 5.4: Techno-economic parameters and CO_2 emissions of pumped-hydro storage in CalAMo.

	Round-trip efficiency	Lifetime	Investment costs	Fixed O&M costs	Variable O&M costs	Direct CO_2 Emissions	Life cycle CO_2 Emissions
	[-]	[years]	[\$/kWh]	[\$/kW]	[\$/kWh]	[kg_{CO2}/kWh]	[kg_{CO2}/kWh]
Pumped Hydro	0.80	40	165	15.90	0.00025	0	0.024

5.2.3. Solar technologies

In the model are included solar photovoltaic plants and concentrated solar plants. Both technologies were modelled considering each plant in its real position, anyway they present some differences in how they were described.

Solar PV power plants were modelled giving as available resource hourly timeseries per installed kW obtained through Renewables.ninja. [44] These timeseries already consider PV conversion efficiency, that is why PV technology has a unitary efficiency in the model. To obtain the timeseries it was considered a system loss of 0.1. Tilt angles were assumed depending on latitude using estimates available in bibliography of optimal angles for various locations of the world. [50] Tracking was considered only for the plants in which its presence could be verified. This technology is forced to produce in every instant to take maximum advantage of a freely available renewable resource such as solar irradiation.

CSP was modelled as a supply_plus technology including a storage. Available resource was obtained as well in this case from Renewable.ninja, but it in this case it was given as irradiation per m^2. [44] In this case the efficiency is not included in the timeseries and so it was considered in the model. Available resource per unit area was then multiplied for each power plant solar aperture area. Storage losses were assumed to be null basing on findings by NREL, as they are a very small fraction per hour with respect to total storage and to power flows involved in the system. [51]

Table 5.5: Techno-economic parameters and CO_2 emissions of solar generation technologies included in CalAMo.

	Energy efficiency	**Lifetime**	**Investment costs**	**Fixed O&M costs**	**Variable O&M costs**	**Direct CO_2 Emissions**	**Life cycle CO_2 Emissions**
	[-]	**[years]**	**[$/kW]**	**[$/kW]**	**[$/kWh]**	**[kg_{CO2}/kWh]**	**[kg_{CO2}/kWh]**
Solar PV	1	25	1660	16.60	-	0	0.048
CSP	0.15	35	8000	-	0.03	0	0.027

5.2.4. Wind technology

Wind farms description is similar to the one used for solar PV. Wind farms were modelled in their real position and use as well Renewables.ninja timeseries per installed kW that already consider efficiency. [44] So, even in this case wind farms efficiency is set equal to 1 in the model. Also in this case, production was forced to utilize the highest possible level of available resource. To obtain the timeseries from Renewables.ninja, the real models of turbines installed in every wind farm where considered. When these were not available in the simulator, comparable models in terms of dimensions and cut-in and cut-off speeds were utilized. Hub heights were assumed compatibly with the respective model of turbine.

Table 5.6: Techno-economic parameters and CO_2 emissions of wind generation technology in CalAMo.

	Energy efficiency	Lifetime	Investment costs	Fixed O&M costs	Variable O&M costs	Direct CO_2 Emissions	Life cycle CO_2 Emissions
	[-]	[years]	[$/kW]	[$/kW]	[$/kWh]	[kg_{CO2}/kWh]	[kg_{CO2}/kWh]
Wind	1	20	1209	38	-	0	0.011

5.2.5. Other technologies

The other technologies included in the model are bioenergy, geothermal and nuclear. All of them were modelled as infinite resource technologies.

Geothermal efficiency was considered equal to 1, as it can use an infinite resource available for free, so considering a different efficiency would not make any difference.

Table 5.7: Techno-economic parameters of other generation technologies included in CalAMo.

	Energy efficiency	Lifetime	Ramping rate	Investment costs	Fixed O&M costs	Variable O&M costs	Combustible costs
	[-]	[years]	[h^{-1}]	[$/kW]	[$/kW]	[$/kWh]	[$/kWh]
Bioenergy	0.2263	25	0.3	4500	62	0.0075	0.0113
Geothermal	1	40	0.65	3950	151.5	-	-
Nuclear	0.3098	43	0.04	3000	89.2	0.0009	0.00294

Table 5.8: CO_2 emissions of hydroelectric generation technologies included in CalAMo.

	CO2 Direct Emissions	Life cycle CO2 Emissions
	[kg_{CO2}/kWh]	[kg_{CO2}/kWh]
Bioenergy	0	0.230
Geothermal	0	0.038
Nuclear	0	0.012

5.3. Transmission technologies and demand

Transmission technologies and demand are defined in a YAML file called Technologies_Transmission_and_Demand.yaml.

As the various transmission lines operate at many different voltages, to simplify the modelling they were arbitrarily divided into seven classes: 70-110 kV, 132-161 kV, 220-275 kV, 300-330 kV, 350 kV DC, 400 kV, 500-533 kV DC. All lines are characterized by per length efficiency. These were assumed basing on data reported by IEA-ETSAP. [52] Losses depend on distance, resistance of the transmission line, transmitted power and voltage. So various efficiencies were utilized for the same class of voltages, depending on the power transmission capacity of the line (it was conservatively assumed that lines would work at nominal capacity). Lifetime for transmission grids was conservatively assumed at 40 years basing on average time of reliable functioning reported in technical bibliography. [53] Capital costs were not considered as only already existing lines were considered for the base case. O&M were derived from SESAM Calliope Hydro model and equal 0.076 $/kWh. [42] Demand is as well defined as a technology. It is characterized by negative available resource which is fed through timeseries of negative values. Demand timeseries were obtained from the Dispa-SET Africa dataset, except for some of the timeseries of SAPP countries, that were instead derived by SESAM Calliope Hydro model. [32], [42] To obtain the demand timeseries for the various regions of Kenya, data from SESAM Calliope Kenya model were utilised to derive the average percentage regional load on the national one. Then the percentages were multiplied for the national timeseries from Dispa-SET dataset, as this is more recent. [32], [41] For Nigeria the national timeseries available in Dispa-SET dataset was divided for the various regions using data about DisCos available on the website of Nigeria’s National Bureau of Statistics. [32], [54]

5.4. Location constraints

There five separate location constraints YAML files, each one describing location constraints specific for each power pool. In these files the locations described in section 4.1 are defined, specifying their name and their coordinates. For each location it is reported how much capacity is installed of each technology, the available resources for hydro, wind and solar, as well as storage for single CSP and pumped hydro power plants.

The following figures show the generation capacity for each country, each picture refers to a power pool. For further information regarding installed power plants a database was created for this project and it is available at https://polimi365-my.sharepoint.com/:f:/g/personal/10533477_polimi_it/EulMWZ8Rtl1Cimnx_uuwyZ0BmknmZ-3DDf7AvFpVnnXLvA?e=EMpyRV.

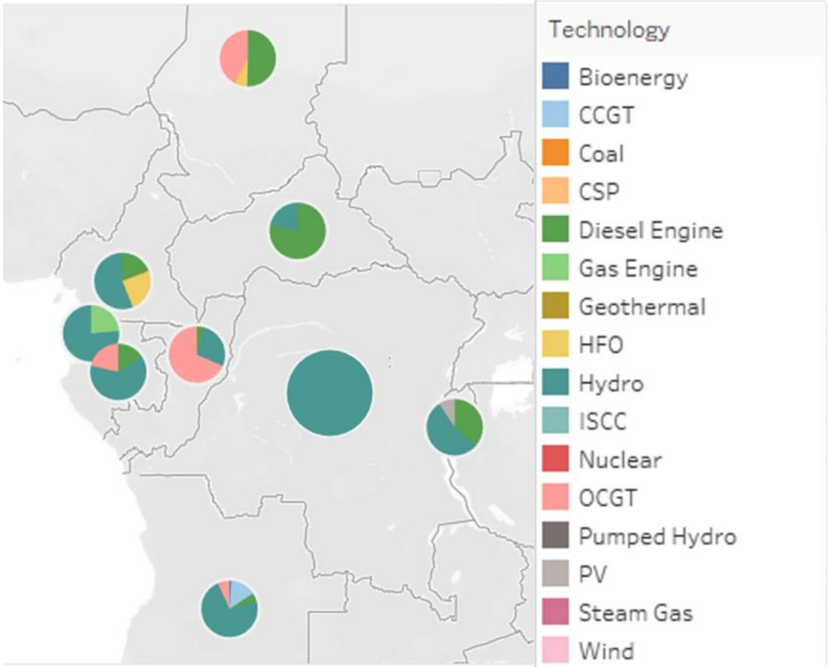

Figure 5.4: Capacity mix for countries included in the CAPP.

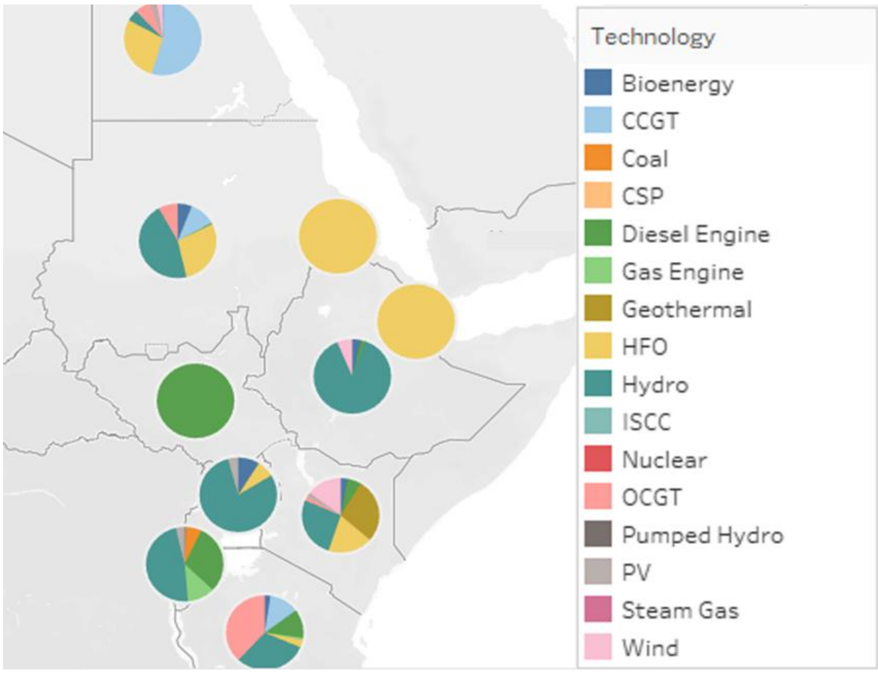

Figure 5.5: Capacity mix for countries included in the EAPP.

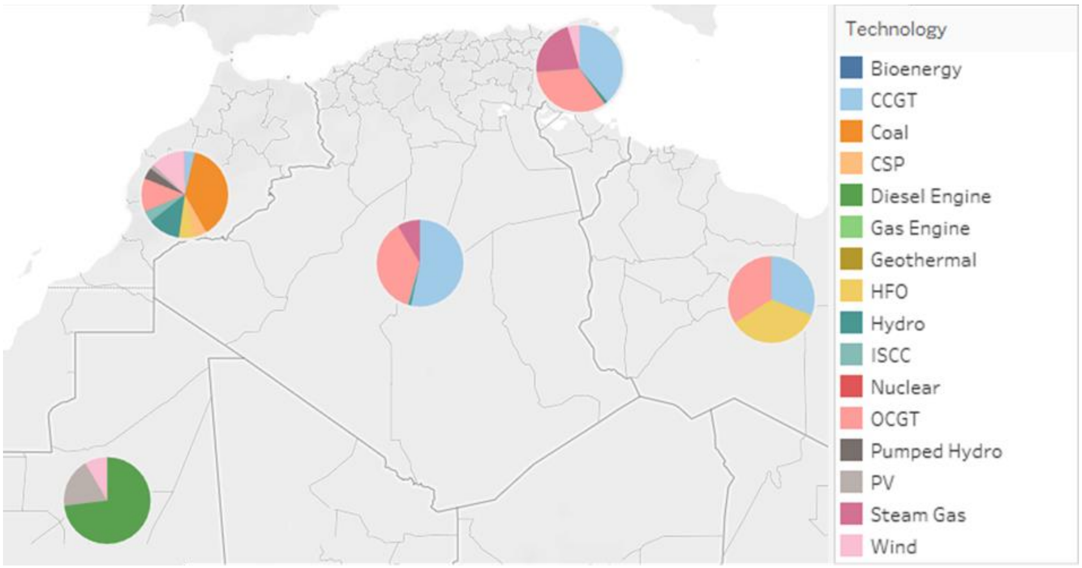

Figure 5.6: Capacity mix for countries included in the NAPP.

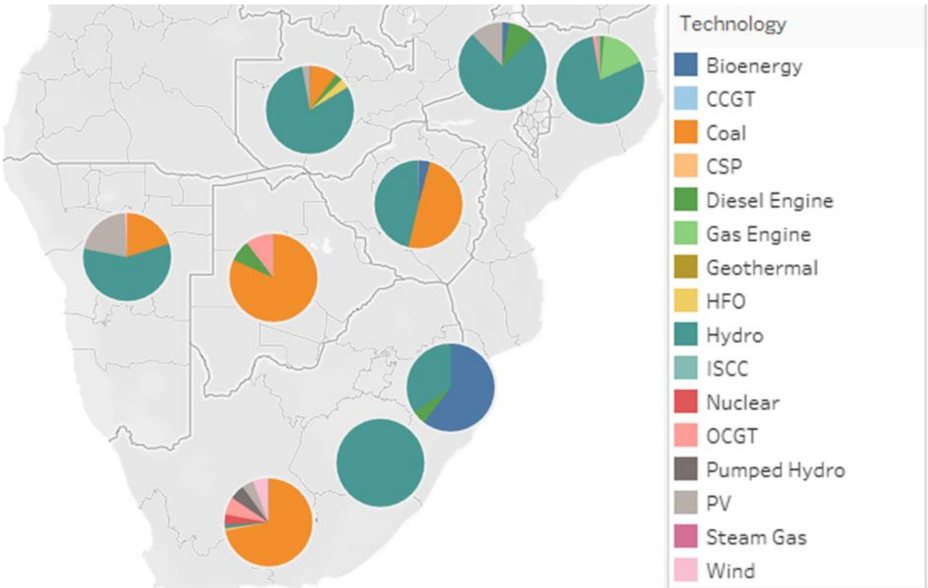

Figure 5.7: Capacity mix for countries included in the SAPP.

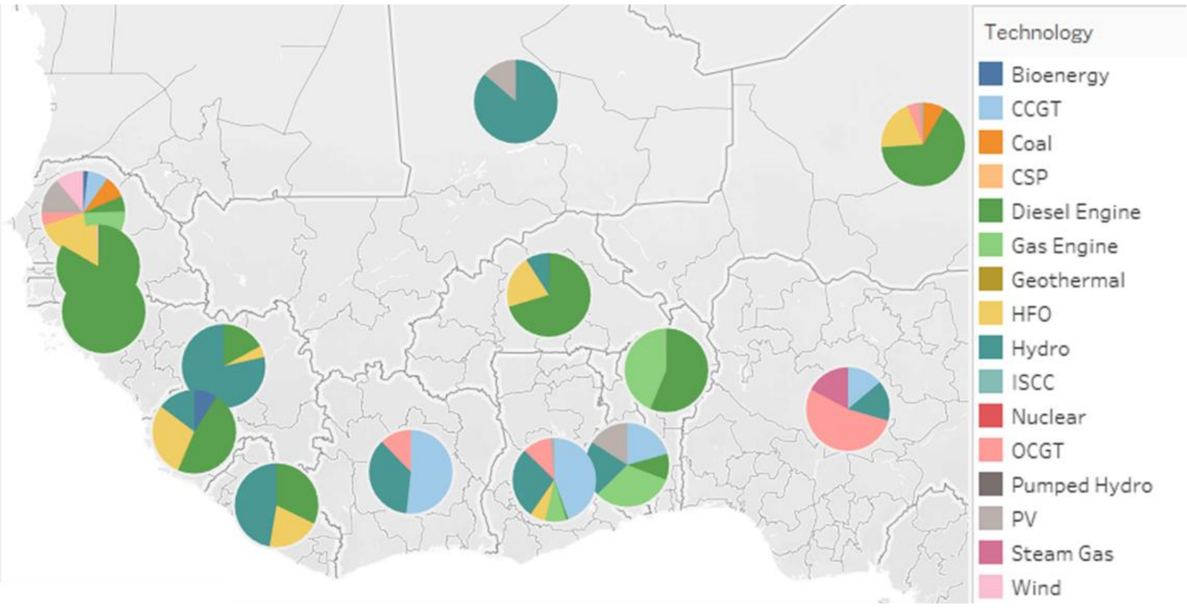

Figure 5.8: Capacity mix for countries included in the WAPP.

5.5. Transmission links

Existing transmission links are reported in five Transmission_Links YAML files, each one referring to a Power Pool. For each link typologies of existing lines, nominal capacities and lengths are reported, as well as estimated efficiency per 10 km of line. In few cases existing links between two countries were not considered as these do not connect the main grids but only secondary ones, therefore connecting only a small percentage of national populations and capacities. The links connecting the African continent to Europe (linking Morocco to Spain) and the Middle East (Egypt to Jordan) were neglected for the sake of simplicity. The external countries could have been modelled as a demand timeseries, but this would have been quite inaccurate since the trades with these countries can vary a lot in different years. Figure 5.9 reports the configuration of the continental grid considered for the base model. Further information for each line can be found in the database created for this project and available at https://polimi365-my.sharepoint.com/:f:/g/personal/10533477_polimi_it/EulMWZ8Rtl1Cimnx_uuwyZ0BmknmZ-3DDf7AvFpVnnXLvA?e=EMpyRV.

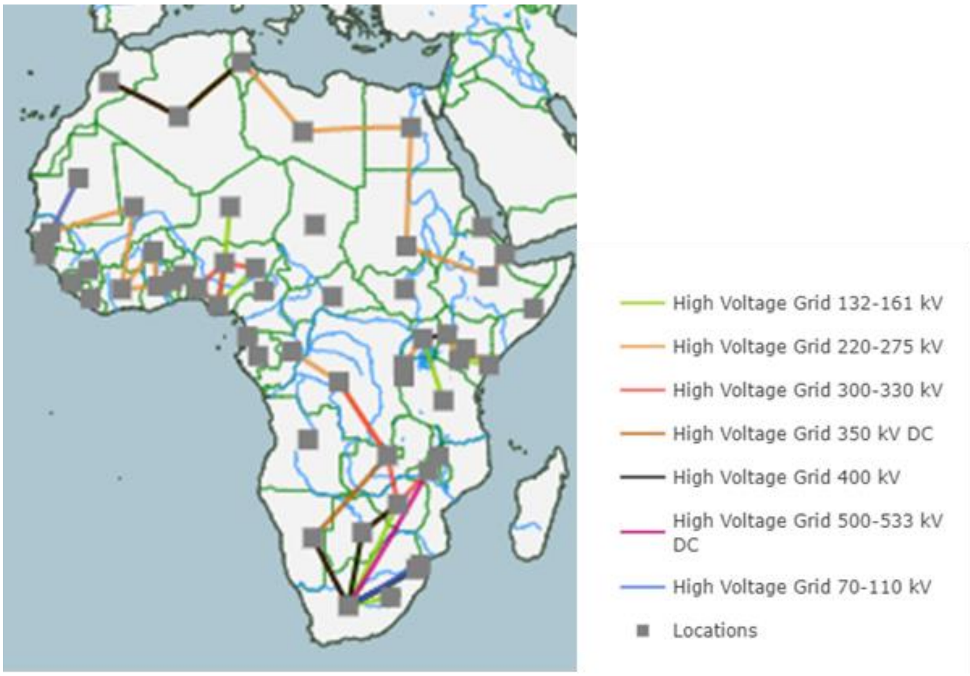

Figure 5.9: Nodes and transmission interconnections considered for the base case.

5.6. New technologies

As already mentioned in section 2.2, the Calliope Africa Model can be run both in operate and planning mode. The first function was used to optimize the operation of existing power stations and transmission grid, while the second one was employed to study the energy system expansion in a variety of scenarios for 2040 based on IEA's Africa Energy Outlook. These scenarios are thoroughly described in chapter 7.

In order to constraint the model in the planning process, installable technologies, maximum installable capacity in each location and possible transmission links must be defined. New installable generation technologies are OCGT, CCGT, ISCC, HFO, nuclear, small and large hydro, PV, CSP, onshore wind, bioenergy and geothermal.

Coal was not included since public opinion is turning against the realization of new power plants, making it difficult for new projects to reach completion. Furthermore, in 2021 China has announced that it would quit financing coal power stations outside national territory and before this announcement almost every proposed coal power station in Africa relied on Chinese financing. [55] It was chosen to consider only gas fueled OCGT and CCGT because, even though the model would prefer oil as a fuel (since it costs less), natural gas is usually preferred since it is free of residues that can damage the turbine and about 90 % of existing gas turbines function using natural gas. [56]

For fossil fuel technologies, the same techno-economic parameters presented in section 5.2.1 were utilized. Updated costs from the IRENA's "Renewable Power Generation Costs in 2020" were used instead for renewable generation technologies, since they experienced substantial variations over the last years (see Figure 1.2).

Regarding new transmission lines, two technologies can be installed by the model to expand the grid, an AC technology and a DC one. It was assumed that new interconnections will be realized with best available technologies, so highest per-distance efficiencies of already existing lines were assumed for new transmission technologies. Investment costs are divided into two parts, one depending on transmission capacity, which are the cost of substations and ACDC converters for DC lines, and one depending on distance, that is the cost of the lines.

Table 5.9: Fixed and O&M costs for new renewable power stations.

	Investment costs	Fixed O&M costs	Variable O&M costs
	[$/kW]	[$/kW]	[$/kWh]
Large Hydro	2045	40.9	-
Small Hydro	2747	82.4	-
PV	971	9.0	-
CSP	3356	-	0.013
Wind	1585	38	-
Bioenergy	1692	50	0.005
Geothermal	3780	97	-

Table 5.10: Techno-economic parameters for new transmission lines.

	Efficiency per distance	Investment costs per TC	Investment costs per distance	Variable O&M costs
	[1/(10 km)]	[$/kW]	[$/(kW*10 km)]	[$/kWh]
AC transmission line	0.995	17.350	40.64	0.0076
DC transmission line	0.9995	247.350	20.32	0.0076

6 Base case: Africa energy system as it is

In this chapter results from running the CalAMo in operational mode over a whole year will be analyzed and compared to real data in section 6.1 to validate the model and prove that the collected data and the represented energy system are sufficiently reliable to be used as a base to shape scenarios, which will be discussed in chapter 7. Then other results from the model for the energy system as-is will be examined as well in section 6.2.

As it was thoroughly explained in chapters 4 and 5, the model receives as inputs all grid-connected technologies and capacities installed in each location, electricity demands, existing links between nodes (with the related transmission limits and distances) and technical and economic parameters that characterize each technology. Then, it operates the obtained energy system according to imposed constraints with the objective of minimizing system total costs.

To obtain all input parameters a multitude of databases, reports, websites and datasets from already existing models were analyzed and compared in order to obtain the most realistic representation of the existing energy system. Anyhow, obtaining trustworthy and complete data on the specific characteristics of the Africa energy system is a very difficult task, since even the most reliable databases are in most cases inconsistent with each other or lack of completeness or are not updated. So, even if every single data was checked multiple times and is based on the comparison of multiple sources, it is necessary to validate the model comparing its results with real data about production.

Moreover, every model is intrinsically wrong as it is based on simplifications and assumptions. For example, the CalAMo uses a multi-nodal representation of space that neglects, for instance, many national and regional transmission limits. Technologies are as well simplified and the parameters that describe them are derived from assumptions, even though they are based on typical data for existing plants. Additionally, the model simply operates the energy system to optimize system total costs, but this is an idealization of the real situation. Local grid operators could operate power plants and grids following other logics or they could be limited by external factors such as lack of coordination between utilities and governments or political instability. [31], [57]

6.1. Comparison of energy mixes resulting from CalAMo and IEA data for 2019

In order to verify that the model results are comparable with the real situation, IEA data regarding the energy mix for 2019 will be compared with the one resulting from the model for the entire continent and for 15 selected countries, which comprise about 73 % of the continent's population and more than 85 % of energy production (according to 2019 IEA data). It was chosen to use data from 2019, since it is the last year with IEA data available for all selected countries and to avoid any possible influence of the COVID-19 pandemic. Timeseries for resource availability for renewable energy sources refer as well to 2019, since it was preferred to model a 365-day year (2020 was a leap year), except for hydro timeseries which generically refer to a year with average precipitations. Electricity demand timeseries were originally for 2015 but were recalibrated so that the produced electricity matches total production at country level for the 15 most significant countries with the one of IEA data for 2019. Demands in other countries were homogenously recalibrated to match total Africa production in 2019, which amounted to 856499 GWh. Installed power plants are updated to February 2022.

In Figure 6.1 it is displayed the energy mix of Africa from IEA data and from the model results. It can be observed that the percentages from coal (IEA 30.3 %, CalAMo 31.6 %), natural gas (IEA 39.1 %, CalAMo 40.3 %), hydro (IEA 16.5 %, CalAMo 16.9 %), nuclear (IEA 1.5 %, CalAMo 2 %) and geothermal (IEA 0.7 %, CalAMo 0.6 %) are similar in the two graphs. It is interesting to notice that though at local level there are differences in hydro production due to variations in local precipitations (see following figures), at the continental level these differences balance out. Since the aim of this project is to favor the penetration of renewable energy sources in the African energy mix, it was decided to force PV and wind power stations to always produce when the source is available. Therefore, production from wind and PV in Africa results a bit higher in Calliope results (4 %) than IEA data (2.9 %). Oil power plants, in particular Diesel engines, do not result convenient for the model due to relatively low efficiency (for example, with respect to most gas power plants) and relatively high fuel costs (with respect to coal). Because of this, production from oil power stations is significantly lower in Calliope model (4.1 %) than in IEA statistics (8.3 %). Anyhow, many Diesel engines are mainly used for emergencies that can derive by exceeding transfer limits in local grids, but these are not perceived by the model due to the nodal representation of countries or regions.

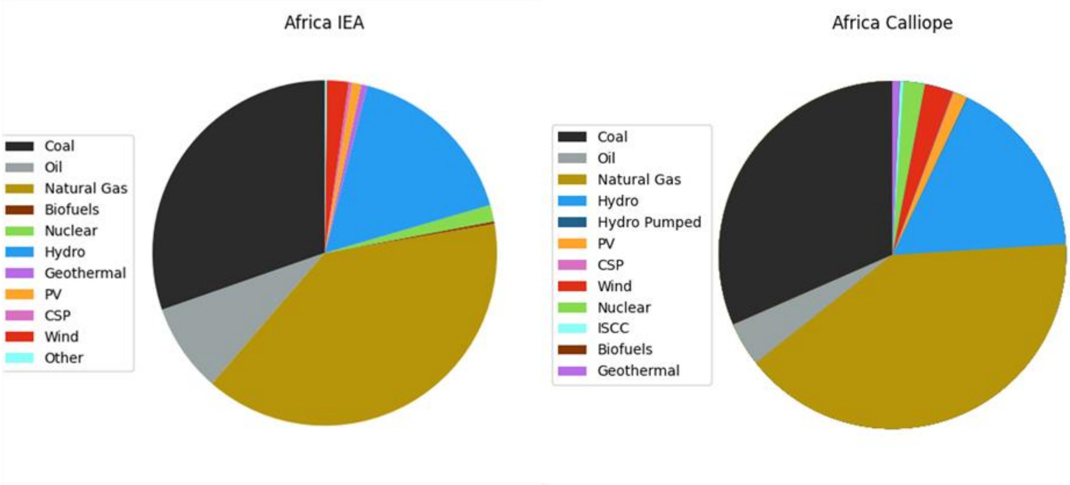

Figure 6.1: Electricity generation mix of Africa from 2019 IEA data and from CalAMo base case results.

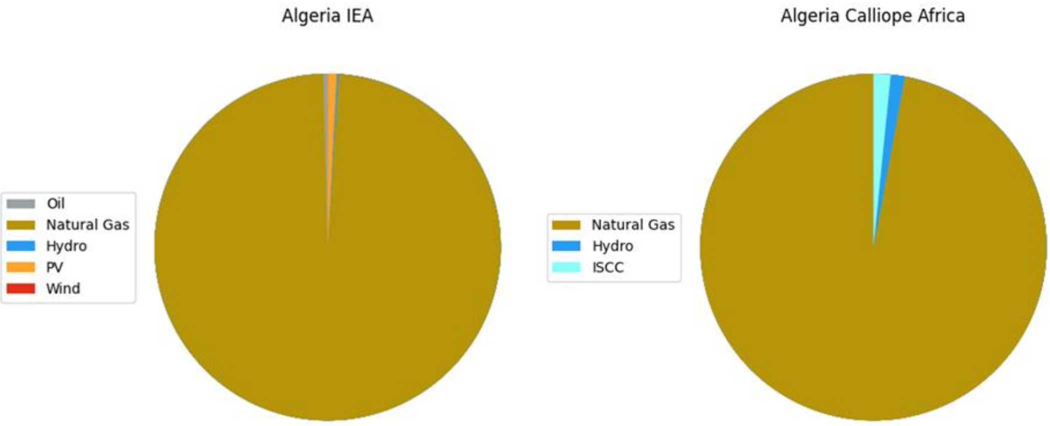

Figure 6.2: Electricity generation mix of Algeria from 2019 IEA data and from CalAMo base case results.

Results for Algeria (Figure 6.2) are very similar to reality and show an energy mix dominated by natural gas (98.6 % IEA, 98.7 % for CalAMo including ISCC). The main differences are the larger production by hydro in the model, probably due to lower rains in Algeria in 2019 with respect to the average year, and production from PV in IEA data. PV was not included in Algeria capacity because existing plants are off-grid or installed on secondary grids.

In Figure 6.3 it is shown the comparison for Angola. Most of the production relies on hydro in both cases and the resulting share is very similar to reality (69.6 % in the model, 70.4 % in IEA statistics). The most relevant difference is the share of production from gas and oil, even though their sum is almost equal in the two cases (IEA 29.6 %, CalAMo 29.3 %). In the model gas is preferred to oil, resulting in 24.5 % of production, against 10.6 % in IEA data. This difference may be due to the 750 MW Soyo I CCGT power plant, completed only by May 2019 but considered in the model for the whole year, and to grid limitations that are not considered in the model (Angola has two secondary grids that are not connected to the main one). In model results there is as well a small share that is produced using bioenergy.

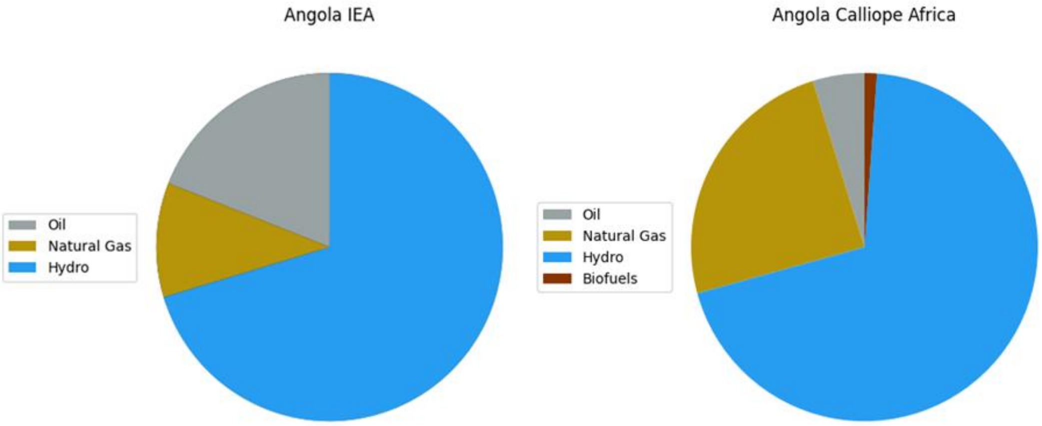

Figure 6.3: Electricity generation mix of Angola from 2019 IEA data and from CalAMo base case results.

Cameroon representation in Figure 6.4 shows a significant difference in production from hydro that is due to higher rainfalls in 2019 with respect to the average, since the model fully exploits the hydro power plants with the capacity factors typical of an average hydrological year. The missing production in model results due to lower production from hydroelectric is covered for a small part using gas plants, but mainly increasing production from oil power plants. CalAMo just utilizes hydroelectric to cover Congo DR demand (Figure 6.5), with a very small difference with 2019 data, where a 0.5 % of the production was covered using Diesel and PV.

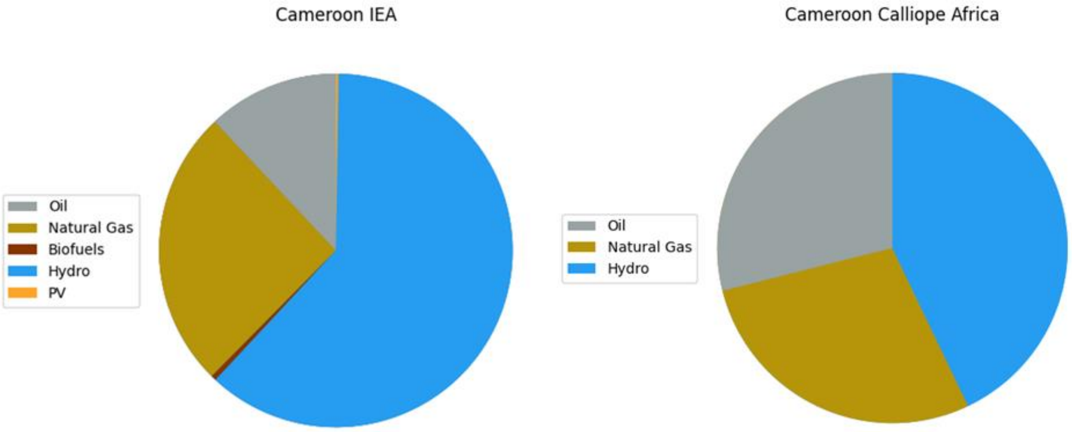

Figure 6.4: Electricity generation mix of Cameroon from 2019 IEA data and from CalAMo base case results.

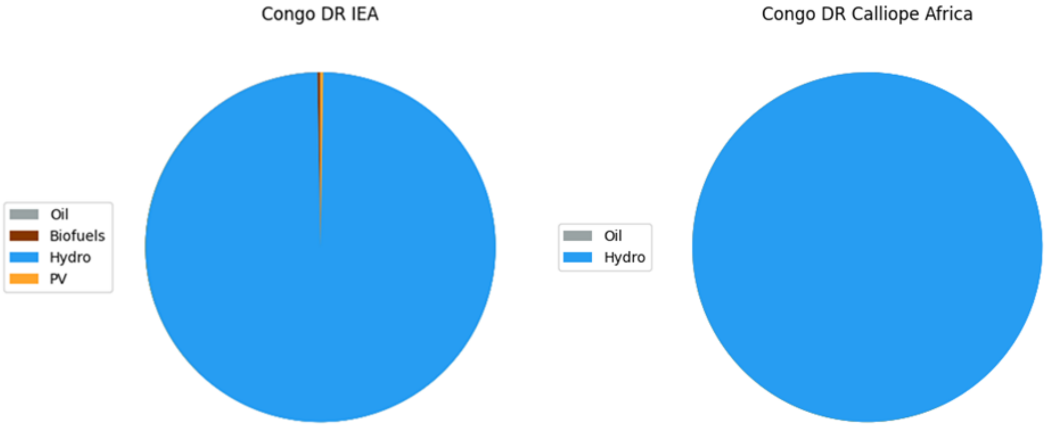

Figure 6.5: Electricity generation mix of Congo DR from 2019 IEA data and from CalAMo base case results.

The case of Côte d'Ivoire is similar to the one of Cameroon, since real production from hydro is larger in IEA statistics due to higher rainfalls in 2019. This part is covered through OCGT and CCGT power plants.

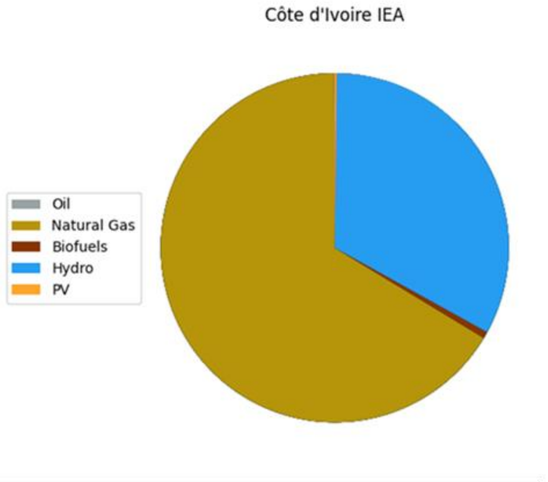

Figure 6.6: Electricity generation mix of Côte d'Ivoire from 2019 IEA data and from CalAMo base case results.

Model results for Egypt (Figure 6.7) have higher percentages of production from hydro (10.1 % CalAMo, 6.8 % IEA) for annual variations in rainfalls and from PV and wind (respectively 1.9 % and 3.1 % for CalAMo, 0.8 % and 1.9 % for IEA) since these sources are forced to produce in the model. Electricity production from gas power plants, particularly CCGT, results preferable for CalAMo which covers a higher share using this technology with respect to data (82.3 %, while it is 77.3 % in IEA statistics). The remaining part is covered through oil plants.

Ethiopia data and model results are very similar. Hydroelectric covers 96.3 % of production according to IEA statistics, while it produces 96.9 % in model results. The remaining part is covered through wind.

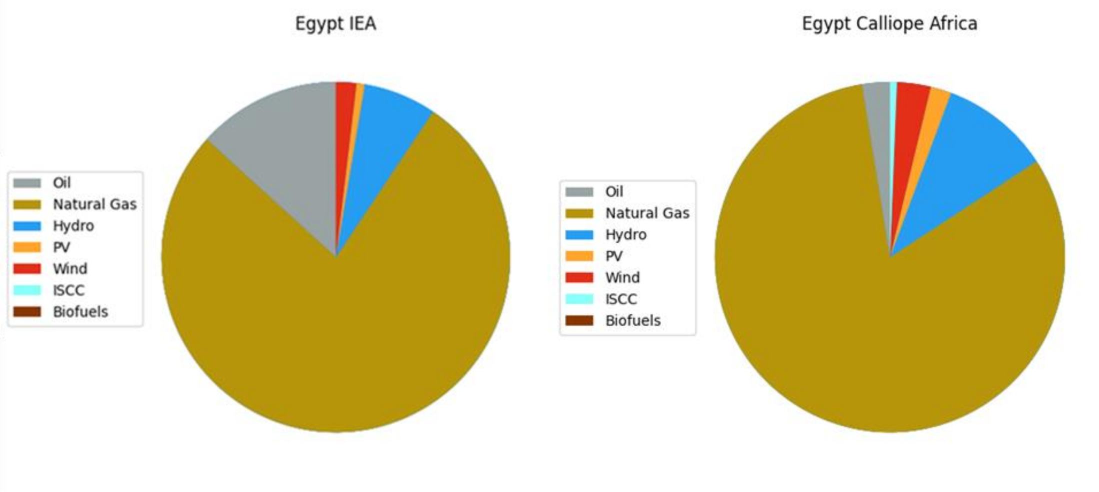

Figure 6.7: Electricity generation mix of Egypt from 2019 IEA data and from CalAMo base case results.

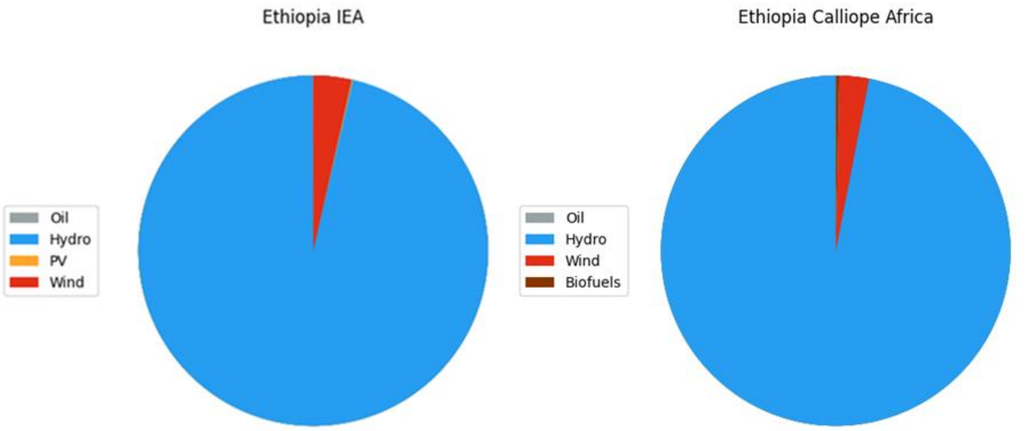

Figure 6.8: Electricity generation mix of Ethiopia from 2019 IEA data and from CalAMo base case results.

Ghana as well shows a difference in hydro production due to higher water abundance in 2019, so production according to IEA (42 %) is sensibly higher than model results (30.8 %). Production from gas is comparable and the remaining part is produced by oil power plants, which have a larger share in the model to compensate for the lower production by hydroelectric.

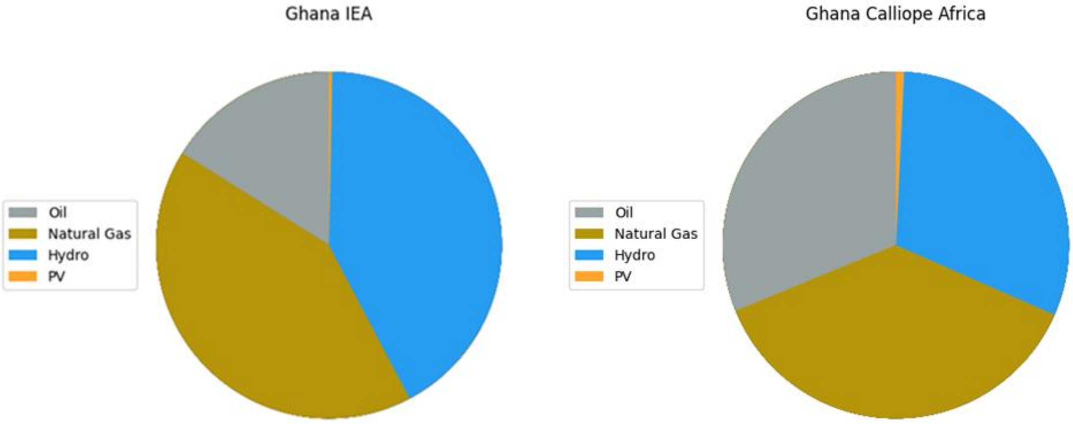

Figure 6.9: Electricity generation mix of Ghana from 2019 IEA data and from CalAMo base case results.

Kenya, in Figure 6.10, relies mostly on geothermal energy and since this does not have related combustible costs and can reach very high capacity factors it is vastly exploited by the model. The results from CalAMo show a higher reliance on geothermal with respect to direct surveys (57.7 %, 45.5 % according to IEA) since the model considers Olkaria 5 plant, which increased Kenya geothermal capacity from 660 to 825 MW, for the whole year, even though this was commissioned only in the second half of 2019. Roughly a third of the energy mix utilizes hydro, with slightly lower production in IEA data due to rainfalls variations. PV produces 1 % of energy in both cases, while wind production results relevantly smaller in the model. Since wind farms were accurately modelled considering their real positions, turbine models and resource availability for 2019 and their production was forced, this could be due to discrepancies between sources, which is a very common issue for data about Africa. The remaining part is covered using oil plants, with a larger share in IEA statistics due to the lower production from geothermal. Electricity is produced mainly from coal in Morocco (Figure 6.11), but the share resulting from the model is higher (78.1 %, 64.6% for IEA), probably because since Morocco depends on imports for coal, for energy security concerns it is preferable to diversify the energy mix, thus producing a fraction using gas and oil. Production from hydro was lower in 2019 due to variations in precipitations. CSP is less exploited in the model because CSP plants were mainly planned for exports and the model does not consider the interconnection with Spain. [58] The remaining part of production is accomplished using wind and PV power stations. Differences of results for wind are similar to the ones discussed for Kenya.

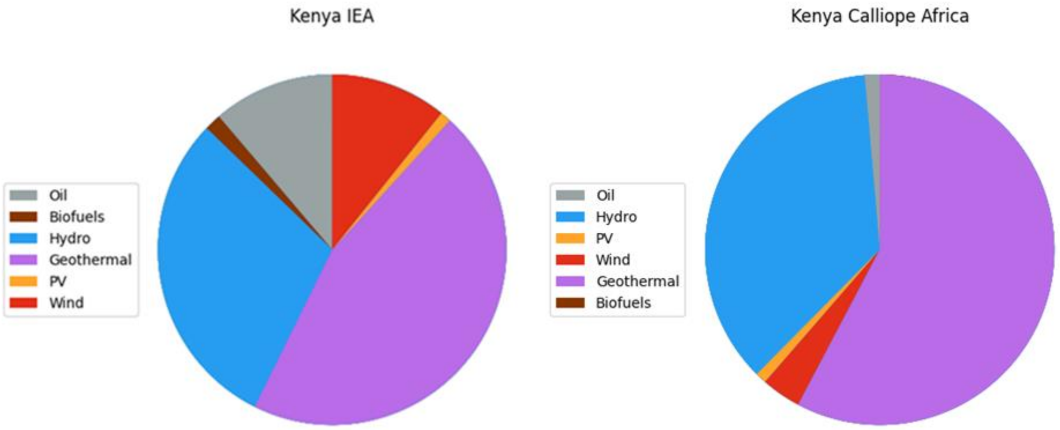

Figure 6.10: Electricity generation mix of Kenya from 2019 IEA data and from CalAMo base case results.

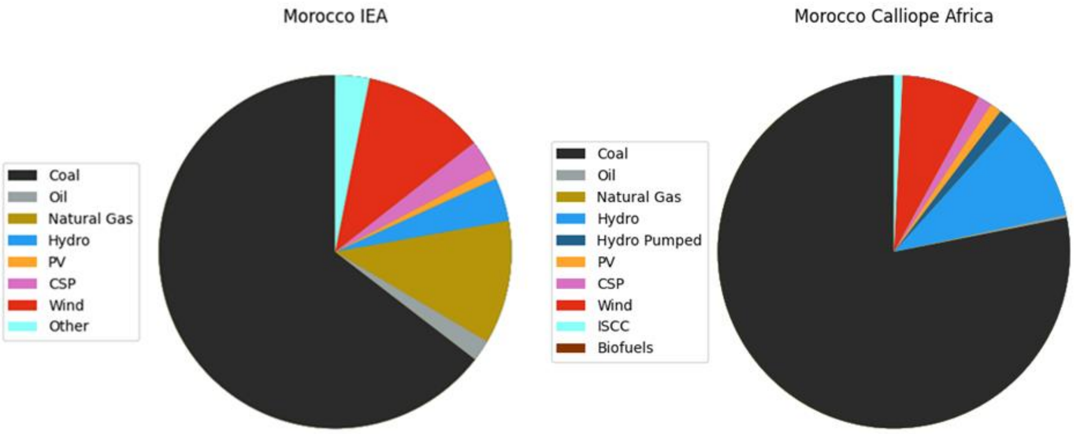

Figure 6.11: Electricity generation mix of Morocco from 2019 IEA data and from CalAMo base case results.

In Mozambique, Nigeria and Sudan (Figure 6.12, Figure 6.13Figure 6.14) higher shares of hydro are observable in IEA statistics for the already discussed differences in water availability. The remaining part is produced using natural gas power stations in the first two countries and oil power plants in the other.

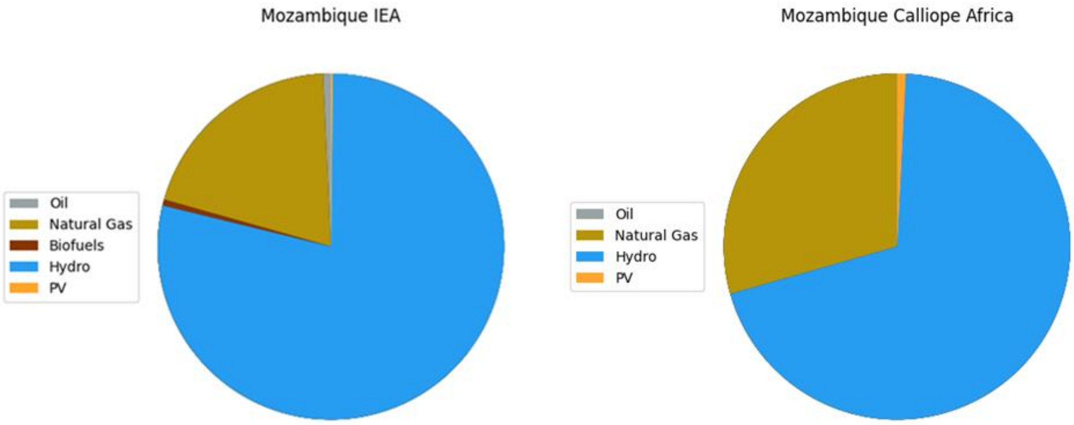

Figure 6.12: Electricity generation mix of Mozambique from 2019 IEA data and from CalAMo base case results.

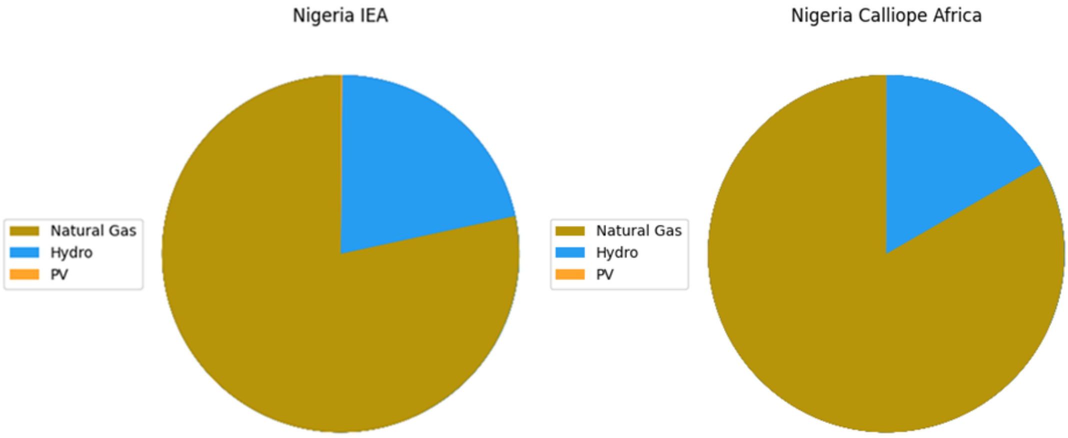

Figure 6.13: Electricity generation mix of Nigeria from 2019 IEA data and from CalAMo base case results.

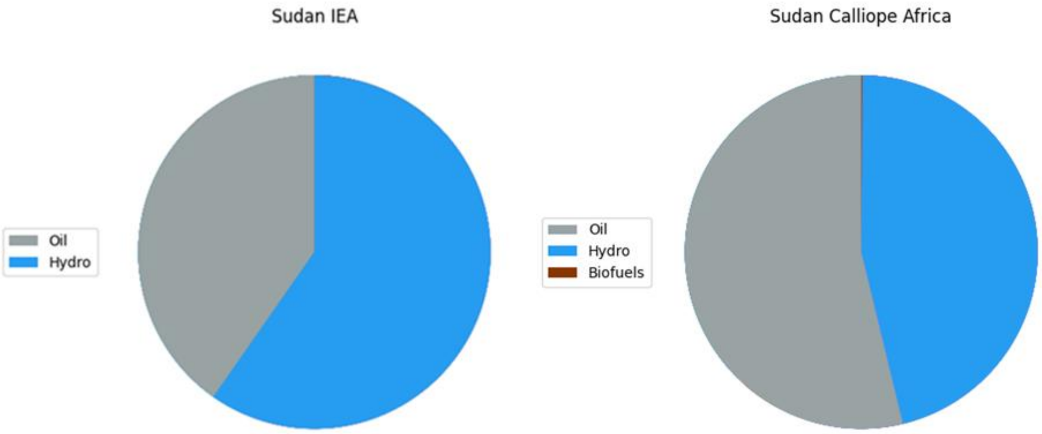

Figure 6.14: Electricity generation mix of Sudan from 2019 IEA data and from CalAMo base case results.

In Figure 6.15 the comparison for South Africa is displayed, showing very similar quantities of production from coal and nuclear in the two graphs (IEA coal 87.7 % and nuclear 5. 2 %, CalAMo 87.1 % and 6.6 %). The other sources for electricity are wind and PV, with a slighter higher share in the model since they are forced to produce, and hydro which is a higher in IEA statistics.

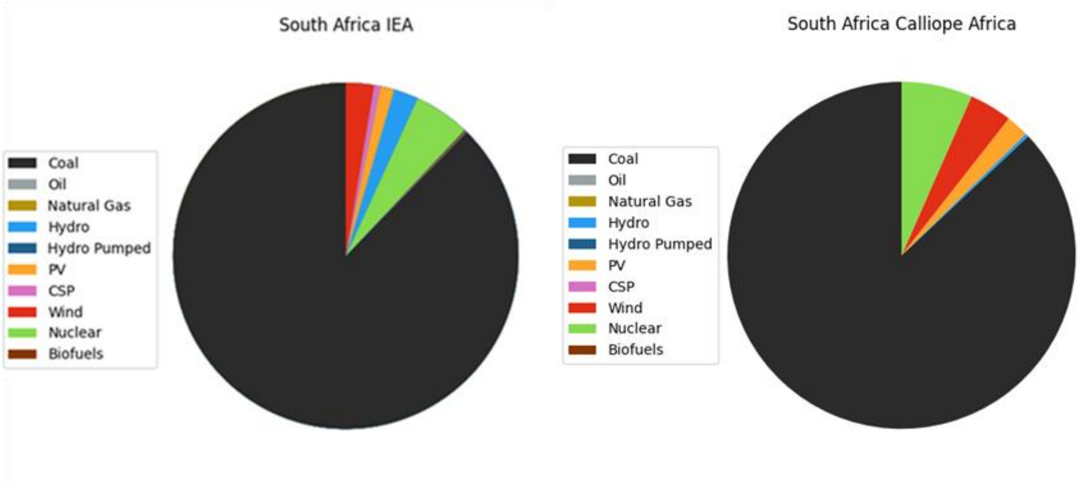

Figure 6.15: Electricity generation mix of South Africa from 2019 IEA data and from CalAMo base case results.

Shares of the energy mix for Tanzania (Figure 6.16) for hydroelectric and fossil fuel power plants are comparable, anyhow the model favors production from gas power stations, thus resulting in lower production from oil.

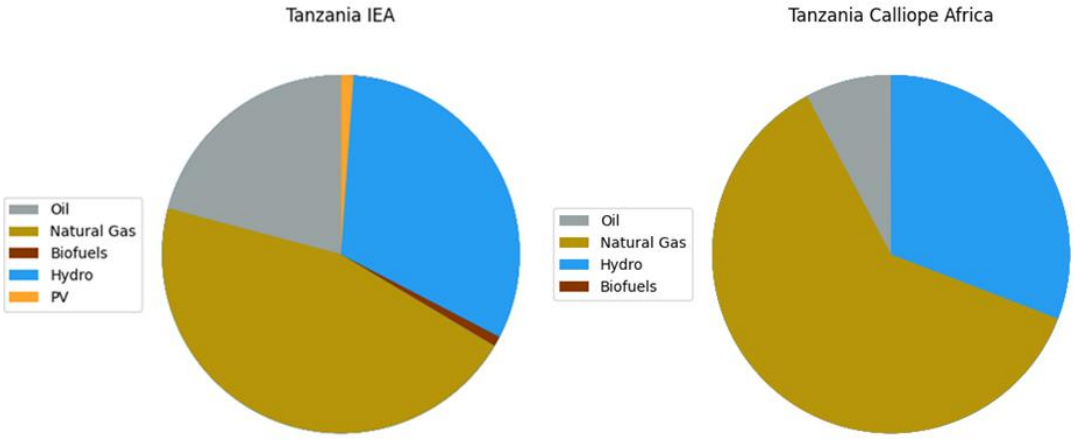

Figure 6.16: Electricity generation mix of Tanzania from 2019 IEA data and from CalAMo base case results.

In the end it can be concluded that though some small differences are present, in particular the ones related to hydroelectric production for local weather variations, the model is overall representative of the energy system. Keeping a focus on the large scale, the energy mixes are comparable and at the continental level the results are quite precise. CalAMo can therefore be used to develop further analyses of scenarios and grid expansions.

6.2. Other results from CalAMo base case

Electricity production by technology as a function of time and comparisons between production and demand at power pool level are displayed in figures from Figure 6.17 to Figure 6.21.

CAPP is dominated by hydro production, so countries have high dependence on water availability for electricity production. Unmet demand is present in Cameroon, Equatorial Guinea and Gabon during dry seasons, since water availability decreases substantially and so does production from hydroelectric plants. The second source of electricity is natural gas, which is utilized particularly from June till December, due to the seasonality of rainfalls in Angola and Congo-Brazzaville, where most natural gas power stations are installed. It is interesting to notice that dry season occurs in different months for different countries, for example it is from June to September in Angola and Congo-Brazzaville, while it is from December to April in Cameroon. Because of this thermal power plants installed in Angola and Congo-Brazzaville, which are underutilized during wet seasons, could be used to cover most, if not all, of unmet demand in the power pool. Anyhow this not possible due to the underdevelopment of the transmission grid and lack of interconnections in this region. Congo DR, thanks to its large installed hydro capacity, has relevant exports towards Zambia, which is the only country importing electricity from CAPP. In fact, this is the only relevant exchange of electricity between two power pools in the whole continent.

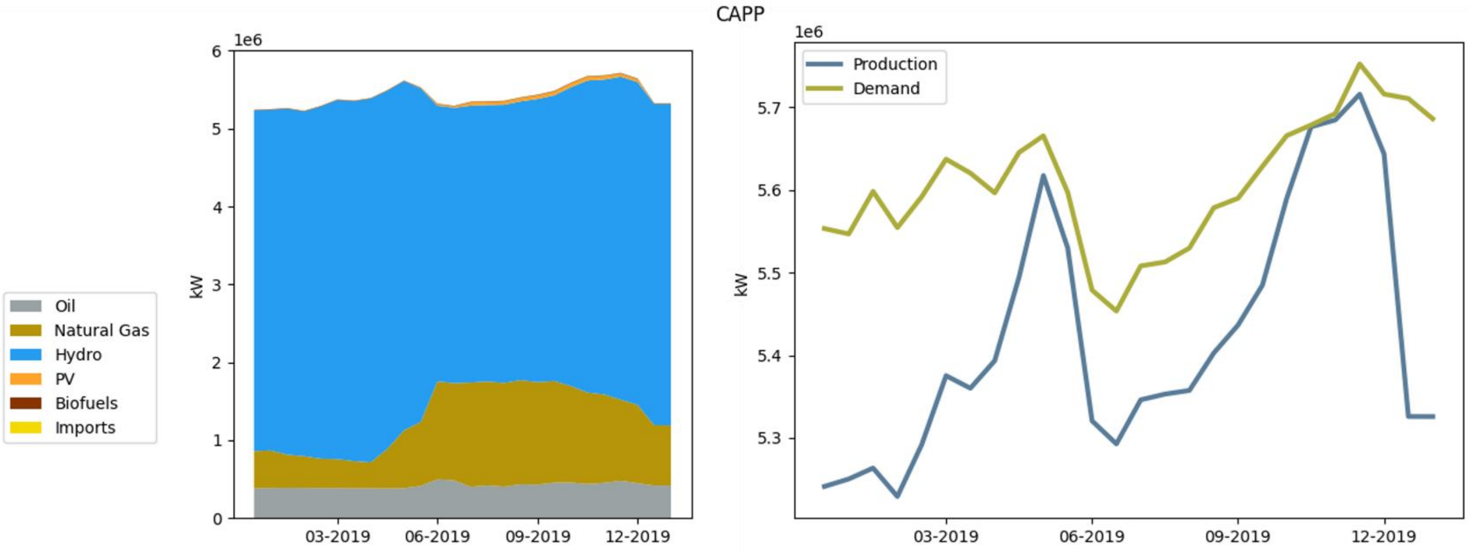

Figure 6.17: Power generation by source along the year and comparison between production and demand for CAPP.

In NAPP and EAPP (Figure 6.18 andFigure 6.19) electricity demand is always met by generation. NAPP mix is dominated by fossil fuels, particularly gas and coal and shows a peak of production and demand during summertime. EAPP main source is as well gas, mainly due to Egypt, while other countries have more varied mixes. The seasonal peak for EAPP is mainly due to Egypt, since other countries have less pronounced changes of demand with seasons due to their geographical position.

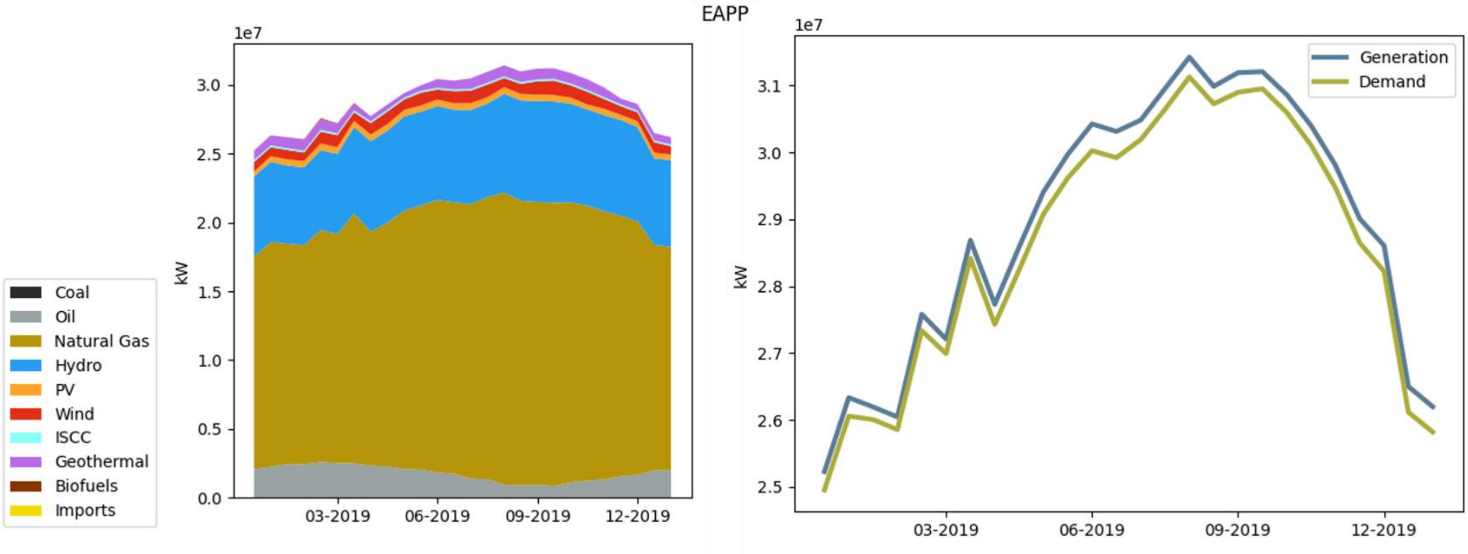

Figure 6.18: Power generation by source along the year and comparison between production and demand for EAPP.

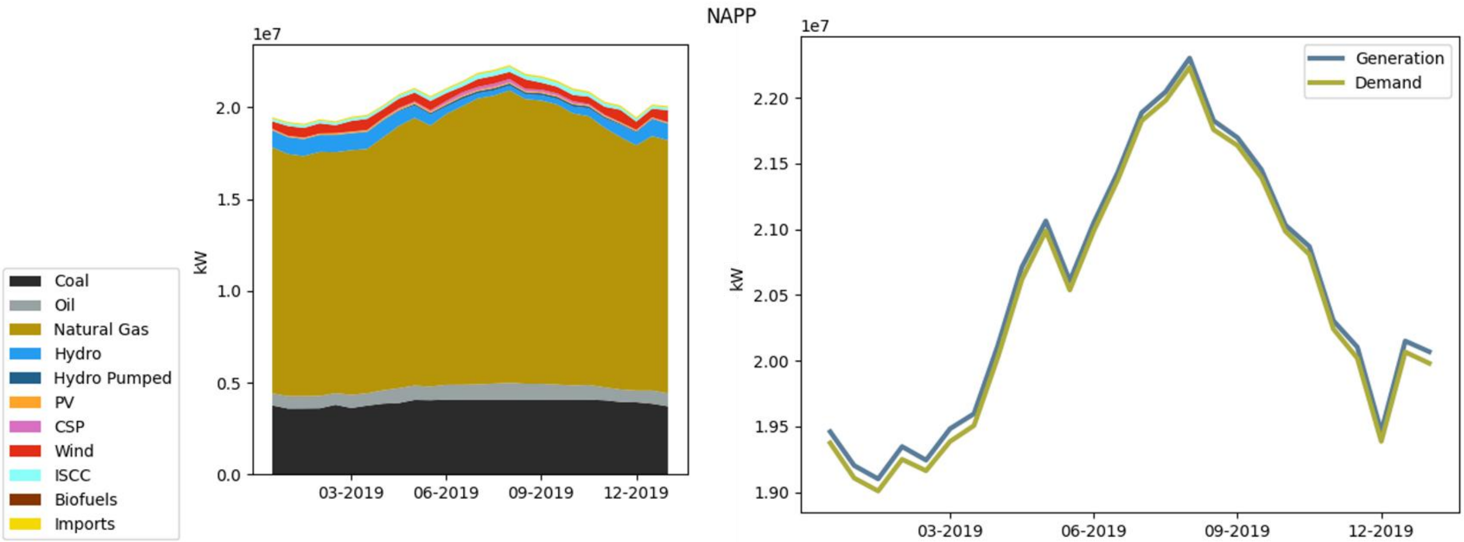

Figure 6.19: Power generation by source along the year and comparison between production and demand for NAPP.

SAPP principal source of production is coal, since most of production is in South Africa, followed by hydro and nuclear. Seasonality is sharply marked with a peak of demand in summer. In most countries energy balance is always maintained, except for Malawi, where demand is never totally met (in particular from May to December, during Malawi dry season). This shows necessity to install new capacity in Malawi or to create interconnections to other countries, since Malawi is isolated from SAPP grid. In WAPP gas and hydro are mainly used to produce electricity. There is not a pronounced seasonality, since its countries are all located at low latitudes. Installed capacity is sufficient to cover electricity demand in every country. Furthermore, production always lies well above demand since there is a significant amount of imports and exports of electricity within the power pool, so that additional production is needed to cover transmission lines losses.

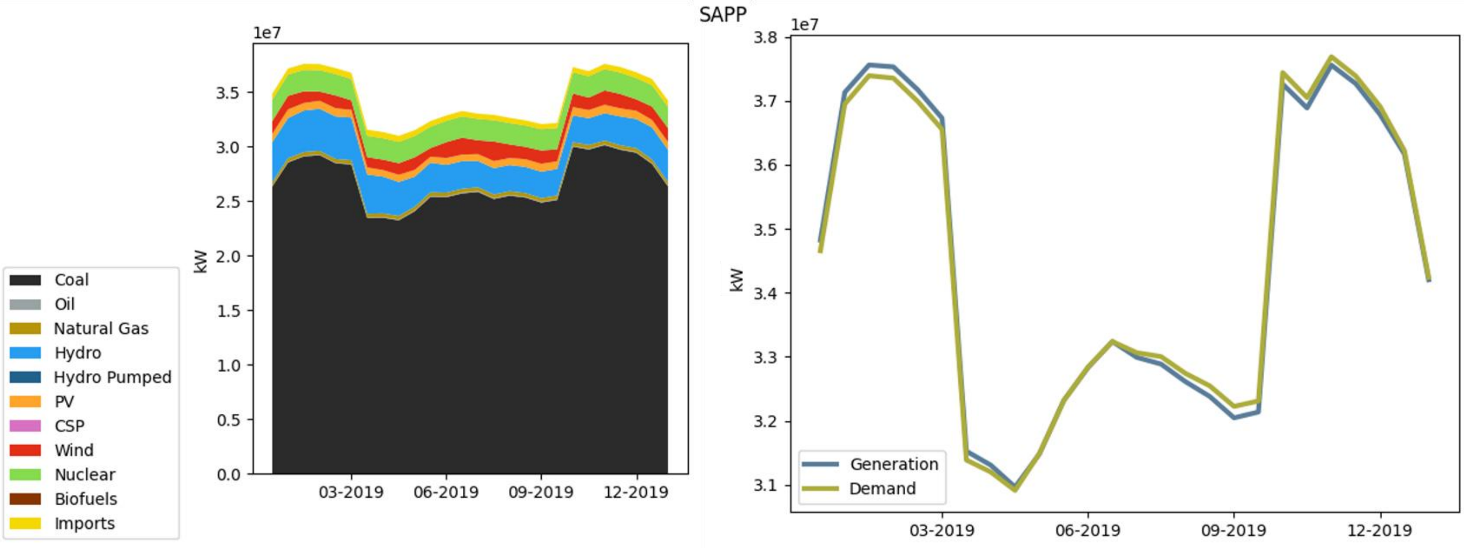

Figure 6.20: Power generation by source along the year and comparison between production and demand for SAPP.

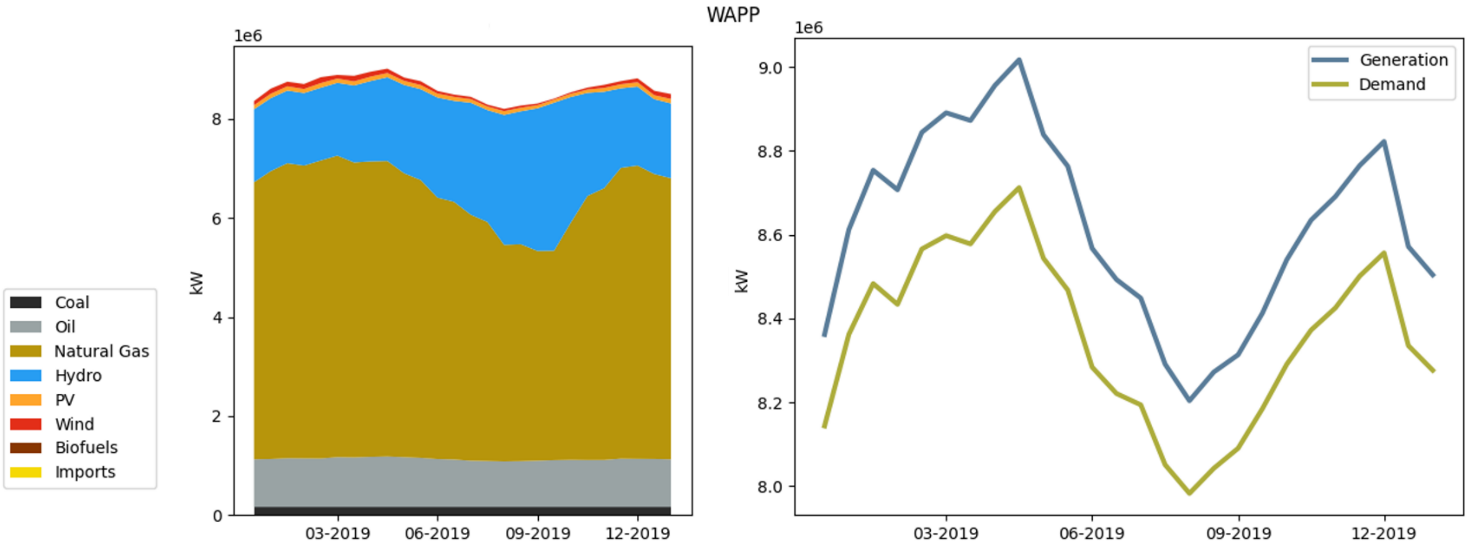

Figure 6.21: Power generation by source along the year and comparison between production and demand for WAPP.

7 Horizon 2040: creating scenarios using the Calliope Africa Model

In this chapter scenarios for 2040 will be introduced and then results obtained from running the model in planning mode for each case will be examined. Though it would be ideal to run CalAMo at the continental level to take into account interactions between different regions and possible interconnections between power pools, scenarios had to be run for single power pools due to limited availability of computational power. For the same reason, runs for EAPP, SAPP and WAPP had to be performed using simplified models, that reduced the number of nodes. The nodes considered for these power pools, separated by semicolons, are the following:

- **EAPP:** Egypt and Sudan; Ethiopia, Djibouti, Eritrea and Somalia; Kenya and Tanzania; Rwanda, South Sudan and Uganda.
- **SAPP:** Botswana, Namibia and Zimbabwe; Malawi and Zambia; Mozambique; South Africa, Eswatini and Lesotho.
- **WAPP:** Benin, Togo, Burkina Faso, Mali and Niger; Côte d'Ivoire and Ghana; Guinea, Guinea Bissau, Liberia, Sierra Leone, Senegal and The Gambia; Nigeria.

As it was explained in chapter 4, the model receives as input demand timeseries and constraints that define the existing power system. While in operational mode the model is only able to use existing technology to optimally meet demand, in planning mode it is as well allowed to expand the existing system using a given set of installable technologies. In this case study, CalAMo can expand the power system using the technologies described in section 5.6. Since renewable generation technologies are subject to local resource availability, maximum installable capacities were defined for each location using technical potentials mainly derived from IRENA and JRC reports. [59]–[61] When local technical potentials for a technology could not be found and gave origin to unreasonable results, they were conservatively assumed to be zero. New VREs technologies were modelled considering available resource in the coordinates of the respective node. Instead, fossil fuel and nuclear technologies were not limited, assuming that infinite quantities of fuels could be produced or imported. New transmission lines can be installed to create new interconnections but also to expand existing ones.

7.1. Considered scenarios

First of all, two scenarios were created to consider two possible projections of electricity demand. 2040 was chosen as target year for scenarios since demand projections are based on scenarios for 2040 described in IEA's 2019 Africa Energy Outlook. Demand timeseries were obtained starting from the base case ones and increasing them accordingly to IEA's predictions. The two scenarios depicted in this report are Stated Policies Scenario (STEPS), which considers currently active and announced policies, and Africa Case scenario (AC), which is a scenario considering fast economic and industrial development in accordance with AU's Agenda 2063. [36] These scenarios were only utilized to project electricity demand, while other implications that could derive from these settings were not considered. Country specific projections of electricity demand were utilized when given in the report to obtain timeseries for 2040, while for other countries it was assumed that they would grow homogeneously to reach the overall projected demand for Africa.

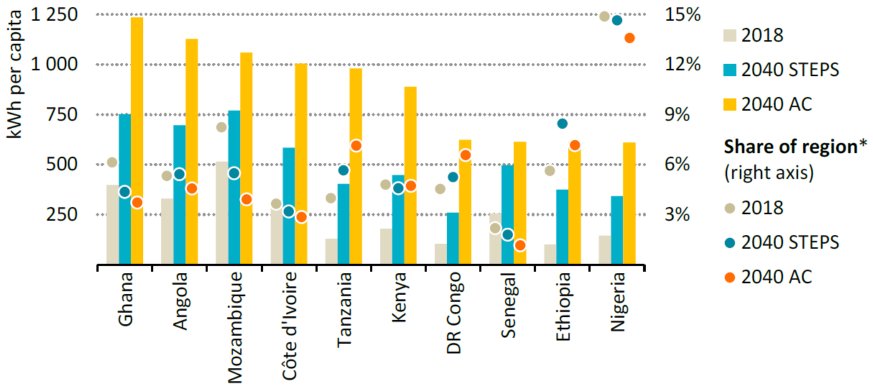

Figure 7.1: Per-capita electricity demand in 2018 and in 2040 for STEPS and AC scenarios and share of electricity demand on Sub-Saharan Africa (excluding South Africa) for selected countries.

In the following figures resulting annual demands for nodes in each power pool are displayed for STEPS and AC scenarios. The largest electricity market is EAPP, while the smallest one is CAPP. In STEPS case Angola is the largest consumer in CAPP, but in Africa Case fast growth in Congo DR allows it to catch up and become the principal actor in the region. In EAPP and SAPP more than 60 % of electricity demand is concentrated in a single node, respectively Egypt-Sudan and South Africa. In AC scenario the Kenya-Tanzania node gains importance in the EAPP, overtaking Ethiopia. In WAPP about 50 % of demand is in Nigeria and another 30 % is in Côte d'Ivoire-Ghana. In NAPP Algeria is responsible for approximately 40 % of consumption.

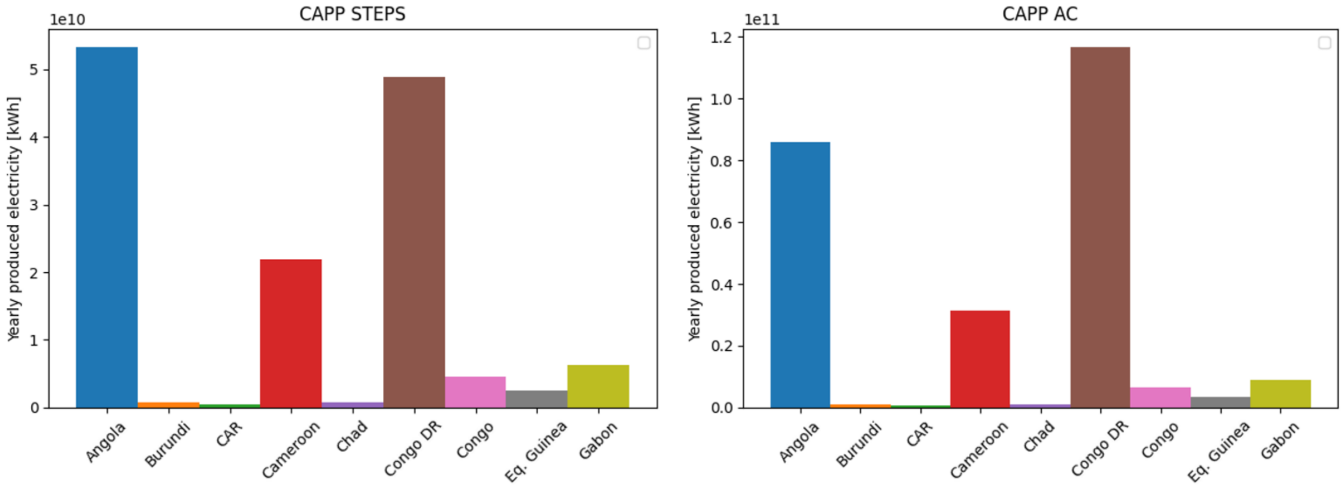

Figure 7.2: Annual electricity demand in CAPP by node in STEPS and AC scenarios.

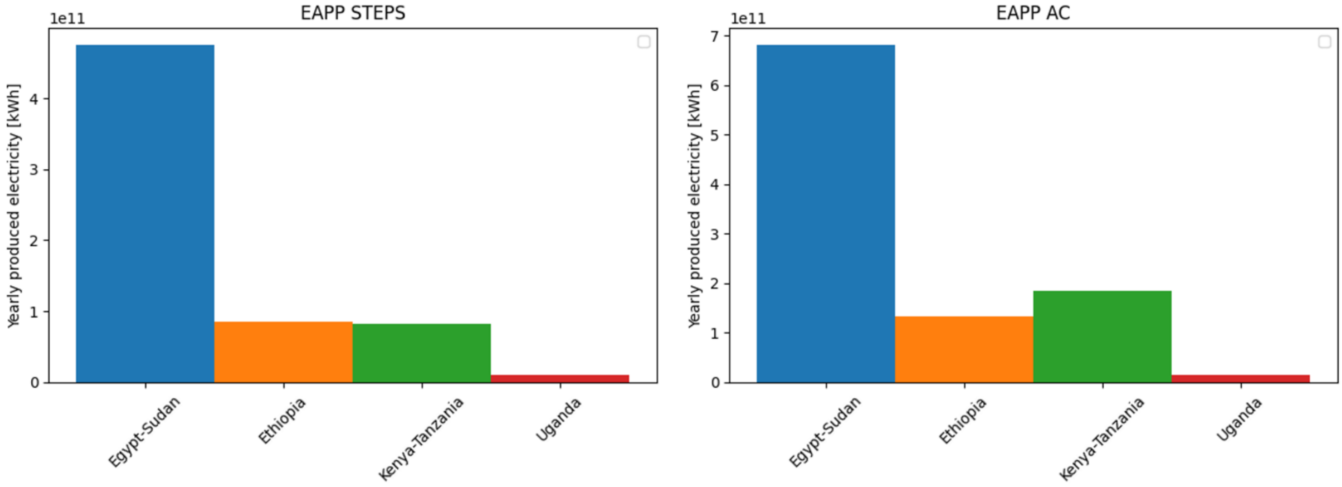

Figure 7.3: Annual generated electricity in EAPP by node in STEPS and AC scenarios.

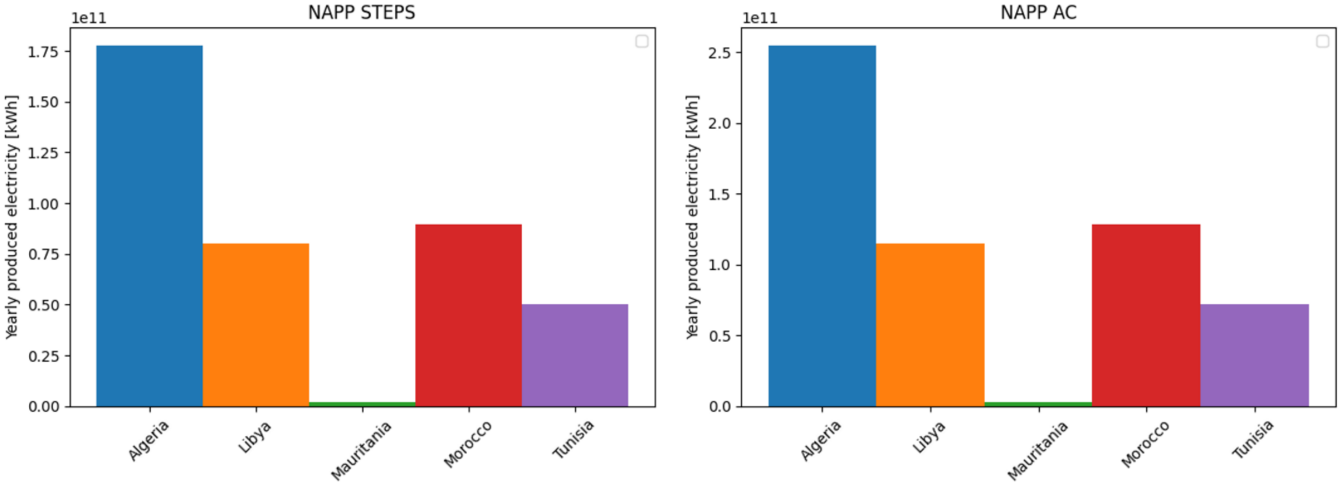

Figure 7.4: Annual generated electricity in NAPP by node in STEPS and AC scenarios.

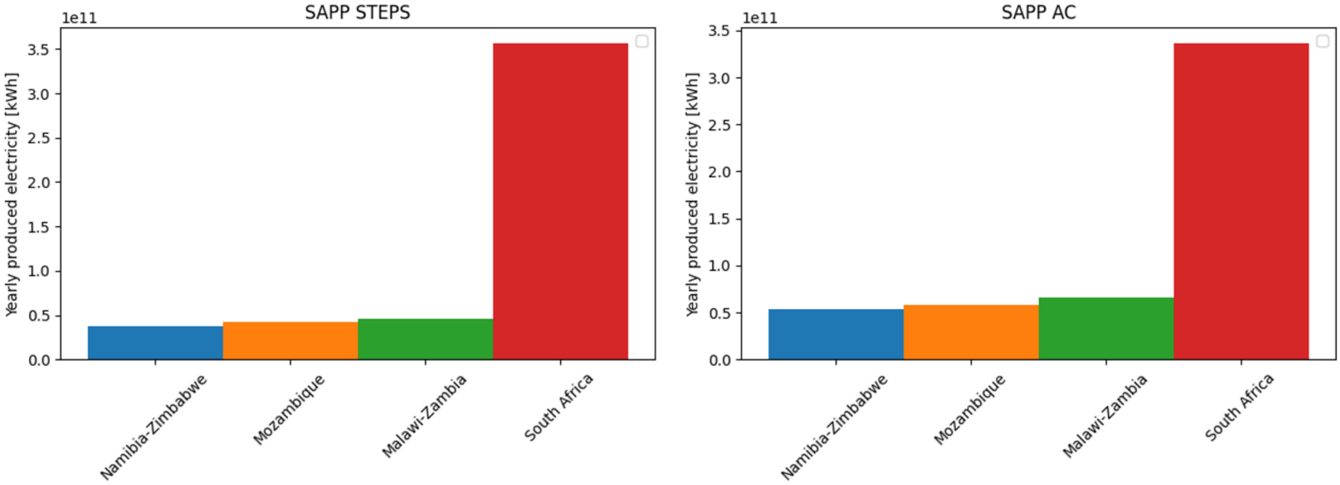

Figure 7.5: Annual generated electricity in SAPP by node in STEPS and AC scenarios.

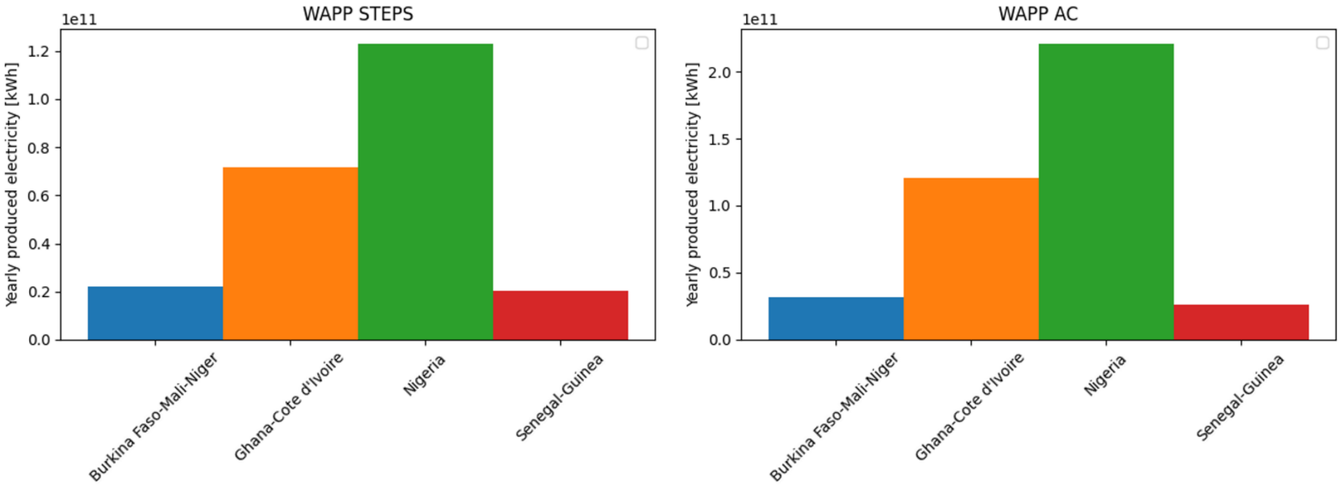

Figure 7.6: Annual generated electricity in WAPP by node in STEPS and AC scenarios.

Other two scenarios were then created applying a CO_2 cap to previously described scenarios. The imposed emission cap is equal to the annual quantity of CO_2 that can be emitted by Africa electricity sector to be compatible with an increase of 1.5 °C in global temperature with respect to pre-industrial levels. The cap for Africa was derived from a report by JRC, then CO_2 caps for single power pools were calculated in a simplified manner assuming their proportionality to electricity demand of each power pool. [61]

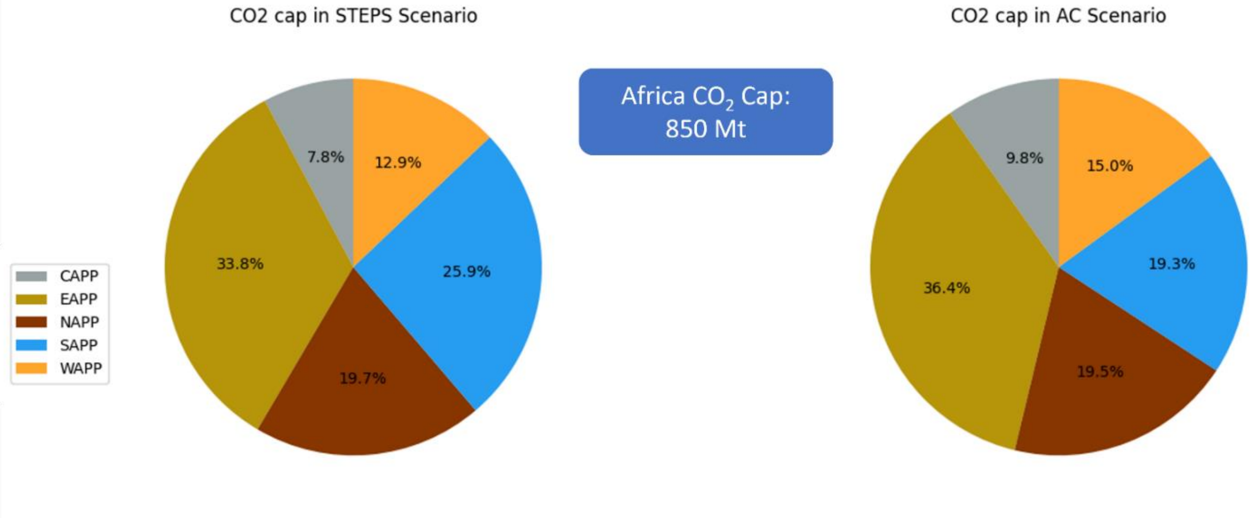

Figure 7.7: CO_2 cap for Africa in 1.5 °C scenario and subdivision by power pool for STEPS and AC scenarios.

7.2. STEPS scenario

In Table 7.1 new installed generation technologies for STEPS case can be observed. Since in this scenario it is not imposed a CO_2 cap, large capacities of CCGT and OCGT are installed. The other dominating technology is large hydro, which is preferred to small hydro for the lower investment cost per unit of capacity and lower O&M. PV and wind are installed in regions with low hydro potentials and capacity factors, but high wind and solar potential. PV is installed in all NAPP countries except for Morocco, while wind is installed in Algeria and in the Egypt-Sudan node. In regions with adequate water availability hydro is the first choice to increase the base load thanks to low operational costs and since it does not depend on short-term variability of the resource. Large capacities of hydro are installed in every power pool, except for NAPP and WAPP, which are characterized by lower availability of water. The best options for peak capacity are instead gas-fueled power plants thanks to lower investment costs, even though operational costs are higher, since they are used with lower capacity factors. In particular CCGT is usually preferred to OCGT, but in some cases, when power stations are needed to produce at very low capacity factor to meet fast changes in demand, OCGT is installed, since CCGT has higher investment costs and is as well constrained by a ramping rate. In the CAPP very large capacities of hydro are installed due to the low development of the regional power system compared to the projected demand. Hydroelectric plants are built in the countries with higher capacity factors to meet national demand and to export to nearby countries. 737 MW are therefore installed in Gabon, 3.1 GW in Cameroon and almost 3.9 GW in the Republic of the Congo (utilizing the whole available potential for this country). In EAPP new hydro capacity is almost completely installed in the Egypt-Sudan node, utilizing completely the technical potential for large hydro. Since, with the exception of Morocco, in NAPP there is low hydro potential and availability of water, almost 8 GW of CCGT, more than 10 GW of PV and 2 GW of wind are installed instead. In SAPP large hydro capacity is installed in Mozambique and in the Malawi-Zambia node, in both cases exploiting the total available technical potential. In the WAPP only CCGT power plants are installed, mostly in Nigeria (9336 MW).

Table 7.1: New generation capacity by power pool and technology in STEPS scenario.

	STEPS				
	CAPP	**EAPP**	**NAPP**	**SAPP**	**WAPP**
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**
CCGT	6732	19468	7875	7848	14727
OCGT	932	4811	0	1794	0
Large Hydro	7891	3266	0	8508	0
PV	0	0	10530	0	0
Wind	0	454	2057	0	0

Adding the CO_2 cap creates different scenarios only for NAPP and SAPP, since in the other regions, even adding new gas power plants, the cap is not reached. In NAPP almost 1.4 GW of CCGT capacity that was installed in the case without cap is not built. This capacity is substituted by an equivalent capacity of nuclear (0.9 GW in Tunisia and 0.4 GW in Libya), which is used to increase the baseload of the region. Slightly higher capacities of solar and wind are as well installed. In SAPP less than a tenth of CCGT and OCGT capacity is installed with respect to the case without cap. Like in the NAPP this capacity is almost entirely substituted by nuclear (5.2 GW in South Africa, 1.6 GW in Botswana-Namibia-Zimbabwe and 1.1 GW in Malawi-Zambia). 4.5 GW of PV are as well installed in South Africa while almost 1 GW of small hydro is installed in Mozambique (since large hydro potential has already been exploited). Only 530 MW of CCGT are still installed in the power pool in the Malawi-Zambia node.

Table 7.2: New generation capacity by power pool and technology in STEPS 1.5 °C scenario.

STEPS 1.5 °C Scenario		
	NAPP	**SAPP**
	[MW]	**[MW]**
CCGT	6498	530
OCGT	0	267
Large Hydro	0	8508
Small Hydro	0	976
PV	10861	4555
Wind	2340	0
Nuclear	1365	8113

In Table 7.3 are shown new interconnections in STEPS scenario with and without emission cap. The main difference between the two cases is the drop in new capacity in lines connecting South Africa to other nodes, probably due to the impossibility of using the large installed capacity of coal for exports without exceeding the imposed emission cap.

Table 7.3: New interconnections within power pools in STEPS without CO_2 cap and in STEPS 1.5 °C scenarios.

STEPS			**No CO_2 Cap**	**1.5 °C Scenario**
		Technology	**[MW]**	**[MW]**
CAPP				
Angola	Congo DR	DC	106	106
Burundi	Congo DR	DC	10	10
CAR	Congo	DC	25	25
Cameroon	Eq. Guinea	AC	254	254
Cameroon	Chad	DC	74	74
Congo DR	Congo	AC	2638	2638
Congo	Gabon	DC	81	81
Gabon	Eq. Guinea	AC	232	232
EAPP				
Egypt	Ethiopia	DC	1019	1019
Ethiopia	Kenya	AC	242	242
Ethiopia	Kenya	DC	128	128
NAPP				
Algeria	Morocco	DC	992	969
Mauritania	Morocco	DC	136	136
SAPP				
Botswana	South Africa	DC	333	79
Mozambique	Zambia	AC	103	90
Mozambique	South Africa	AC	71	3
Mozambique	Zambia	DC	112	187
WAPP				
Burkina Faso	Nigeria	AC	158	158
Burkina Faso	Nigeria	DC	223	223

Table 7.4: Investment and total cost by power pool for STEPS scenario with and without CO_2 cap.

STEPS		No CO_2 Cap		1.5 °C Scenario	
		[Billion $]	[% of GDP]	[Billion $]	[% of GDP]
CAPP	Annual CAPEX	3.527	1.625	3.527	1.625
	Annual Total Cost	5.802	2.673	5.802	2.673
EAPP	Annual CAPEX	6.097	0.853	6.097	0.853
	Annual Total Cost	28.391	3.971	28.391	3.971
NAPP	Annual CAPEX	3.793	1.168	4.252	1.309
	Annual Total Cost	17.808	5.483	17.814	5.485
SAPP	Annual CAPEX	5.546	1.386	8.508	2.127
	Annual Total Cost	15.440	3.860	16.401	4.100
WAPP	Annual CAPEX	2.653	0.364	2.653	0.364
	Annual Total Cost	11.429	1.570	11.429	1.570

In Table 7.4 are indicated necessary investments and total cost by power pools in STEPS without cap and in 1.5 °C scenario. The highest investment costs are in SAPP and EAPP, since in the first are installed more than 8 GW of hydroelectric (which has relatively high investment costs), while in the second almost 28 GW of new capacity is installed to meet the large growth of demand in the region. The power pools with the highest total costs are instead EAPP and NAPP, due to the high reliance on gas, which has high operational costs related to fuel. Imposing an emission cap, investment costs increase by 12.1 % in the NAPP and by 53.4 % in SAPP. In SAPP the difference is so significant since, to be able to respect the emission cap, the large existing capacity of coal power plants cannot be fully exploited and must be replaced with lower-emitting technologies. Since nuclear and renewables have relatively low operational costs, the difference of total costs in the two scenarios is much lower and amounts to 6.22 % in SAPP and just 0.03 % in NAPP. CAPEX and total annual costs are compared as well with the GDP of the various regions. Though generation and transmission are going to be expanded gradually, they are compared with most recent available GDPs for simplicity and to obtain conservative results. According to IEA, investment in power sector varied between 0.8 % and 1 % of global GDP in the last years. [62] In EAPP and WAPP required investment is below this range and in NAPP is slightly higher. Required investment in CAPP and SAPP is relevantly higher probably because large capacities of hydro, which is a capital-intensive technology, are installed. For all regions total cost share of GDP is lower than the average expenditure on energy in Africa, which amounts to 6 % of GDP (anyhow this value includes other sectors related to energy and it is not clear which is the share dedicated to power sector). [63]

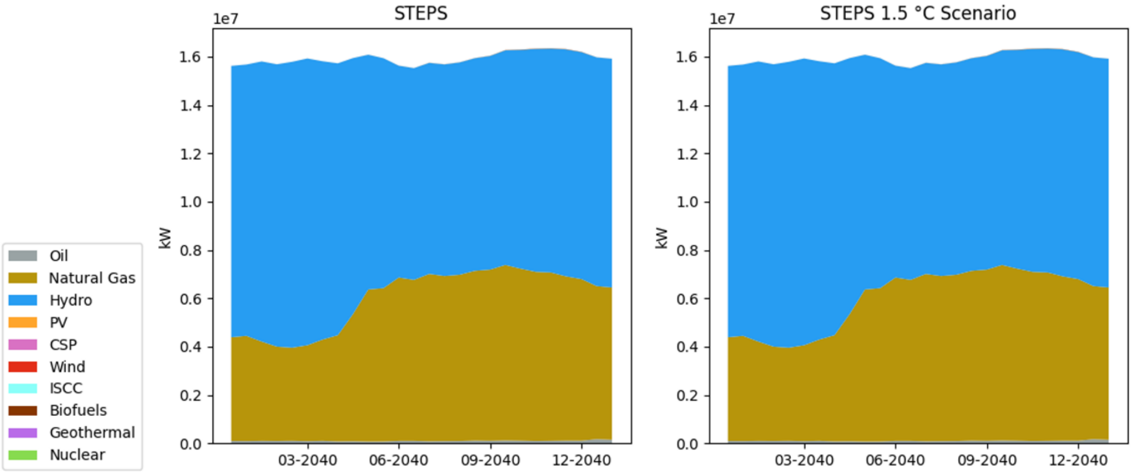

Figure 7.8: CAPP power generation by source along the year in STEPS scenario with and without CO_2 cap.

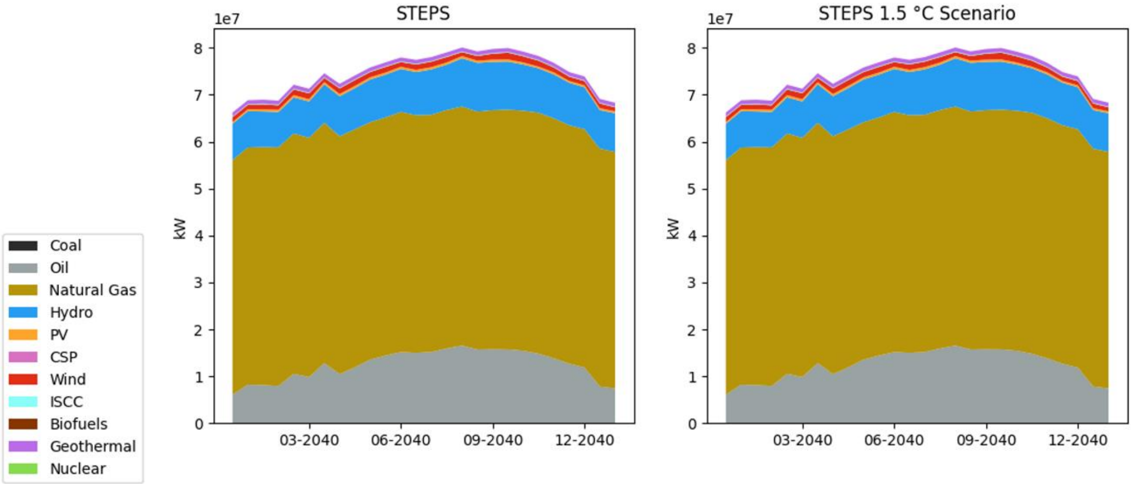

Figure 7.9: EAPP power generation by source along the year in STEPS scenario with and without CO_2 cap.

In CAPP hydro is utilized to produce about 62 % of electricity, while the remaining part is produced by gas power plants (37.1%) and oil (0.7 %). Cameroon and Congo are the countries with the largest newly installed hydro capacity and utilize it as well for export, selling electricity to Chad, Gabon, Equatorial Guinea and Congo DR, thanks to the newly installed interconnections between these countries (see Table 7.3). Angola utilizes at full load already existing hydro capacity and utilizes OCGT and CCGT for peaks of demand. During the wet season Angola exports electricity towards Congo DR, while during dry season it becomes a net importer. Congo DR similarly uses existing hydro for baseload and new gas fuelled power plants for peaks.

In EAPP the energy mix is dominated by natural gas (68.1 % of the electricity mix), followed by oil (16.6 %) and hydro (11.9 %). A small share of electricity is produced using geothermal (1.1 % of the electricity mix, all produced in Kenya), wind (1.5 %) and PV (0.6 %). Due to high seasonal changes in demand in northernmost countries, Egypt and Sudan are net exporters of electricity towards Ethiopia during low-demand season, while they are net importers during high-demand season. Since dry seasons do not coincide in Ethiopia (September to March) and the Kenya-Tanzania node (May to October), Ethiopia exports electricity towards Kenya during its wet season, while it imports during dry season using the two newly built transmission lines.

In the NAPP the 86.5 % of electricity is generated using thermal power plants (65.5% from gas, 12 % from oil and 9 % from coal). Even if PV and wind increase their share with respect to the base case their use remains relatively low, generating respectively 6.9 % and 3.4 % of total electricity. In 1.5 °C scenario generation from fossil fuels is slightly lower (83.1 %), while production from PV and wind is slightly higher (10.8 %). A small share of baseload is produced using nuclear (3 %). CCGT is used for baseload in Algeria, Tunisia and Mauritania. In Libya HFO, CCGT and OCGT are used for baseload, while in Morocco baseload is covered using a combination of coal, CCGT and hydro. In the case with CO_2 cap nuclear is also used for baseload in Tunisia, Libya and Mauritania. In Algeria, Tunisia and Libya newly installed PV capacity and in Algeria new wind farms are used in combination with OCGT to meet peak demand. Interconnections in the region experience trades of electricity between countries in both senses in all cases except for the Morocco – Mauritania line, which is characterized by a net flow towards Mauritania.

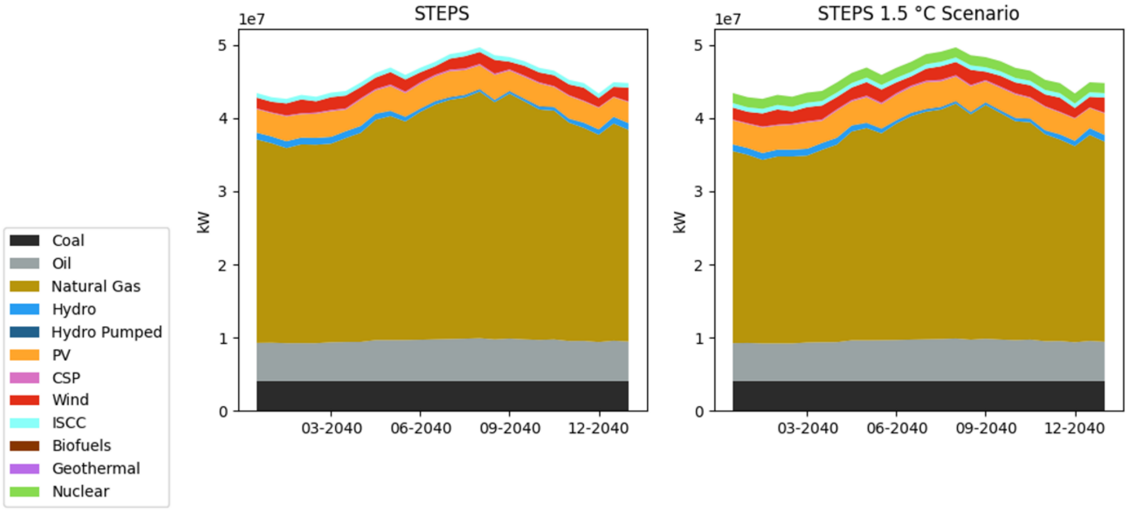

Figure 7.10: NAPP power generation by source along the year in STEPS scenario with and without CO_2 cap.

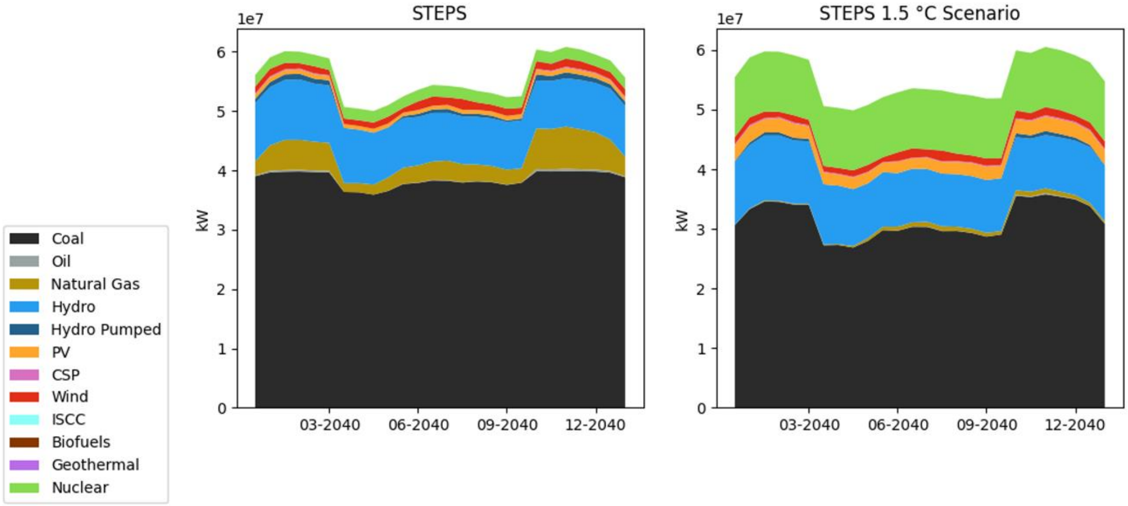

Figure 7.11: SAPP power generation by source along the year in STEPS scenario with and without CO_2 cap.

In the SAPP most of generation in STEPS scenario comes from already existing coal power plants (69.1 % of the mix). Other important sources are hydroelectric (15.6 %), nuclear (3.5 %) and natural gas (7 %), which is mainly used during summer to meet peak demand. PV and wind power stations combined are responsible for 3.3 % of electricity production. Adding a CO_2 cap coal remains the main source of generation, but its share falls substantially to 56.9 %. Nuclear has the second largest share in the electricity mix (18.2 %). Production from hydroelectric power plants increases slightly (17.1 %), while generation from PV and wind almost doubles (reaching 6 % of electricity production). In the case without CO_2 cap in South Africa coal and nuclear are mainly used for baseload, while 4 GW of newly installed CCGT and 1 GW of OCGT (along with already existing OCGT plants) are used to meet the relevantly higher summertime demand. Coal and CCGT are as well the main contributors to the energy mix in the Botswana-Namibia-Zimbabwe along with already existing hydro capacity, mostly installed in Zimbabwe. Mozambique and Zambia-Malawi mainly rely on hydro and CCGT, with the second also using coal and OCGT during dry season. Due to seasonality, South Africa exports electricity towards Mozambique and Botswana-Namibia-Zimbabwe during winter, when demand is lower, while it imports it during summer. In the 1.5 °C scenario in South Africa coal is used at lower capacity factors, especially during the low-demand season. Nuclear is the second contributor to meet baseload demand and it is almost always used at full load. Another important contribution comes from the 4.5 GW of newly installed PV.

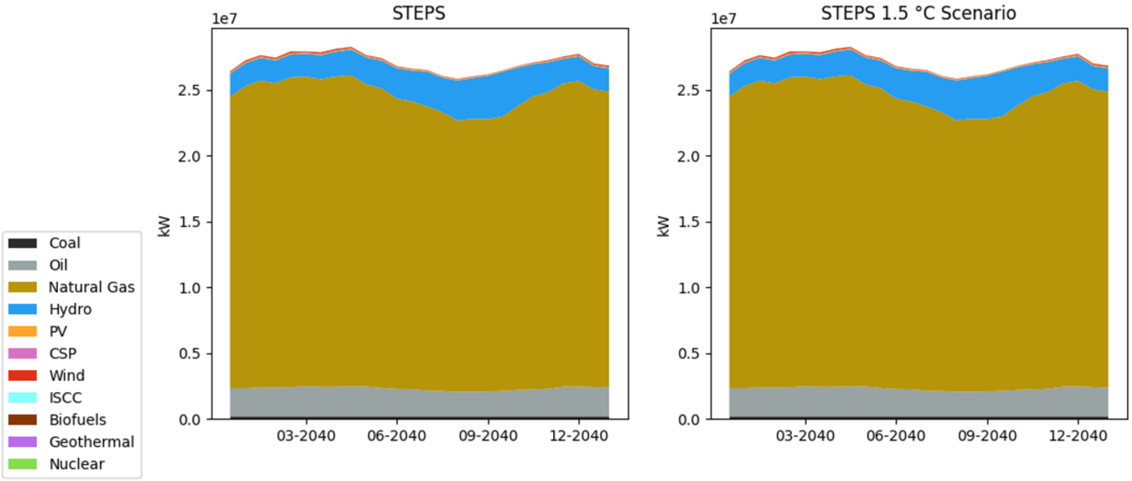

Figure 7.12: WAPP power generation by source along the year in STEPS scenario with and without CO_2 cap.

In WAPP natural gas is used to produce 82.6 % of the region's electricity, while hydro and oil contribute respectively for the 8.2 % and 7.9 %. Electricity trades mainly involve Nigeria and the Benin-Burkina Faso-Mali node, with flows in both directions all along the year.

7.3. AC scenario

In AC scenario 211 GW of new capacity are installed to meet the new demand, compared with the 97 GW of STEPS case. Installed technologies in each power pool are the same, except for the installation of 976 MW of small hydro in the SAPP and the absence of newly installed wind farms in EAPP and NAPP. In CAPP hydro is installed in Burundi (144 MW), CAR (87 MW), Cameroon (4.8 GW), Republic of the Congo (3.8 GW, the same as in STEPS case, since the entire potential is exploited) and Gabon (almost 1.3 GW). In EAPP the same capacity than in STEPS is installed in the Egypt-Sudan node, utilizing the whole large hydro potential for this node, but almost 1.1 GW are as well added in the Uganda-Rwanda-South Sudan node. In the SAPP new large hydro capacity is the same in STEPS and AC scenarios, but in AC new small hydro capacity is also installed in Mozambique. As in STEPS scenario, no hydroelectric capacity is installed in NAPP and WAPP. Large capacities of CCGT are installed both to increase baseload (particularly in countries with low availability of water) and to meet peak demand in all countries except for CAR (which relies on hydro and imports from Congo), Cameroon (that uses hydro for baseload and OCGT for peak demand), Republic of the Congo (same as Cameroon) and Chad (relying on existing HFO and imports from Cameroon for baseload and OCGT for peaks). Largest CCGT additions are in Egypt-Sudan (29.7 GW), Nigeria (20.8 GW), Kenya-Tanzania (20.4 GW), Ethiopia (14.2 GW), Algeria (10.8 GW) and Congo DR (10.6 GW). New OCGT capacity is installed as well in most countries to meet peaks in demand, with largest additions built in Egypt-Sudan (8.3 GW or 44 % of new OCGT capacity).

Table 7.5: New generation capacity by power pool and technology in AC scenario.

	AC				
	CAPP	**EAPP**	**NAPP**	**SAPP**	**WAPP**
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**
CCGT	19400	64447	31790	10011	34721
OCGT	3047	10618	2247	2430	574
Large Hydro	10200	4211	0	8508	0
Small Hydro	0	0	0	976	0
PV	0	0	7893	0	0

In Africa Case the imposition of an emission cap has effects on all regions. CAPP has very slight differences in installed capacity compared to the case without cap. New CCGT capacity is 87 MW lower, while OCGT decreases by 19 MW. This capacity is substituted by additional 17 MW of large hydro and 92 MW of geothermal in Congo DR. In the EAPP only 52.5 % of CCGT capacity is installed with respect to the case without emission limitations, while OCGT new capacity decreases slightly. The share of baseload that was produced by new CCGT power plants is generated by 15.8 GW of geothermal capacity (6 GW in Ethiopia and 9.8 GW in Kenya-Tanzania) and 15.4 GW of nuclear (14.1 GW in Egypt-Sudan and 1.3 in Kenya-Tanzania). In the NAPP 25 % of CCGT capacity is installed with respect to the case without constraints on CO_2 and is mainly substituted with 23 GW of nuclear (9.5 GW in Algeria, 5.2 GW in Libya, 4.9 GW in Tunisia, 3.4 GW in Morocco) and 700 MW of geothermal (all installed in Algeria, using the whole estimated potential). New OCGT capacity is slightly smaller, while new PV capacity increases by 692 MW. In SAPP no new thermal power plants are built. Instead, 12.5 GW of nuclear (3.9 GW in Malawi-Zambia and Botswana-Namibia-Zimbabwe, 3 GW in South Africa and 1.7 GW in Mozambique) and 30.8 GW of PV (29.9 GW in South Africa) are installed. In the WAPP 59 % of CCGT new capacity is built and the missing part is substituted by 14.3 GW of nuclear, all developed in Nigeria.

Table 7.6: New generation capacity by power pool and technology in AC 1.5 °C scenario.

	AC 1.5 °C Scenario				
	CAPP	**EAPP**	**NAPP**	**SAPP**	**WAPP**
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**
CCGT	19313	33844	7943	0	20484
OCGT	3028	9963	2234	0	566
Large Hydro	10217	4246	0	8508	0
Small Hydro	0	0	0	976	0
PV	0	0	8585	30841	0
Geothermal	92	15825	700	0	0
Nuclear	0	15414	23160	12516	14277

In Table 7.7 new interconnections for AC scenarios are displayed. The most notable differences in additions in the two scenarios are observed in the SAPP. Adding a CO_2 cap a much lower interconnection capacity is built between Botswana-Namibia-Zimbabwe and South Africa, probably motivated by the fact that South Africa cannot use its coal power plants for exports not to exceed the cap on emissions. Transfer capacities between Mozambique and Zambia-Malawi and between Mozambique and South Africa increase relevantly, allowing larger exports of electricity generated from hydro.

Table 7.7: New interconnections within power pools in AC without CO_2 cap and in AC 1.5 °C scenarios.

AC				
			No CO_2 Cap	**1.5 °C Scenario**
		Technology	**[MW]**	**[MW]**
CAPP				
Angola	Congo DR	DC	174	175
Burundi	Congo DR	DC	8	8
CAR	Congo	DC	34	34
Cameroon	Eq. Guinea	AC	337	340
Cameroon	Chad	DC	111	112
Congo DR	Congo	AC	2326	2327
Congo	Gabon	DC	73	74
Gabon	Eq. Guinea	AC	215	216
EAPP				
Egypt	Ethiopia	DC	1642	1642
Ethiopia	Kenya	AC	808	791
Ethiopia	Kenya	DC	82	99
NAPP				
Mauritania	Morocco	DC	137	137
SAPP				
Botswana	South Africa	DC	846	277
Mozambique	Zambia	AC	171	679
Mozambique	South Africa	AC	787	895
Mozambique	Zambia	DC	43	591
WAPP				
Burkina Faso	Nigeria	AC	47	49
Burkina Faso	Ghana	DC	4	6
Burkina Faso	Nigeria	DC	196	198
Ghana	Senegal	DC	174	165

Table 7.8: Investment and total cost by power pool for AC scenario with and without CO_2 cap.

AC		No CO_2 Cap		1.5 °C Scenario	
		[Billion $]	[% of GDP]	[Billion $]	[% of GDP]
CAPP	Annual CAPEX	5.985	2.758	6.020	2.774
	Annual Total Cost	12.398	5.712	12.399	5.713
EAPP	Annual CAPEX	12.797	1.790	22.468	3.143
	Annual Total Cost	49.368	6.906	49.475	6.921
NAPP	Annual CAPEX	6.330	1.949	12.764	3.930
	Annual Total Cost	27.875	8.583	27.977	8.614
SAPP	Annual CAPEX	6.298	1.574	13.256	3.314
	Annual Total Cost	17.324	4.331	19.706	4.926
WAPP	Annual CAPEX	5.348	0.734	9.115	1.252
	Annual Total Cost	20.589	2.828	20.650	2.836

In Table 7.8 investments and total costs for each power pool in AC scenario with and without cap are displayed. In the case with the CO_2 cap, investment costs increase very slightly for CAPP, while changes are much more relevant in the other power pools. Investment costs increase respectively by 75.6 % in the EAPP, 101.6 % in the NAPP, 110.5 % in the SAPP and 70.4 % in the WAPP. The cause of this remarkable increase in investment cost is mainly caused by the large amount of newly installed nuclear and, in EAPP and NAPP, geothermal capacity. Total costs are instead very similar in the two cases, since nuclear and geothermal (but also PV and hydro) have very low operational costs. The largest difference in total costs is in the SAPP (13.7 %), since a part of existing coal power plants must be substituted with lower emitting technologies to meet demand and respect the emission cap. Investment costs are much higher than 1 % of GDP, which is the average investment in power sector indicated by IEA for recent years, particularly in 1.5 °C scenario. To overcome this challenge governments should create a policy framework to stimulate FDI (Foreign Direct Investment) in power sector. FDI in 2021 already amounted to 83 billion $ (1.3 times required investment in 1.5 °C scenario) across all sectors. [64] Another way to obtain necessary capital for investments in the power sector is public aid, that in 2019 was 151.7 billion $ or 2.38 times required investment in 1.5 °C scenario. Anyway, aid dedicated to climate adaptation is still not sufficient and was one of the main themes at COP26 (see section 1.1). [65] Total annual costs are higher than the percentage of GDP dedicated to energy sector in Africa (6 %), but lower than 10 % of GDP, that is the typical value for most regions across the world. [63]

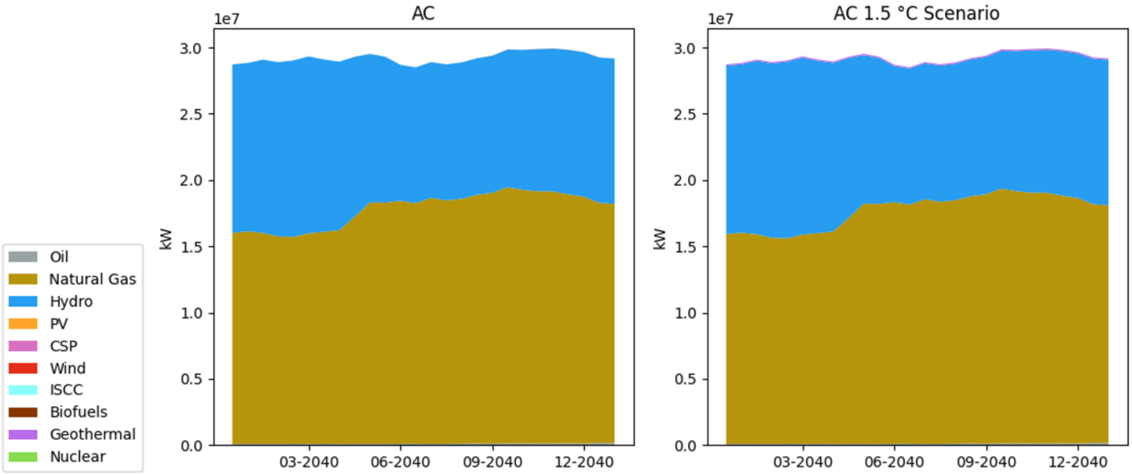

Figure 7.13: CAPP power generation by source along the year in AC scenario with and without CO_2 cap.

In CAPP the share of electricity coming from hydro is much lower than in STEPS cases (39 %) and the main source for electricity becomes gas (60.6 % without cap, 60.3 % with cap) thanks to more than 22 GW of new gas fuelled power plants. The remaining electricity is produced through oil power station (0.4 %) and, in the 1.5 °C scenario, geothermal (0.3 %). Angola existing hydroelectric capacity is used at full load during the whole year. From January to May (rain season) CCGT capacity is used for peak demand, while in the second part of the year it is used for baseload and OCGT capacity is used for peaks. Angola trades electricity with Congo DR, exporting towards it from January to May and importing electricity in the second half of the year (in particular in November and December). The vast majority of electricity generation in Cameroon and the Republic of the Congo is based on large hydro. Cameroon exports electricity all year round towards Equatorial Guinea and Chad. The Republic of the Congo is a net exporter towards Congo DR, while it has trades in both directions with CAR and Gabon (in this case exports are concentrated from March to June, while imports from June till October). In Cong DR generation is largely based on CCGT and already existing large hydro power plants.

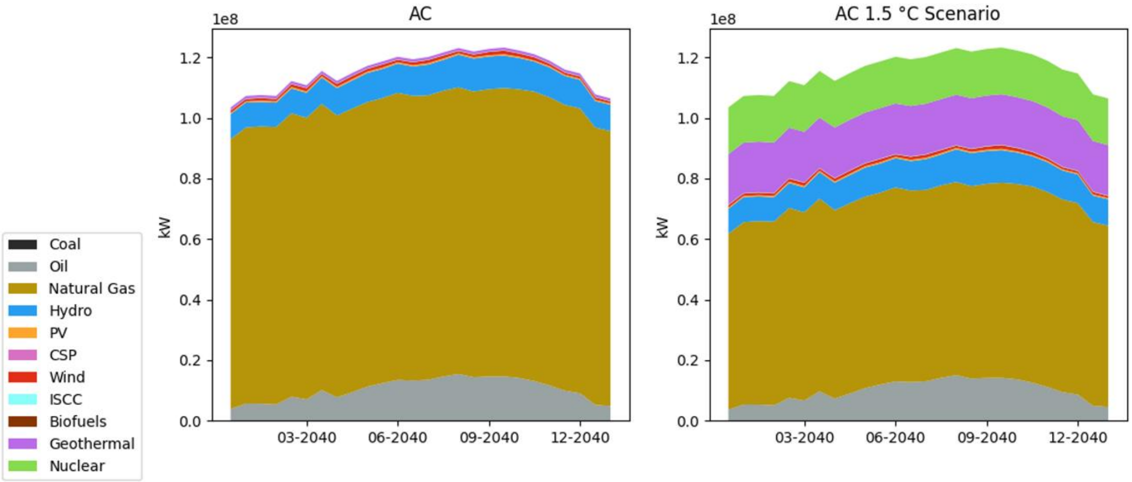

Figure 7.14: EAPP power generation by source along the year in AC scenario with and without CO_2 cap.

Most of electricity produced in the EAPP is generated using natural gas (81 %, 54.4 % in 1.5 °C scenario). Imposing the CO_2 cap 14.4 % of electricity is produced by geothermal and 13.3 % by nuclear. These two technologies are used as a replacement for gas power plants for baseload. The remaining production is from oil (8.9 % without cap, 8.6 % with cap), hydro (8.1 %) and other renewables (0.8 % wind, 0.4 % PV; in the case without cap 0.7 % with geothermal). In the case without CO_2 cap, generation in Egypt-Sudan is mainly based on gas (79.3 %) and oil. A small share is produced using hydro and other renewables. In all other nodes electricity is mainly produced from gas (along with small shares of hydro and, in Kenya-Tanzania, geothermal) except for the Uganda-Rwanda-South Sudan node, where 86.8 % of electricity is from hydroelectric. In the 1.5 °C scenario a large share of production from gas in Egypt-Sudan is substituted by nuclear. In Kenya-Tanzania and Ethiopia geothermal is deployed to substitute a large share of baseload gas fuelled power plants, producing approximately 50 % and 40 % of electricity in the two nodes. A small share of gas power plants is substituted with nuclear in Kenya-Tanzania. Changes in the electricity mix in the Uganda-Rwanda-South Sudan region are instead quite limited. Electricity trades in the region resemble the ones of STEPS case, even though the involved amount of electricity is much higher.

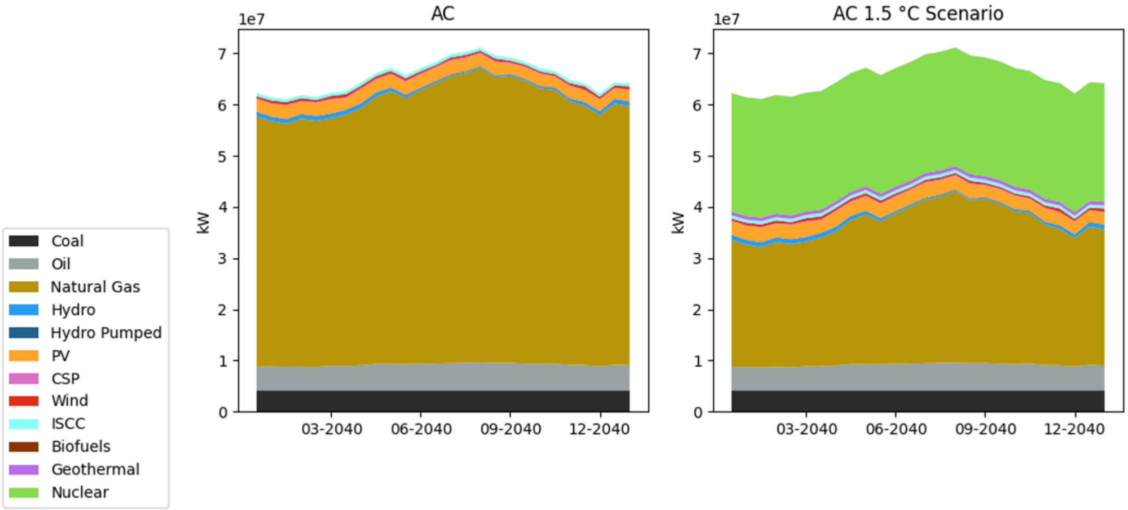

Figure 7.15: NAPP power generation by source along the year in AC scenario with and without CO_2 cap.

In the NAPP without limiting CO_2 emissions 94.2 % of the electricity comes from fossil fuel generation (80.2 % natural gas, 7.8 % oil and 6.2 % coal). Imposing an emission cap, the share of generation from thermal power plants falls to 57.5 % (43.5 % gas, 7.8 % oil and 6.2 % coal) and it is largely substituted by nuclear (35.4 % of the electricity mix). A small share of renewable is present in both cases (without cap: 3.7 % PV, 1.1 % hydro, 0.7 % wind and 0.3 % CSP; with cap: 4 % PV, 1.1 % hydro, 1.1 % geothermal, 0.7 % wind and 0.3 % CSP). In the case without emission cap all countries rely mainly on CCGT power plants, with important contributions of coal in Morocco and HFO in Libya. Imposing an emission cap, a large fraction of the baseload is met using nuclear. Morocco exports all year round towards Mauritania and Algeria. Trades in both directions involve Tunisia with Algeria and Libya.

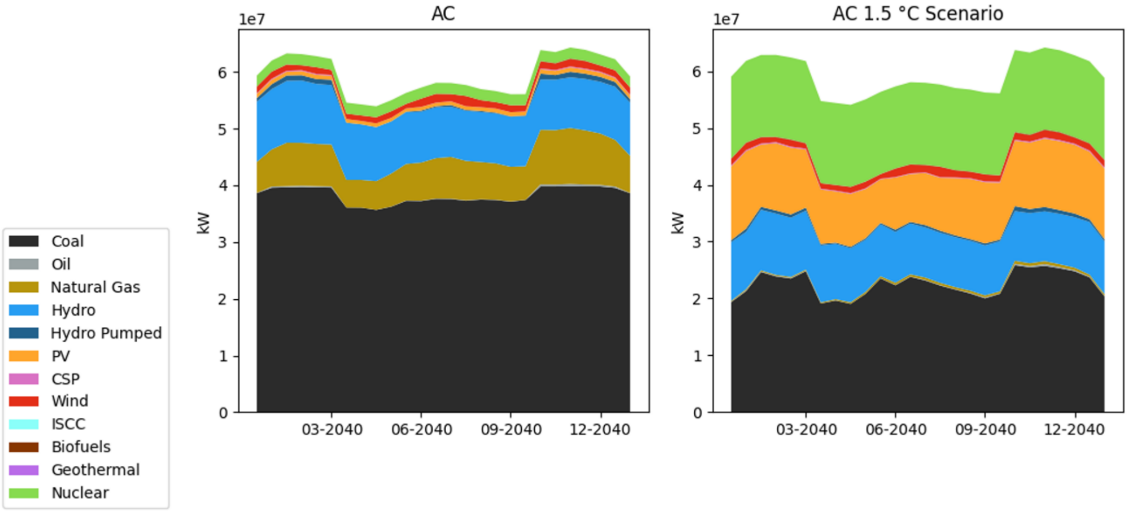

Figure 7.16: SAPP power generation by source along the year in AC scenario with and without CO_2 cap.

In AC scenario without limiting emissions fossil fuels constitute more than three quarters of total generation in SAPP (64.4 % coal, 12 % gas and 0.2 % oil), hydro produces 16.8 % of electricity, while the rest is constituted by nuclear (3.3 %) and other renewables (2 % wind, 1.2 % PV and 0.1 % CSP). In the 1.5 °C scenario coal, gas and oil share is only 38.8 %, while nuclear share increases drastically to reach 24.3 % of the electricity mix. Hydro production slightly decreases to 16.5 %, instead solar generation increases sharply, reaching 18 % of generation from PV. Wind production remains stable. In South Africa generation still comes from existing coal power plants for almost 90 %, since electricity demand growth is more limited than in other countries, as the electricity sector is already quite established. With the emission cap, generation from coal falls to 55.3 % and production from nuclear and PV rises respectively to 12.7 % and 26.5 % of generated electricity. In Malawi-Zambia half of energy generation is from hydro and another large share from gas. In the 1.5 °C scenario approximately half of generation is still from hydroelectric, while the other half is from nuclear. In Botswana-Namibia-Zimbabwe coal, CCGT and hydro are used for baseload and OCGT to meet peaks in demand, while adding a CO_2 cap nuclear becomes the main source in the electricity mix (approximately 60 %). In Mozambique hydroelectric makes up for 80 % of production, while the remaining part is produced by gas power stations. In 1.5 °C scenario a quarter of generated electricity comes from nuclear, which substitutes most of the gas share. Thanks to the existing and new interconnections, electricity trades involve all nodes. South Africa exports electricity to Botswana-Namibia-Zimbabwe and Mozambique during winter, while it imports from these countries during summer. Zambia-Malawi node imports electricity from Mozambique and Botswana-Namibia-Zambia during the dry season. In the 1.5 °C scenarios all countries both import and export electricity.

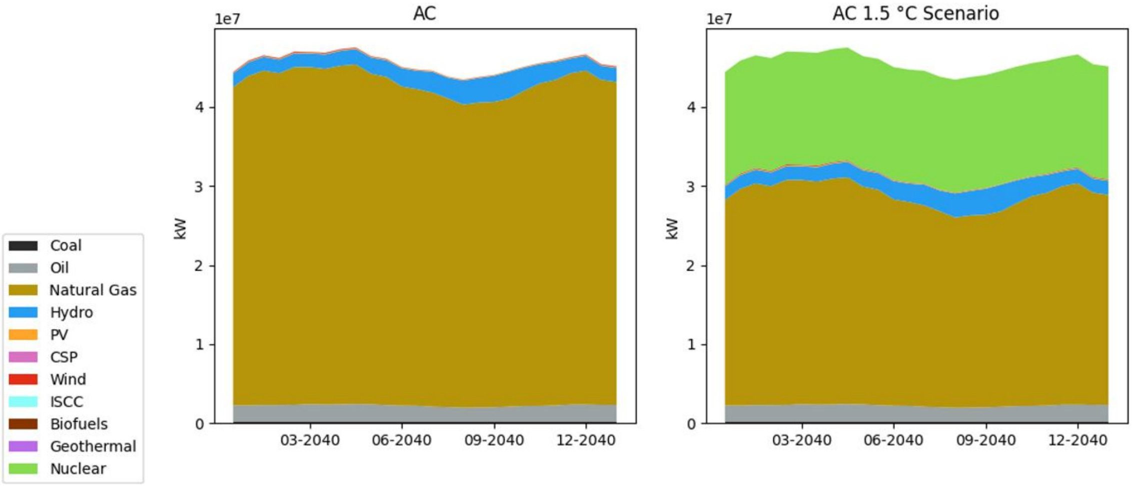

Figure 7.17: WAPP power generation by source along the year in AC scenario with and without CO_2 cap.

In the WAPP electricity is mainly produced using gas (89.8 % without cap, 58.5 % in the 1.5 °C scenario) and, in the case with CO_2 cap, by the newly installed 14.3 GW of nuclear (producing 31.3 % of region's electricity). In both cases, the remaining share is produced through existing hydroelectric (4.9 %) and oil (4.6 %) power stations. In AC case, the generation mix of every node resembles the overall power pool one, since all countries rely largely on gas, with only small shares of hydro and HFO. In 1.5 °C scenario 56.9 % of electricity generation in Nigeria is from nuclear, which is utilized instead of gas power plants (in the AC case without cap Nigeria electricity generation is for 97.6 % from gas). Main electricity trades are between Nigeria and the Benin-Burkina Faso-Mali node in both directions and exports from the Ghana-Côte d'Ivoire node to Senegal-Guinea region.

7.4. STEPS and AC scenarios with no new nuclear capacity

In 1.5 °C scenario large capacities of nuclear are installed in NAPP and SAPP for STEPS case and in all power pools except CAPP for AC scenario. Anyhow, as of 2022 South Africa has the only functioning nuclear power plant used for generation in the continent. Egypt is by now the only other country considered to be ready to develop a nuclear program, having in project to build a new 4.8 GW power plant in the next years. [66] Algeria, Ghana, Morocco and Nigeria operate research reactors and other countries, such as Kenya, Tanzania and Tunisia, plan to start nuclear programs soon. [67] Anyhow, nuclear requires high investments and construction times are in the order of 5-10 years. [68] Furthermore, nuclear necessitates highly specialized technicians, frequent maintenance and an adequate regulatory framework. Due to widespread political instability, lack of capitals and inadequate legislation in several countries, there is high uncertainty that these projects will be completed or even started. [66] Because of this, the cases in previous sections where new nuclear capacity was installed are analysed another time removing nuclear from the set of installable technologies the model can choose from.

Table 7.9: New generation capacity by power pool and technology in STEPS and AC 1.5 °C scenario in STEPS and AC 1.5 °C scenarios with no new nuclear capacity.

	STEPS 1.5 °C Scenario No Nuclear		**AC 1.5 °C Scenario No Nuclear**			
	NAPP	**SAPP**	**EAPP**	**NAPP**	**SAPP**	**WAPP**
	[MW]	**[MW]**	**[MW]**	**[MW]**	**[MW]**	**[MW]**
CCGT	7430	4139	40321	23413	7649	25811
OCGT	0	4709	7158	3155	1610	0
Large Hydro	0	8508	22564	0	12733	15872
Small Hydro	0	976	0	0	1144	0
PV	12708	29138	15211	37719	49635	33505
CSP	0	0	0	0	0	2808
Wind	3929	0	5490	28792	11148	0
Geothermal	0	0	15825	700	0	0

In all regions and in all cases very large capacities of VREs are built to substitute nuclear. A much higher capacity is needed since PV, CSP and wind have much lower capacity factors than nuclear. Furthermore, extra capacity of new gas fuelled power plants must be built to grant baseload, due to the variability of renewable resources availability. In NAPP 1.3 GW of nuclear installed in STEPS 1.5 °C scenario is substituted building approximately 1.9 GW extra capacity of PV, 1.6 GW of wind and 0.7 GW of CCGT. PV is built in all countries except Morocco, while wind farms are constructed in Algeria and Libya. Almost 7.5 GW of PV and 3.3 GW of wind are installed in Algeria. In AC scenario, besides the already mentioned technologies, 0.7 GW of geothermal are installed in Algeria, as well as 3 GW of OCGT. PV is installed in all countries (12.5 GW in Algeria, 11.9 GW in Morocco, 10.1 GW in Libya), wind in all countries except Morocco (17.2 GW in Algeria, 7.3 GW in Tunisia). In SAPP, as a replacement for 8 GW of nuclear almost 25 GW of PV, 3.5 GW of CCGT, 4.5 GW of OCGT and 0.8 GW of small hydro are built. 26.5 GW out of 29 of PV are built in South Africa. In AC scenario extra 19 GW of PV, 11 GW of wind and 4 GW of hydro are installed with respect to the case with nuclear, besides 9.2 additional GW of gas power stations. Almost 75 % of new PV and the whole new wind capacity is installed in South Africa. Large new hydroelectric capacities are installed in all nodes except South Africa. In EAPP large hydro is installed in all nodes, using the whole available potential in Egypt-Sudan and Kenya-Tanzania. All region’s geothermal potential is exploited, and 9.8 GW are installed in Kenya-Tanzania and 6 GW in Ethiopia. 15.2 GW of PV and 5.5 GW of wind are installed in Egypt-Sudan. In the WAPP nuclear is replaced building 5 extra GW of CCGT, besides 15.8 GW of hydro, 33.5 GW of PV and 2.8 GW of CSP. All CSP capacity and most capacity of other technologies (13.4 GW of CCGT, 12 GW of hydro and 18.7 GW of PV) are installed in Nigeria.

Regional grids are in general more integrated than in the case with nuclear to allow dispatch of electricity from renewable variable sources in other nodes and increase the resilience and efficiency of the power systems.

In STEPS case investment costs are about 3 % higher for NAPP and 7 % for SAPP than investment cost in STEPS scenario with nuclear. Total costs are instead almost the same. In AC scenario investment costs are significantly higher than in the case with new nuclear capacity (8.9 % higher for EAPP, 22.6 % for NAPP, 15.7 % for SAPP and 45.4 % for WAPP). Investment costs increase more in regions where there are lower capacity factors for hydro, in particular in WAPP the need to rely on CSP for a part of the baseload has a very relevant impact on investment.

Comparing to the case with nuclear, total costs are 0.8 % higher in EAPP, 3 % in NAPP, 9.7 % in SAPP and 13 % in WAPP. Investments costs are much higher, in particular in AC scenario, than the 1 % of GDP indicated by IEA as the share dedicated to investments in power sector in last years. [62] Total costs are instead lower than 10 % of GDP, that is the average value for expenditure in energy in most regions of the world. [63]

Table 7.10: New interconnections within power pools in STEPS and AC 1.5 °C scenarios with no new nuclear capacity.

			STEPS 1.5 °C Scenario No Nuclear	**AC 1.5 °C Scenario No Nuclear**
		Technology	**[MW]**	**[MW]**
EAPP				
Egypt	Ethiopia	DC	[redacted]	1696
Ethiopia	Kenya	AC	[redacted]	731
Ethiopia	Kenya	DC	[redacted]	158
NAPP				
Algeria	Morocco	DC	917	0
Algeria	Tunisia	DC	0	821
Libya	Tunisia	DC	0	343
Mauritania	Morocco	DC	135	134
SAPP				
Botswana	South Africa	DC	185	689
Mozambique	Zambia	AC	126	413
Mozambique	South Africa	AC	86	4179
Mozambique	Zambia	DC	197	519
WAPP				
Burkina Faso	Ghana	DC	[redacted]	1078
Burkina Faso	Senegal	DC	[redacted]	1
Burkina Faso	Nigeria	DC	[redacted]	931

Table 7.11: Investment and total cost by power pool for scenarios with CO_2 cap and no new nuclear capacity.

CO_2 cap, No new Nuclear		**STEPS**		**AC**	
		[Billion $]	**[% of GDP]**	**[Billion $]**	**[% of GDP]**
EAPP	Annual CAPEX	[redacted]	[redacted]	24.466	3.422
	Annual Total Cost	[redacted]	[redacted]	49.871	6.976
NAPP	Annual CAPEX	4.403	1.356	15.652	4.819
	Annual Total Cost	17.824	5.488	28.805	8.869
SAPP	Annual CAPEX	9.113	2.278	15.340	3.835
	Annual Total Cost	16.678	4.169	21.626	5.406
WAPP	Annual CAPEX	[redacted]	[redacted]	13.249	1.820
	Annual Total Cost	[redacted]	[redacted]	23.341	3.206

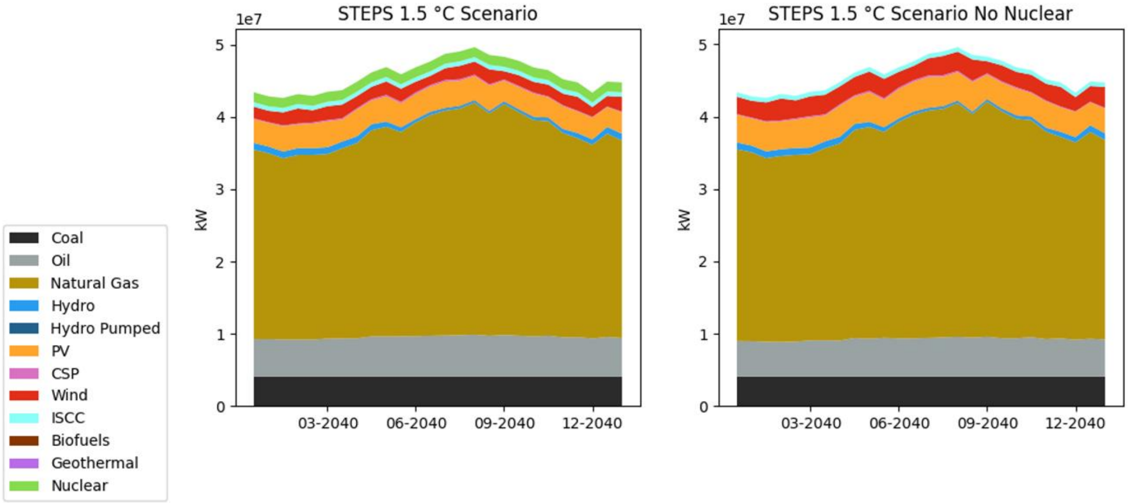

Figure 7.18: NAPP power generation by source along the year in STEPS 1.5 °c scenario with and without new nuclear capacity.

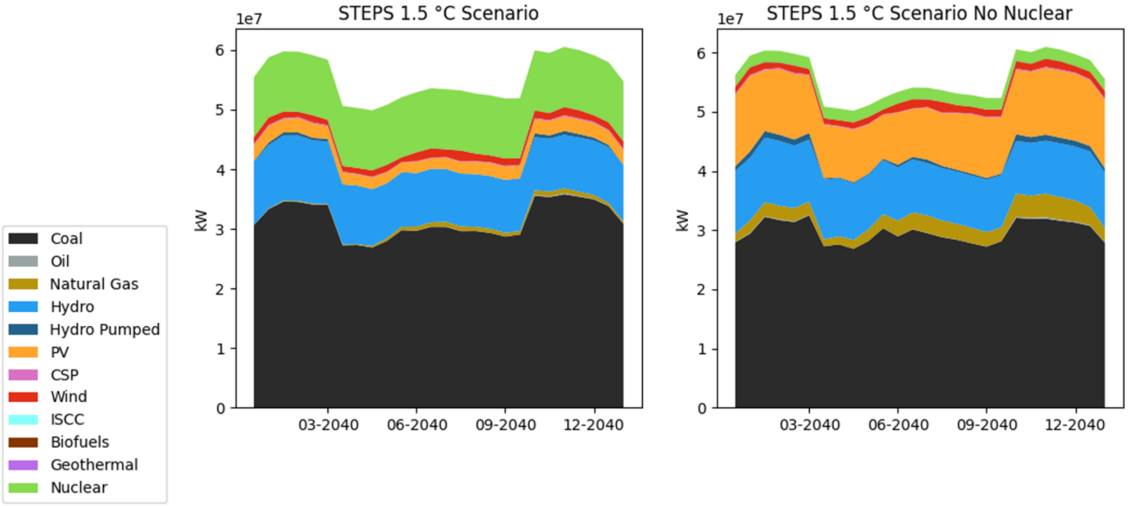

Figure 7.19: SAPP power generation by source along the year in STEPS 1.5 °c scenario with and without new nuclear capacity.

Electricity mixes of Algeria and Morocco in STEPS scenario without new nuclear are very similar to the case with nuclear. More relevant changes can be observed instead in other countries. In Mauritania nuclear is substituted with additional production from gas, in Tunisia mainly with gas, but also with a small additional share of PV, while in Libya it is substituted increasing generation from PV by 3 % and introducing new wind farms. Electricity flows between countries are very similar to STEPS 1.5 °C scenario with nuclear.

Electricity mix in SAPP in STEPS case without new nuclear is characterized by higher production from PV and natural gas, which reach 18 % and 4.6 % of generated electricity. Production from coal is slightly lower, while generation from other technologies remains stable. The small share of nuclear is due to the already existing Koeberg power plant. In Botswana-Namibia-Zimbabwe the electricity that was produced from nuclear is generated from the newly installed gas and PV power plants (respectively producing 12.4 % and 16.2 %) and by increasing the capacity factor of existing coal capacity (reaching 45.6 % of the electricity mix). In Mozambique gas share is slightly higher (8.6 %), while hydro production is practically the same than in the case with nuclear. In Malawi-Zambia nuclear is replaced mostly by gas (18.3 % of production), but also the shares of hydro, coal and PV increase marginally. In South Africa generation from PV increases to get to 22.2 % of production, instead production from coal is slightly lower (66.1 % instead of 73 %) not to exceed the CO_2 cap. Trades of electricity between nodes are generally more spread out across the year with respect to STEPS scenario with nuclear. The most relevant flows, occurring in both directions, is the one involving South Africa and Mozambique and the one between South Africa and Botswana-Namibia-Zimbabwe.

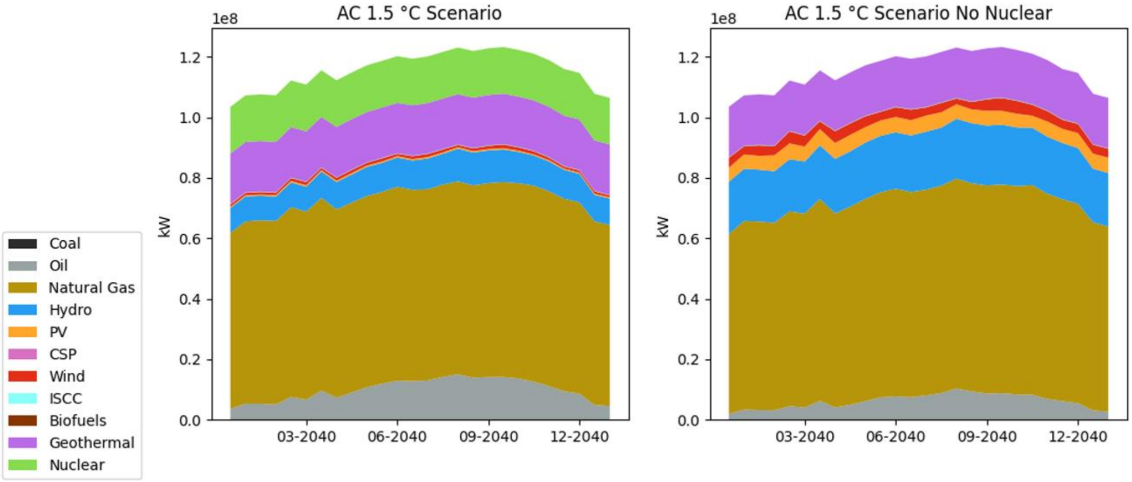

Figure 7.20: EAPP power generation by source along the year in AC 1.5 °c scenario with and without new nuclear capacity.

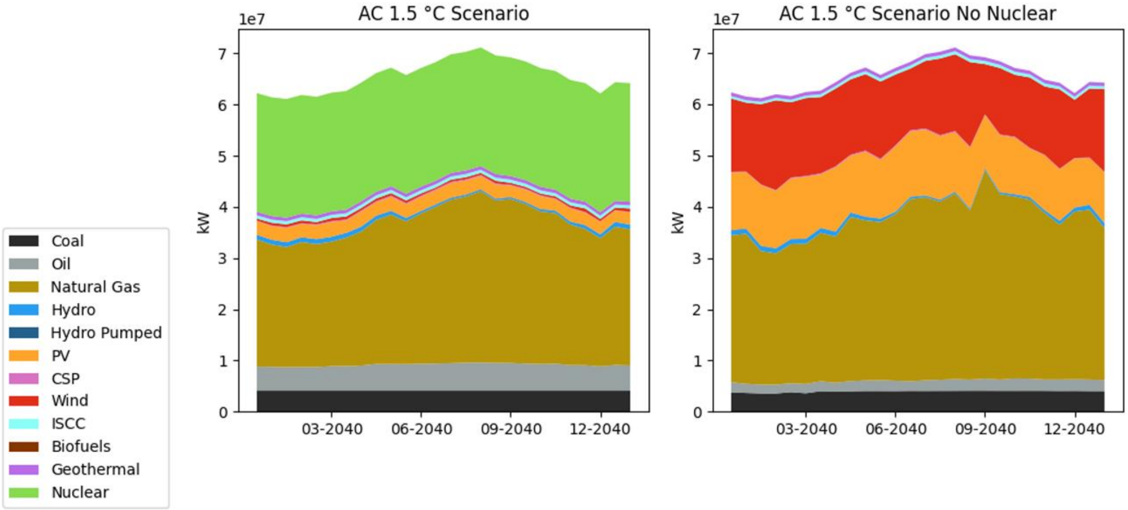

Figure 7.21: NAPP power generation by source along the year in AC 1.5 °c scenario with and without new nuclear capacity.

In the EAPP nuclear is replaced using PV (4.3 % of the electricity mix) and wind (2.8 %), besides additional production from hydro (from 8.1 % to 15.9 %), which is possible thanks to additional installations. The share of gas is slightly higher, while the share of oil a little lower. Production from geothermal maintains stable. In Egypt 75.7 % of production comes from gas, higher than in the case with nuclear (61.7 %), in part to compensate for nuclear, but also to reduce production from oil. PV and wind are as well used to substitute nuclear (6.3 % and 3.9 % of the electricity mix). In Ethiopia and Kenya-Tanzania generation from gas decreases considerably to contain region’s emissions. This portion is instead generated from hydro, which reaches 46.4 % of generation in Ethiopia and 22.8 % in Kenya-Tanzania. Production from fossil fuels decreases slightly in Uganda node and hydro gets to 93.1 % of the electricity mix. Flows of electricity between nodes are similar to the scenario with nuclear, even though the amount of exchanged electricity is somewhat higher.

Electricity mix in NAPP has a larger share of gas with respect to the case with nuclear (48.6 %) and a lower share of oil (3.2 %). PV and wind reach relatively high shares in the electricity mix (respectively 17.2 % and 21.7 %). In Algeria, Libya and Morocco the total share of generation from thermal technologies is almost the same in the two cases, anyhow, in the case without nuclear, an additional share of production from gas is used to substitute highly emitting oil power plants. Nuclear is substituted with PV and wind in Algeria and Libya (reaching 12.6 % of PV and 30.3 % of wind in Algeria and 23 % of PV and 14.1 % of wind in Libya) and with PV in Morocco (which gets to 24.8 % of the electricity mix). In Tunisia and Mauritania wind and PV are utilized as well instead of nuclear, but an increase of production from gas is needed to maintain the baseload. Electricity trades involve all countries, which both import and export electricity (except Mauritania, which remains a net importer from Morocco) utilizing the more integrated transmission grid to balance out the variability of renewable resources.

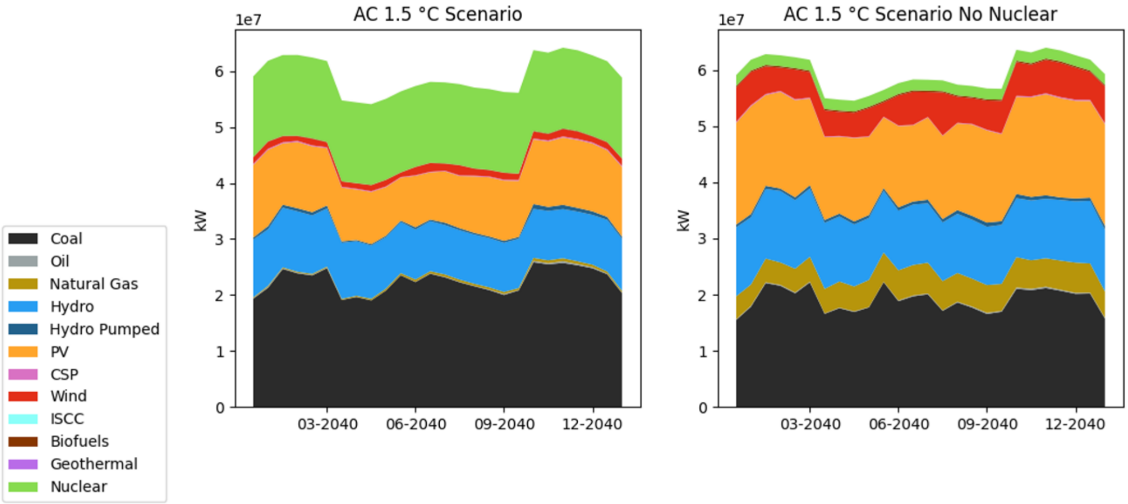

Figure 7.22: SAPP power generation by source along the year in AC 1.5 °c scenario with and without new nuclear capacity.

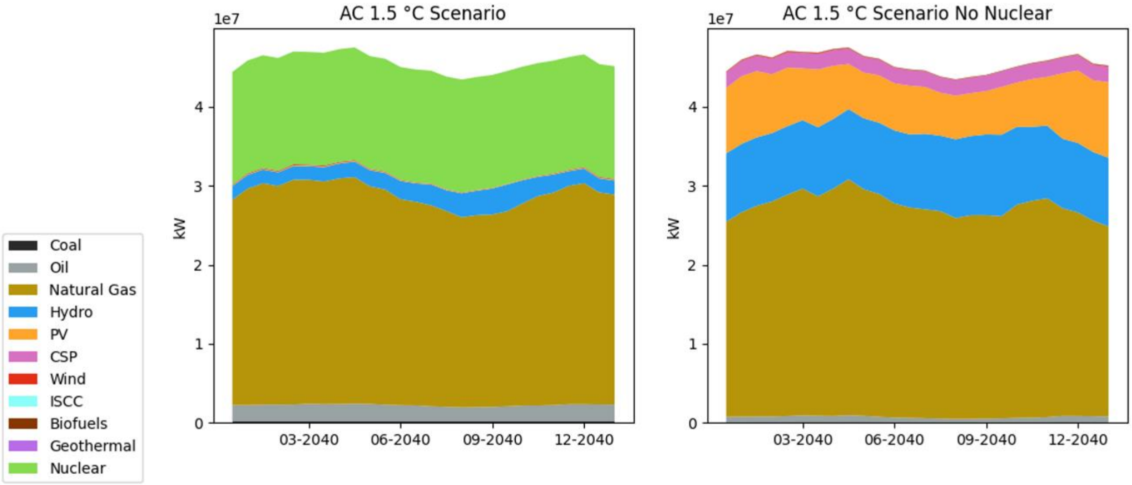

Figure 7.23: WAPP power generation by source along the year in AC 1.5 °c scenario with and without new nuclear capacity.

In the SAPP more than a quarter (28.8 %) of generated electricity is from PV, wind generates 8.8 % of electricity and hydro 18.8 %. In all nodes except South Africa new gas power plants are built and operated to substitute nuclear. To compensate higher emissions from gas power stations, coal power plants are operated at lower capacity factors, so that the share of electricity from coal decreases from 38 % to 32.1 % of the mix. In South Africa almost half of generation is from coal and nearly the same share is from PV and wind (respectively 31.6 % and 13.3 %). In Mozambique and Malawi-Zambia the main technology is hydro, with shares similar to the ones observed in the case with nuclear. The remaining part of electricity is produced in these two countries for one third using PV and for two thirds with gas. Trades involve all nodes and are distributed along the year, without showing marked seasonality.

In the WAPP gas remains the most utilized technology for generation, with a very similar share to the previous case (58.7 %). Production from oil is reduced to limit CO_2 emissions and accounts to just 1.4 % of the electricity mix. Nuclear is replaced with additional production from hydroelectric, that thanks to newly built capacity is used to generate 20.1 % of region's electricity, and newly installed PV and CSP (respectively 15 % and 4.3 % of electricity mix). Though nuclear was installed only in Nigeria, changes can be observed in all nodes. Since to maintain the baseload in Nigeria it is necessary to increase the share of gas in the national mix from 40.7 % to 53.6% (passing from 44.5 to 55.3 Gt of CO_2 emissions), in the other nodes production from fossil fuels must decrease not to exceed the emission cap. Consequently, generation from renewables increases to maintain the energy balance. In the Burkina Faso-Mali node the share of gas is just 31.8 % (compared to 89.1 % in the case with nuclear), instead hydro increases its share from 4.3 % to 23.4 % and PV from 0.7 % to 43.4 %. In Côte d'Ivoire-Ghana and in Senegal-Guinea region production from fossil fuels decreases while the share from renewables increases (in particular PV, which in Senegal-Guinea reaches 20.7 % of the mix). Besides gas, the remaining part of Nigeria's electricity generation comes from a mix of renewables technologies, with 24 % of total electricity produced from hydro, 14.4 % from PV and 7.9 % from CSP, using the only new CSP power plants installed in the continent. New interconnections allow for trades involving all countries. All nodes both import and export to balance out the variability of renewable sources.

Conclusions and future developments

The African continent is the region with the least developed economies and the lowest rates of access to electricity in the world. Yet, fast demographic and economic growth is being experienced in the region. Africa's population is expected to nearly double by 2050, and the AU's Agenda 2063 and many other programs aim to transform the continent's economy and improve the quality of life to achieve high standards for all citizens. In a world where climate change is an increasing threat towards ecosystems and societies, the way in which the continent will fulfill this process of development can have massive effects on the whole world.

Within this framework, the energy sector is one of the key players, as it forms the backbone of social and economic development, but it is also one of the production areas with the highest greenhouse gas emissions. Adequate energy policies have a fundamental role in ensuring sustainable expansion of power systems, but for them to be effective they must rely on extensive technical support. Energy planning can serve as a guidance for policymakers to create measures that favor the deployment of low-emitting technologies. A variety of energy models has been created to describe the African power system. Anyhow, some of them does not have satisfactory temporal resolution, which is a fundamental feature for an accurate representation of an energy system, while others do not optimize the expansion of the power system. Therefore, a new multi-nodal bottom-up model was created using the Calliope environment to support policies for sustainable electrification of the African continent.

The Calliope Africa Model (CalAMo) representation of Africa has a spatial resolution of at least one node per country, a one-hour temporal, and an accurate representation of renewable energy installations that considers the availability of resources over time at the actual location of the installations. The input data for CalAMo were obtained through a careful data collection process using and comparing a variety of publicly available databases and reports.

Then, the model was validated comparing its results for the existing power system with existing data, concluding that model's results are representative of the real system. Minor differences are mainly related to annual variations in availability of renewable resources.

Scenarios for 2040, created considering different projections for demand based on STEPS and AC scenarios from IEA's Africa Energy Outlook, were analyzed. So, the same scenarios were studied one more time imposing an emission cap to grant compatibility with a 1.5 °C increase of global temperature. It was also considered an additional case which does not allow new installations of nuclear, since complexities related to this technology give origin to high uncertainty over its extensive deployment in low-income countries with widespread political instability. All scenarios had to be run for single power pools and, in some cases, simplifying the model due to limitations in availability of computational power.

From the analysis it can be deduced that without constraining CO_2 emissions results are not compatible with a 1.5 °C increase in temperature in NAPP and SAPP in STEPS case and in all regions in Africa Case. Furthermore, it is inferred that the imposition of an emission cap, while causing a sharp increase in required investments, results in a marginal increase of total costs in most regions, thanks to the limited operational costs of nuclear and renewable sources. The greatest total cost penalties are in the SAPP, as this region relies on an already more developed carbon-intensive energy system, and a significant fraction of existing capacity must be replaced with low-emission technologies to meet the emissions cap. This shows how important it is to invest in sustainable supply technologies from the outset, so as not to incur further economic penalties by converting to low-emission technologies at a later stage. Total costs are in line with typical shares of GDP dedicated to energy, but required investments are sometimes much higher than the average shares of GDP dedicated to investments in the power sector. Investment in renewables, excluding large hydropower, over the 2010-2020 period amounts to about \$ 5 billion per year, but is still far from the \$ 6.8 billion required in the STEPS case without nuclear power or the \$ 36.3 billion in the AC scenario without nuclear power. Moreover, these investments have been concentrated mainly in a few countries with more developed policies that have allowed investors to limit their risks. Although global investment in renewables comes mainly from the private sector, this is not true in Africa, where IPPs still account for only a small share of generation and are concentrated in only a few countries. [37] Another result of the model is that grid integration is critical when there is high penetration of VRE technologies to balance fluctuations in locally available resources.

In conclusion, the results of the model suggest that the creation of location-specific policy frameworks that favor the most appropriate low-emission technologies and grid expansion, and that enable the creation of a secure environment for public and private investment, should be a priority to enable sustainable electrification on the continent.

This project can be the basis for a number of future developments. First, various types of utility-scale storage could be added to the installable technologies to test the effect this might have on VREs. Having the adequate computational power to run continental-scale scenarios, analyses could be conducted to study the cost impact of new inter-power pool connections. More rigorous electricity demand projections could be made to improve the reliability of the scenarios. In addition, the model could be expanded to consider the varying availability of renewable sources in different climate years.

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Acronyms

AC: Alternating Current (Chapter 5); Africa Case (Chapter 7)

AU: African Union

CAGR: Compound Annual Growth Rate

CalAMo: Calliope Africa Model

CAPEX: Capital Expenditures

CAPP: Central African Power Pool

CAR: Central African Republic

CCGT: Combined Cycle Gas Turbine

COMELEC: Comité Maghrébin de l'Electricité

COP: Conference Of the Parties

CSP: Concentrated Solar Power

CSV: Comma-Separated Values

DC: Direct Current

DisCo: Distribution Company

DR: Democratic Republic

EAPP: Eastern Africa Power Pool

ECOWAS: Economic Community of West African States

ECREE: ECOWAS Centre for Renewable Energy and Energy Efficiency

EREP: ECOWAS Renewable Energy Policy

ETSAP: Energy Technology Systems Analysis Program

GDP: Gross Domestic Product

GIS: Geospatial Information Systems

HFO: Heavy Fuel Oil

IAEA: International Atomic Energy Agency

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

IPP: Independent Power Producer

IRENA: International Renewable Energy Agency

ISCC: Integrated Solar Combined Cycle

JRC: Joint Research Centre

LCOE: Levelized Cost of Electricity

NAPP: North Africa Power Pool

NDC: Nationally Determined Contribution

NetCDF: Network Common Data Form

NREL: National Renewable Energy Laboratory

OCGT: Open Cycle Gas Turbine

O&M: Operation and Maintenance

OnSSET: Open-Source Spatial Electrification Tool

OSeMOSYS: Open-Source energy MOdelling System

PV: Photovoltaic

SACREEE: Southern African development community Centre for Renewable Energy and Energy Efficiency

SAPP: Southern African Power Pool

SDG: Sustainable Development Goal

SESAM: Sustainable Energy Systems Analysis and Modelling

STEPS: Stated Policies Scenario

TEMBA: The Electricity Model Base for Africa

UN: United Nations

UNDP: United Nations Development Programme

US: United States

USD: United States Dollar

VRE: Variable Renewable Energy

WAPP: West African Power Pool

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