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Benchmarking Study of Energy Modelling Tools in a Multi-Nodal Approach

Case Study: Sudan Electric Power Sector

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To the soul of the Sudanese December revolution martyrs. May the Sudan you died for see the light.

Abstract (English Version)

Recently, Energy modeling systems have experienced a renowned attention from Energy Engineers as well as policy makers around the globe as the debate about climate change and its anthropogenic nature has been the focus of attention in the past two decades. Therefore, hundreds of tools have been developed to mathematically model the complexity of the energy sector. The modelling systems vary along different aspects: the geographical scope, the time horizon, the technical logic, etc. the relevance of energy models has also experienced a boost lately with the aim of integrating the variable renewable energy systems in the electricity grid.

This thesis proposes a modelling of Sudan's electricity sector to evaluate most feasible pathways toward universal access of electricity in the country emphasizing the role of renewable systems toward that end. Three open-source, bottom-up models are utilized (OSeMOSYS, Calliope, and Hypatia), the three models present a high degree of freedom for the user regarding time and space representation with some limitations associated with the convergence time. The main feature of this study is the geographical division of the country into different regions which enables an accurate reflectance of reality. This thesis in its core also compares, benchmarks, and investigates the different used energy models to highlight the effect of different objective functions, logic, resolution on the outcomes. The study also signifies the relevance of electricity importation for Sudan which proves to be a key factor toward the universal access goal.

Abstract (Italian Version)

Recentemente, i sistemi di modellazione energetica sono stati oggetto di una rinomata attenzione da parte degli ingegneri energetici e dei responsabili politici di tutto il mondo, poiché il dibattito sul cambiamento climatico e sulla sua natura antropica è stato al centro dell'attenzione negli ultimi due decenni. Pertanto, sono stati sviluppati centinaia di strumenti per modellare matematicamente la complessità del settore energetico. I sistemi di modellazione variano in base a diversi aspetti: l'ambito geografico, l'orizzonte temporale, la logica tecnica, ecc. La rilevanza dei modelli energetici ha subito un'impennata negli ultimi tempi con l'obiettivo di integrare i sistemi di energia rinnovabile variabile nella rete elettrica.

Questa tesi propone una modellazione del settore elettrico del Sudan per valutare i percorsi più fattibili verso l'accesso universale all'elettricità nel Paese, enfatizzando il ruolo dei sistemi rinnovabili a tal fine. Vengono utilizzati tre modelli bottom-up open-source (OSeMOSYS, Calliope e Hypatia), che presentano un elevato grado di libertà per l'utente per quanto riguarda la rappresentazione temporale e spaziale, con alcune limitazioni associate al tempo di convergenza. La caratteristica principale di questo studio è la suddivisione geografica del Paese in diverse regioni, che permette di riflettere accuratamente la realtà. Questa tesi, inoltre, confronta, confronta e indaga i diversi modelli energetici utilizzati per evidenziare l'effetto delle diverse funzioni obiettivo, della logica e della risoluzione sui risultati. Lo studio evidenzia anche la rilevanza dell'importazione di energia elettrica per il Sudan, che si rivela un fattore chiave per raggiungere l'obiettivo dell'accesso universale.

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Chapter 1
INTRODUCTION

Energy system modelling can be defined as a mathematical approach used to project and balance future demand of energy to a certain amount of energy supply under different time scales and geographical constraints. It works through a code that encompasses information, built-in equations, and data to account for technology expenses, state-of-the-art, actual power plant condition, and other parameters. Energy models are used widely nowadays to improve the implementation of different scenarios and polices, with regards to strict climate change policy, energy security, and concerns for economic and social development, they are now experiencing growing relevance. Due to the continuous development of energy models in recent years, several new models with different modelling capabilities have been released.

One of the main issues in developing countries is energy access, which has various definitions according to the International Energy Agency (IEA) [1] :

I. "Household access to a minimum level of electricity."
II. "Household access to safer and more sustainable (i.e., minimum harmful effects on health and the environment as possible) cooking and heating fuels and stoves."
III. "Access to modern energy that enables productive economic activity, e.g., mechanical power for agriculture, textile, and other industries."
IV. "Access to modern energy for public services, e.g., electricity for health facilities, schools, and street lighting."

having access to energy that is of high quality, trustworthy, affordable, and safe may have a massive impact on people's lives. It can facilitate telecommunications, education, and better healthcare while reducing human work and improving comfort. It can assist women, cut down on time spent collecting fuel, and lessen the negative effects of dirty cook stoves [1]. Access to a consistent and high-quality energy supply can increase economic activity and productivity, which in turn can open-up chances for employment, wage growth and gender equality. Additionally, it can enhance the safety of the public and make it easier to supply services in the areas of education, health, and e-governance.

The 2030 Agenda serves as the new global framework for national and international dedication to finding answers to the world's greatest problems, including extreme poverty, climate change, environmental degradation, and health issues. The 17 Sustainable Development Goals (SDG's) are the cornerstones of the 2030 Agenda. “Universal access to affordable, reliable, and modern energy for all” by 2030 (Sustainable Development Goal (SDG) 7) is essential and a driving force for enhancing the working and living situations of everyone in the world. Several major SDGs are hampered by the lack of modern energy access, particularly for the most vulnerable and underprivileged communities. The widespread use of modern energy also contributes to reducing ecological degradation and reaching inclusive net-zero emissions by 2050. [2]

The energy usage in the developing countries is rapidly increasing throughout the years due to different reasons: the annual growth of population demanding access to affordable and reliable sources of energy, the economic development in these countries, as the society and individuals become wealthier, their lifestyle improve, and they start using more energy whether for powering their industries or purchasing electronic goods and increasing urbanization by moving to the main cities and towns.

1.1 Background

1.1.1 Africa and Sudan Energy Dilemma

Africa is a continent rich in energy resources yet poor in energy supply. There are many factors that contribute to the poor energy supply according to Africa energy outlook in 2019 [3], they are mainly related to low governmental investment, absence of free market in energy supply and distribution, absence of international investment in the energy sector, political instability, and regional disparities. The electricity supply dilemma in Africa poses threats to all other sectors and it results in:

1. Poor health and educational services.
2. Deficient performance of the industrial sector.
3. Massive use of biomass (wood and charcoal).
4. Millions of premature deaths yearly.

In terms of installed generation capacity, per-person electricity use, and household access to electricity, Africa trails behind every other continent of the world. With a total population of around 1.3 billion people, less than 242 GW of installed capacity is deployed in the continent according to the IEA [4]. Africa is home to fifteen of the nations with the lowest per capita energy consumption rates in the world [3], resulting in over 640 million Africans living without access to electricity. The average electricity access percentage in Sub-Saharan African countries is less than 50% as of 2020 according to the World bank [5], despite the noticeable improvement compared to the early 2000s (from 26% in 2000 [6] to 46% in 2020 [5]). The average amount of people gaining access to electricity yearly has doubled from 9 million a year between 2000 to 2013 to 20 million yearly in the period between 2014 to 2019 [3]. The rural to urban division has been diminished in North Africa’s Arab countries, but the percentage is still very wide in Sub-Saharan Africa, where 78% of population in urban areas have access to electricity while only 28% of population in rural areas have connections based to estimates from the World Bank in 2020 [5]. Even countries with good economic indicators like South Africa, which is considered the best-supplied country in the Sub-Saharan African region suffers from the frequent blackouts. Sudan is an African country located in the North-eastern part of the continent and it is the third largest

African country with an area of almost 1,900,000 km^2, this large land is occupied only by forty-five million people making it one of the lowest countries in terms of population density. The capital is Khartoum, and it represents the economic, industrial, and political center of the country. The nominal GDP per capita was below 765 US dollars/capita in 2021 making it a low-income country [7].

Sudan electricity sector is rated among the best sectors in the region with a 3750 MW installed supply capacity according to IEA [4] in 2021, the system losses are relatively low, service costs amount to 20 cents per kWh which is average by the region, the electricity access percentage is a bit higher than other Sub-Saharan African countries average with 47.3% access in 2019 based on the World Bank report [8] and this percentage remain the same for the time being. The sector is heavily subsidized by the government leading to the lowest electricity tariff in Sub-Saharan African countries. The electricity sector is characterized by obvious regional disparities where access percentage in the northern and eastern states that has higher numbers of people with Arabian ethnicity is much higher. Services costs are expected to rise because of the depreciating local currency which may result in a power crisis. The Sudanese electricity sector like the rest SSA is experiencing an accelerated growing demand with an average annual growth rate of 11% since 2013 [8]. Rich resources are abundant in Sudan. In actuality, the nation's natural resources are its principal source of income. These stand for fertile land, an abundance of surface and ground water from the Nile rivers, or other riches like livestock, gold, and various other embedded minerals. Petroleum, hydroelectricity, biomass, and renewable energy sources make up most Sudan's key energy sources. Electric power production, oil refinery, and wood-to-charcoal conversion are the three basic transformation and conversion processes. Sudan is a major "untapped" market for renewable energy, given its enormous technical potential for renewable energy sources including geothermal, wind, biomass, sunshine, and others.

The issues facing Sudan's economy are particularly harsh. Oil money, which at the time made up more than half of the government's budget, was lost because of South Sudan's 2011 secession. In addition, the United States imposed economic sanctions on Sudan in 1997. In October 2017, these restrictions were largely relaxed, making it possible for Americans and businesses doing business with Sudan to conduct banking and commercial activities.

The inclusion of Sudan in the list of nations that sponsor terrorism has only served to worsen the impact of the lengthy economic isolation. Uncertainty over the macroeconomic structure was amplified by a series of successive changes in the administered exchange rate. Due to 383 percent inflation and the Sudanese Pound's decline in value in 2021 [9], Sudan's economic performance continued to suffer.

The Sudanese electricity sector experienced unbundling across the technical lines in 2010. Prior to that, it had been monopolized by the national electricity sector which is a state-owned company that functioned as a vertically integrated utility responsible for production, transmission, and distribution of electricity. After the unbundling act, the sector had been divided into four companies that lie under a holding company that oversees them named the Sudanese electricity holding company. The four technical companies are: Sudanese thermal power generation, Sudanese hydropower generation company, Sudanese electricity transmission company and Sudanese electricity distribution company. Regardless of the unbundling, the sector companies remain as integral part of the ministry of oil and petroleum depending on the government budgetary allocations having little to no say regarding finances, investments, and personnel management. In 2018 the mandate for the Sudanese hydropower generation company was extended to include other renewable energies such as solar and wind [8].

1.1.2 Energy Models

Energy systems models are crucial tools for producing a variety of analyses and insights on the supply and demand for energy. Over the period of the second half of the 20th century energy models had developed. Another synonym for energy system models that is widely used is the Integrated Assessment Models (IAM) which is based on mathematical optimization to find the least- cost solution in some sense. The first energy system model was designed by the International Energy Agency (IEA) under the Energy Technology Systems Analysis Program (ETSAP) in 1976 [10]. The International Institute for Applied Systems Analysis (IIASA), established in 1972 as a hub for interdisciplinary research, started working on an energy systems model not long after it was established [10]. These two models are still relevant today. Although these and subsequent models were initially created primarily for use in the Energy Information Administration (EIA) member countries and other large, developed economies, they have since been used for analysis in a wide range of contexts, from small off-grid systems in developing countries to large-scale continent-wide assessments in developed economies, However, they were very ineffective because they could only study one energy sector and one energy flow.

Later, many energy system models were developed to study the energy sector such as: MARKAL, MESSAGE, EFOM, OSeMOSYS and Calliope. They have shown to be quite helpful for designing the entire national energy system as well as for optimizing the operational strategy for generating electricity. The energy models development can be linked to oil dilemma in the seventies [10] when both business and decision-makers understood how crucial long-term sustainable energy planning is. Models for energy systems assisted analysts in understanding a field that had become more complicated and in creating scenarios for the field's potential future development. Energy systems models, however, not only made it feasible to create scenarios, but also to formalize the disparate knowledge regarding the intricate interactions in the energy industry.

The difficulty with categorizing energy models is that there are several ways to describe the various models, but only a small number of models that fall into a single, clearly defined category, they can be divided based on [10] [11] :

1. Geographical coverage: Project, Local, National, Regional or Global

The geographical coverage indicates the level of analysis, which is a crucial aspect in figuring out how models should be structured. the global models depict the whole economy or situation, whereas the regional level typically refers to international regions like Europe, the African Countries, East Asia, etc., National models include all significant sectors in a nation at once while treating global market factors as exogenous. Regions within a nation are referred to as the local level, which is subnational. A national or even multinational project is included in the project level.

2. Time horizon: Long, Medium and Short Term

The short, medium, and long terms do not have a common definition, but they are important since various economic, social, and environmental phenomena are significant at various time scales. The structure and goals of the energy models are thus determined by the timeframe. While short run models must include "disequilibrium" and "transitional" impacts such as unemployment rate, long run assessments may assume economic equilibrium (i.e., resources are fully distributed).

3. Mathematical approach:

Techniques including linear programming, mixed integer programming, and dynamic programming are frequently used. Of course, it is also feasible to combine different methodologies within a model.

- Linear Programming (LP):

A linear function is maximized or minimized when subjected to certain restrictions in a mathematical modeling technique called linear programming. This method has been effective for directing quantitative choices in the social and physical sciences, industrial engineering, and corporate planning. Only situations where activities may be described as linear equalities or inequalities can be dealt with using this technique. The fact that all variables must be constant and the fact that LP leads to selecting the cheapest resource up to its maximum before using any other options simultaneously for the same item are disadvantages. Another disadvantage is LP models may be extremely sensitive to changes in the input parameters. This method is employed in practically all optimization models and is used in long-term technologically oriented energy research as well as national energy planning.

- Mixed Integer Programming (MIP):

Mixed Integer programming is basically a linear programming expansion that enables more specific formulation of technical aspects and relationships when modeling energy systems. The requirement that at minimum one of the parameters can only have integer values is added as an extra condition. Operations research uses this method extensively.

- Dynamic Programming:

Dynamic Programming is a method for efficiently solving a class of overlapping subproblems with optimal substructure in computer programming.

4. Analytical Approach: Bottom-Up & Top-Down

   i. Bottom- up models have long served as the foundation for modeling energy systems. The technological elements of the energy system are described in great depth in bottom-up models but fail to take into consideration the feedback from the macroeconomic system and microeconomic judgment. They must simplify due to their extensive richness to remain readable. Additionally, they are separated into multi-agent models, simulation models, and optimization models.

- Multi-Agent models: accommodate for market flaws, but they are only applicable to energy-conversion technology.
- Simulations models: typically examine scenarios to evaluate how technology-focused actions behave. They are typically applied to models that examine future demand and associated emissions (MESAP, LEAP, NEMS, and PRIMES).
- Optimization models: used to optimize and analyze energy investment options by finding the best choice to meet the goal. The included processes in optimization models must be defined analytically, and this has the drawback of requiring a fair amount of mathematical expertise. In optimization models, linear programming methods are frequently used. (MARKAL/TIMES, OSeMOSYS and Calliope).

ii. Top-Down Models can be described as model that use an “economic approach” and analyze different economic variables to reach the best solution. They are divided into four categories: Input-output models, Econometric models, General Equilibrium models and System dynamic models.

5. General purpose:
   i. To forecast or predict the future.
   ii. Scenario analysis: to explore different futures based on different realities.
   iii. Back-casting: looking back from the future to the present.

1.2 Objectives of the Thesis

In this study a comparison and investigation both quantitatively and qualitatively for different energy modelling tools is developed to highlight the differences in results and therefore suggested policies. Namely the open-source energy modelling system (OSeMOSYS), Calliope and Hypatia models are being investigated in this study. The case study chosen to reflect this is the Sudanese energy sector. The study also serves to demonstrate, investigate, and quantify the significance of the primary result variations between multi-node Energy system models. All the models included in this study are considered bottom-up energy models with the variety of choosing the geographical constraints, but with some limitations on the time resolution.

- OSeMOSYS is an open-source model created for long-term integrated evaluation and energy planning. It can be used at scales ranging from that of continents down to that of individual nations, regions, and even individual villages. The time resolution and the horizon in OSeMOSYS is defined by the user.
- Calliope is an open-source energy model designed to study the energy systems that are characterized with a high share of renewable energy and other types of generation. It is also used to assess the scenarios with hourly time-steps in a multi-node energy system.
- Hypatia is a framework for modeling the energy system that may be used to optimize both the system's annual capacity deployments and hourly dispatch. Its goal is to reduce the system's overall discounted cost by taking into account all necessary cost factors within each of its optimization modes.

This thesis is also aiming to provide guidance to the Sudanese power sector in its endeavor toward universal electricity access by suggesting the possible generation and grid network expansion strategies toward that end. The study explores the pathways toward universal access by means of domestic generation and electricity importation from the neighboring countries.

1.3 Research method

Although Sudan is administratively divided into fifteen states, dividing it into five primary regions is the most politically adapted and they are:

1. North Sudan
2. East Sudan
3. West Sudan
4. Center Sudan
5. The Capital (Khartoum)

The similarities between the grouped states in terms of access to services and electricity, as well as the living standards are reflected in this division in addition to the ethnic and political situation. For all the energy models included in this study, the same Reference Energy System (RES) of the Sudanese electricity sector was applied to highlight the difference in the results between these models given the same RES as input. To handle the geographical complexity of the case and include the interaction between the power generation units and the transmission network, the design of nodes technique was adopted in all the scenarios studied. The primary contribution resulting from the use of a multi-node-based modeling tool in this project is represented by the creation of models from scratch to assess energy systems with a thorough examination of renewable energy sources or other variable energy production.

The information and data used in this study has been gathered from both national and international sources, of course with a priority to the last updated local sources. Due to the perturbation that happen in Sudan in the last three years starting from the revolution of civilians against the ruling party demanding for the democratization, The armed forces used their power to stage a coup d'état and seize control from the civilian government leaving the country without a stable government structure until the time being, we could not find recent data from the local sources that express the energy sector in Sudan for the last year, so most of the data used in this thesis is coming from an international entities: International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations (UN) and the World Bank.

Additionally, the acquired data is put through a quality check to prevent double counting and to determine the degree of uncertainty, so many entities in Sudan were contacted to be sure that the acquired data reflect the present situation of the Sudanese electricity sector and mainly they were:

- Sudanese Electricity Holding Company (SEHC)
- Sudanese Thermal Power Generation Company (STPG)
- Sudanese Hydropower Generation Company (SHGC)
- Sudanese Electricity Transmission Company (SETCO)
- Sudanese Electricity Distribution Company (SEDC)
- Ministry of Energy and Mining

1.4 Thesis Structure

The following chapters contain most of this thesis. The idea of energy system modeling and energy access is introduced in the first chapter. It outlines the primary goals of the project and provides some background information on the energy crisis in Africa and Sudan. It also includes a brief history about the energy models and their classification. The second chapter provides information on literature evaluations pertaining to recent benchmarking studies for energy models and provides a thorough explanation of the energy modelling publications linked to the Sudanese energy sector.

The third chapter offers a review of the Sudanese power sector profile with a special focus on the Sudan energy sector and its crucial parameters: Total Primary Energy Supply (TPES) and Total Final Consumption (TFC). It also identifies the key players in the sector, explains how they interact with one another to contribute to the energy system, and gives a broad overview of the nation's energy resources. The chapter also covers the nation's historical and current patterns of electricity production and consumption. Finally spotting the light on the institutional structure and guiding polices of the power sector. The fourth chapter provides an overview of the three model settings and how they operate, as well as the steps taken for data gathering and resource assessment for Sudan. The transmission line network modeling and forecasting methods for the demand sectors through 2030 are also covered in this chapter. The scenarios used in the research are finally defined.

The fifth chapter provides the three models (OSeMOSYS, Calliope and Hypatia) outputs for the different scenarios, as well as generation, transmission, imports, and exports for each region and the total investments and operating costs. This chapter also includes a comparison and benchmarking of the outcomes from various models. The sixth chapter outlines the key findings of this thesis as well as potential directions for further research.

Chapter 2
LITERATURE REVIEW

To investigate the relevant literature written about the comparison between Bottom-up optimization energy systems modelling tools and the modelling of the Sudanese energy sector we carried a systematic literature review for the two topics divided into three phases:

I. Phase 1: Vast search using the database engine ScienceDirect. The strings used for searching the two topics are tabulated below.

II. Phase 2: Redaction of the collected papers and studies was performed by excluding the off-topic results i.e., comparisons between energy building tools and software, Sudan total primary energy supply modelling, etc. Since the search phrases used are generic a huge number of results were eliminated in this phase, the term energy system is widely used in the literature for different topics that are unrelated to the study scope (e.g., Natural Gas and oil supply systems, electric power transmission systems)

III. Phase 3: Thorough examination of the qualified papers to determine their relevance as well as their citation in other articles.

The literature targeting studies about energy modelling tools comparison mostly qualitatively described the existing energy models to classify them and outline the challenges they are facing rather than quantitatively compare the results from different models. On the other hand, the literature focusing on Sudan's energy sector outlook is mostly developed by international organizations rather than individual researchers or groups of researchers.

Table 2.1 - Search Phrases for literature review.

Benchmarking Studies Related	Sudan energy sector related
Comparison of Energy modelling tools	Modelling of the Sudanese energy sector
Benchmarking study for energy modelling tools	Sudan power sector modelling
Overview of Energy systems modelling tools	Sudan Energy outlook
Bottom-up energy modelling tools comparison	Sudan electricity sector expansion scenarios

2.1 Benchmarking Studies for Energy Systems modelling tools

The literature review shows that most of the literature intended to compare various energy modelling tools takes off by presenting a kind of systematic classification of the energy modelling tools in order to present a ground for comparison of the wide range of the studied models for example Pefenninger. S. et al [10] classified energy models into four broad categories depending mainly on their purpose and building structure into:

- Energy systems optimization models: Models covering the entire energy system, primarily using optimization methods, with the primary aim of providing scenarios of how the system could evolve.

- Energy systems simulation models: Models covering the entire energy system, primarily using simulation techniques, with the primary purpose of providing forecasts of how the system may evolve.

- Power systems and electricity market models: Models focused exclusively on the electricity system, ranging in methods and intentions from optimization/scenarios to simulation/prediction.

- Qualitative and mixed methods scenarios: Scenarios relying on more qualitative or mixed methods rather than detailed mathematical models.

Alternatively, M. Prina et al [12] used models approach to the problem in order to classify models to three main categories:

- Top-Down models: Top-down models are typically adopted by economists and public administrations. These models focus on connecting the energy system to other macro-economic sectors.
- Bottom-Up models: Bottom-up models analyze in detail the components and interconnections between the different energy sectors
- Hybrid models: an integration of both approaches either through a hard or soft link.

The starting point of energy systems modelling tools comparison by listing the classification of the models also is apparent in H. K. Ringkjob et al [13] work where they followed the overarching typology presented by Després et al [14] that classifies energy models based on general logic, the spatiotemporal resolution as well as the technological and economic parameters of the models. Except for the paper presented by [12] the authors however clearly indicate that the classification is not intended to present a state of art paradigm and rather just used for the sake of argument and grouping the different models to create a common ground when comparing similar models.

Another common feature in the literature is to present the challenges that energy models are facing representing a sector that is continuously growing more complex for instance, [10] argue that the main issues faced by the energy models and modelers nowadays are:

1. resolving time and space.
2. balancing uncertainty and transparency.
3. addressing the growing complexity of the energy system.
4. integrating human behavior and social risks and opportunities.

Meanwhile, [12] think of the issues faced especially by bottom-up energy systems models to be related to the different dimensions of resolutions:

1. Time resolution.

2. Space resolution.
3. Techno-economic resolution.
4. Sector coupling resolution.

The authors argue that fine resolution in all of the different abovementioned dimensions is essential to obtain more stable and realistic results and uses a qualitative scale ranging from high to low in order to classify and compare models against those merits.

In [13] the authors state that time and space resolution are a main factor in obtaining realistic and robust results when Variable Renewable Energy Sources (VRES) are considered due to their intermittent nature and high spatial variability specially for wind turbines technologies. This conclusion seems to be agreed on by the different literature as the duality of time/space resolution is emphasized in all the literature.

In the vast majority of literature found authors realize the trade-off between detailed approach presented by a highly refined time and space domain and the increasing complexity of obtaining a stable solution and the computing powers required to run scenarios for example [15] and [16] both presented the argument that a low variability in the presentation of time might results in an overestimate of the VRES share however a higher time resolution requires high computing power and running time to obtain a mathematically stable solution.

Moreover, the literature focused on the importance of the time horizon offered by the model and how it is a main concern for modelers and policy makers when they choose a model. [12] used the time horizon as a main feature to further subdivide Bottom-up models in their novel classification criterion. Closely related to the time horizon, authors concentrated on pinpointing the different logic used by bottom-up models between snapshot logic and capacity building approach where the former merely provides a desired end state unlike the latter which presents the way to reach that end.

The literature in [10] and [17] also concentrated on the dichotomy of planning/operational models where planning models presents an optimization toward expanding capacity to meet a future demand for a given scenario while operational models optimize the technology dispatching and usually require a high number of time slices and resolution of hours.

[12] authors concluded that calliope is classified as a high temporal and space resolution model whilst OSeMOSYS is a high spatial low temporal resolution model. They also pointed out that Calliope uses a snapshot logic while OSeMOSYS uses a capacity deployment approach. [13] concluded similar results classifying both Calliope and OSeMOSYS as investment decision support tools however calliope unlike OSeMOSYS also works as operation decision supporter. They pointed out that calliope could use both LP and MIP techniques whilst OSeMOSYS only uses an LP approach however recent updates includes the possibility of using a MIP approach. The high time resolution of calliope compared to OSeMOSYS is also emphasized with the two models having a fine geographical resolution and horizon.

2.2 Sudan Energy System Modelling

The Sudanese power sector experienced its largest boom during the mid-2000s due to the peace treaty signed between the central government in Khartoum and the southern social movement resulting in cash flow to the country as a result of exporting crude oil. during that period and prior to the secession of South Sudan the developing economy assisted the government in building a new infrastructure for the power sector and promoted planning of future energy systems that allows for a universal access in the early 2030s. Regardless, studies forecasting the future of the Sudanese power sector are few and mainly developed by the Sudanese authorities through third party companies or international entities. This can be traced to the difficulty of obtaining legal rights to use optimization energy models amid the American sanctions imposed on the country for allegedly supporting terrorism which hindered the capabilities of individual researchers on building models for the Sudanese power sector.

The last updated least cost plan presented by the Sudanese government dates to 2012 by a third-party counseling company. The plan is developed for the year 2012-2030 to achieve the Sudanese energy policies by achieving universal access in 2030 according to the World bank [8]. The result of the plan Shows a high new installed capacity of fossil fuels-based technologies introducing coal steam turbines to the mix. The underlying assumptions and the used model are restricted to government officials. However, the plan is quite outdated, and the prices of fossil fuels and the projections are not validated any more. On

June 30, 2019, the world Bank presented its final report [8] assessing the Sudanese electricity sector and within the report the world bank associates presented a least cost optimization study for future capacity building in Sudan. The report starts by describing the current situation of the Sudanese power sector from the different technical and financial perspectives comparing it to the regional electricity sectors. It also presents the current guiding policies of the Sudanese electricity sector. The second part of the report is concerned with the financial outlook of the sector in a troubled economy, pointing out the expected struggles and challenges that are expected. In the third section the report presents least cost planning as a priority to recover the sector from the recent problems it has been undergoing. In particular, the section provides a preliminary least-cost generation expansion plan for the years 2019-2030 with more focus on the years 2019-2023. The main purpose of developing the plan is to compare it to the above-mentioned government plan in terms of required Capital investment and operating costs. The underlying assumptions and used models are not clearly mentioned nor indicated in the report. However, it is set to meet the government plan of increasing the electricity demand yearly by 10% toward 2030 and not achieving universal electricity access. The results show that toward 2023 22% of the installed capacity would be Solar PV and wind turbines. The highest contribution though is expected to be associated with HFO combined cycle gas turbines reaching 33.8%. The model does not include a modelling of the transmission lines though and is not refined regionally.

In 2021, the International Renewable Energy Agency (IRENA) presented its report titled Planning and prospects for renewable energy power: Eastern and Southern Africa [18]. The large and detailed study is devoted to presenting an outlook for the possible scenarios of developing the power sector across the southern and eastern parts of Africa. The study that runs from 2020 to 2040 is very extensive and open regarding the used data. The analysis is performed on each country on its own leading to an overall optimized plan for different scenarios. The study starts by stating the current state of the power sectors across the studied area mainly discussing the power demand profile and historical growth, it moves on to describe how the potential of the different resources were calculated and it helped in our developing of criteria to assess the potential. The main assumptions made during the study are then clearly listed for each part. The demand is growing according to the IRENA EAPP Plan where the demand grows by 6% from 2020-2030 and 3% from 2030-2040. The other assumptions are also listed. The model used in this study is the SPLAT model specially developed by IRENA for African countries, it is a capacity expansion planning model, and it is built on the MESSAGE model developed by IIASA and adapted by IAEA. The time resolution defined is three seasons per year. For the reference scenario the results show a high contribution of wind and solar PV reaching a total of 6 GW installed capacity in 2040.

Chapter 3 SUDANESE POWER SECTOR PROFILE

3.1 Energy Sector in Sudan

Oil, hydropower, biomass, and renewable energy are Sudan's key energy sources. Electric power production, oil refinery, and wood-to-charcoal conversion are the three main transformation and conversion processes. According to estimates by the International Energy Agency (IEA), Sudan's major energy supply is 20.3 million tons of oil equivalent (toe) in 2019, with biomass resources accounting for 61%, fossil fuels (mainly oil) 34.5%, and hydroelectricity 4.5% of the total energy supply [19]. From the country’s Sankey diagram (Figure 3.1), it is worth noting that the electric power conversion process suffers high losses, in 2019 the losses reach about 40%. Even though Sudan's energy supply position has improved over the past ten years thanks to the usage of its own oil deposits and the building of dams along the Nile, the South Sudan secession represents a significant setback for the country. Sudan has lost 60% of its biomass energy resources, 75% of its oil reserves, and 25% of its hydropower potential since South Sudan's secession in July 2011.

Large-scale, untapped renewable energy potential is available in Sudan. Sudan has a greater potential for solar and wind energy than most other Sub-Saharan African nations. Most of the country regions have a strong solar potential while the Red Sea coast and the interior of the Northern State have considerable site-specific potential for wind energy. The Sudanese government is also investigating the nation's geothermal potential. These renewable resources are, however, mostly unused. The only renewable resource that has been heavily utilized for power production is hydropower

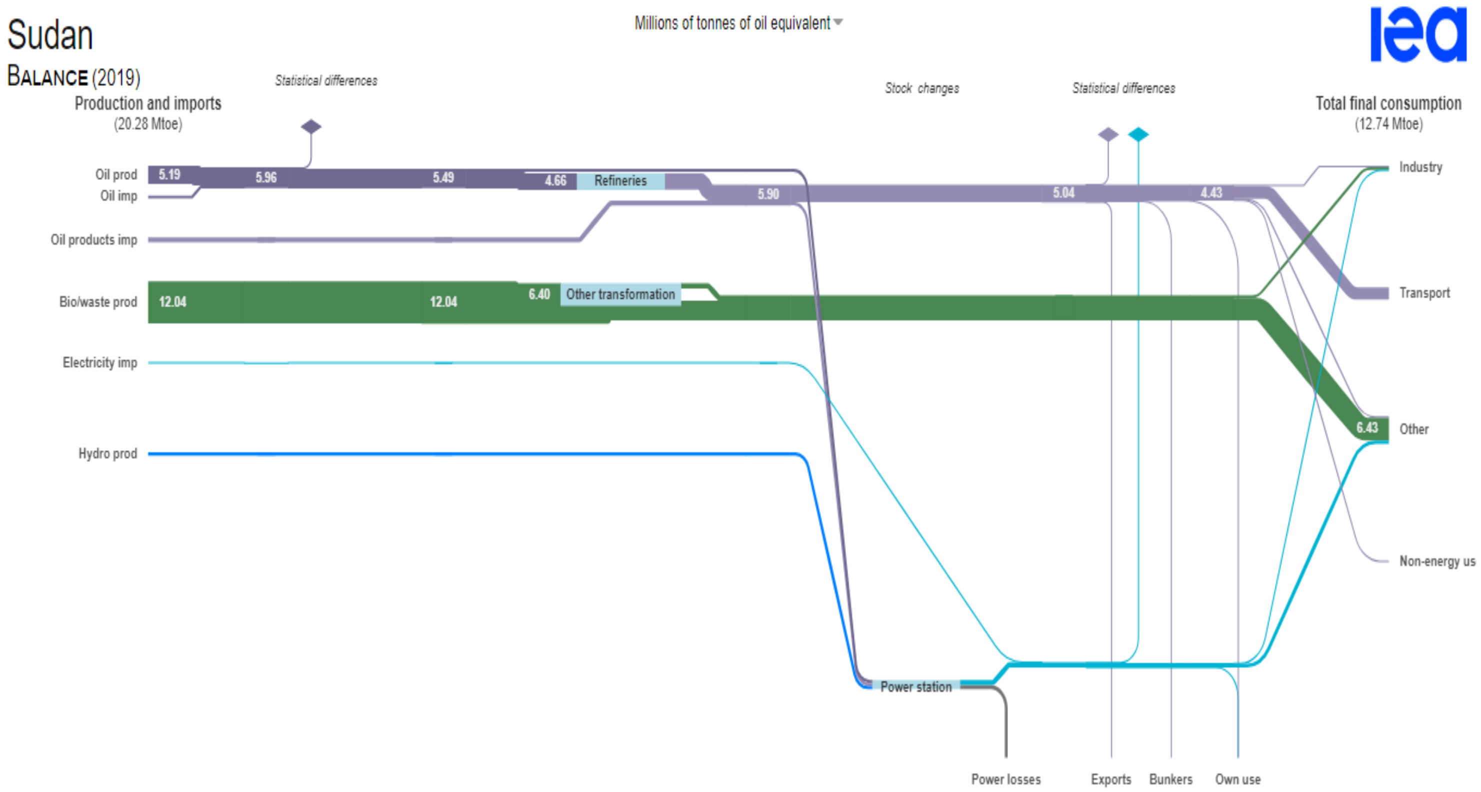


Figure 3.1 - Sudan Sankey diagram 2019. Source [19]

The final energy consumption in Sudan is about thirteen million tons of oil equivalent (toe) according to the last updated data by IEA and it is devoted mainly to five sectors: industry, transport, residential, agriculture and services. The most demanding sector in terms of final energy consumption is the residential (45%), followed by the transportation sector (27%) and the service sector (14%) [20]. The trends of TFC are depicted in the graph below (Figure 3.2), showing how over the past ten years, the total final consumption of Sudan has increased. The use of biofuels and household residues, advancements in healthcare and education, improvements in the transportation and industrial sectors have been the key causes of this increase

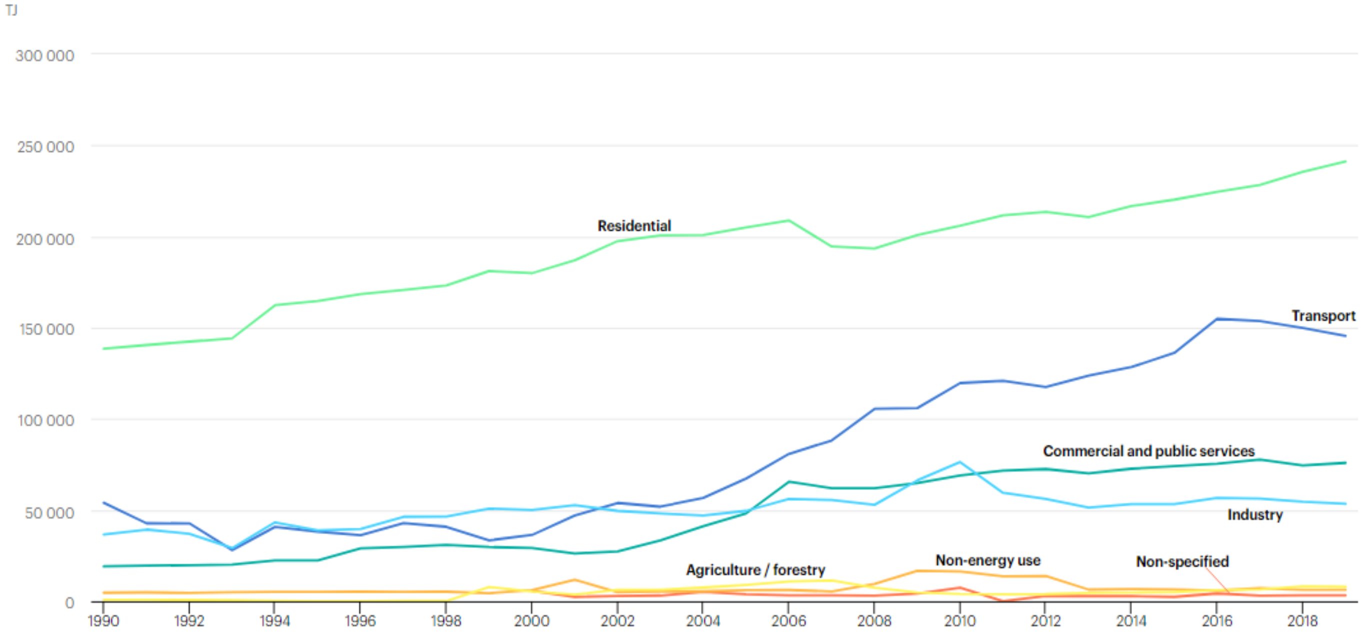


Figure 3.2 - Total Final Consumption (TFC) by sector, 1990-2019. Source [20]

3.2 Electricity Sector in Sudan

The electrification rate in Sudan is growing throughout the years and the government of Sudan is investing in expanding the distribution network and in off-grid electrification solutions. The electrical industry in Sudan is running more effectively than in other nations in the region. Sudan has one of the biggest power networks in Sub-Saharan Africa, with a 3.75 GW hydroelectric and thermal power producing capacity. Sudan ranks among the highest performers in Sub-Saharan Africa in that category thanks to low system loss and universal bill collection. The sector does, however, suffer many of the operational difficulties in administration and finance that are typical of the nations in the region, such as limited access to power and load shedding during the busiest times of the summer. Most of the population's access to electricity is reserved for urban and relatively wealthy groups while western region residents have extremely limited access to electricity. Although the sector has been connecting a sizable number of customers to the grid, population growth has mostly ruled out improved access.

3.2.1 Demand

Due to population expansion, a rise in the GDP in the middle of the 2000s, and the electrification of urban areas, Sudan's demand for electricity has been steadily rising since the early 2000s [21], and this trend is now accelerating. Residential demand accounts for roughly 60% of the total electricity supply. The remaining sectors split the non-residential demand, with half going toward service demands. Even though households account for most of the demand, as of 2018, just 32% of the population have access to electricity [8].

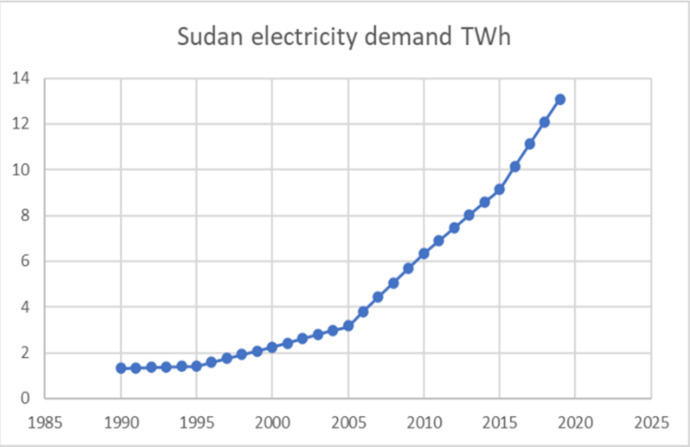


Figure 3.3 - Sudan electricity demand growth, 1990-2019.
Source: own elaboration from [21]

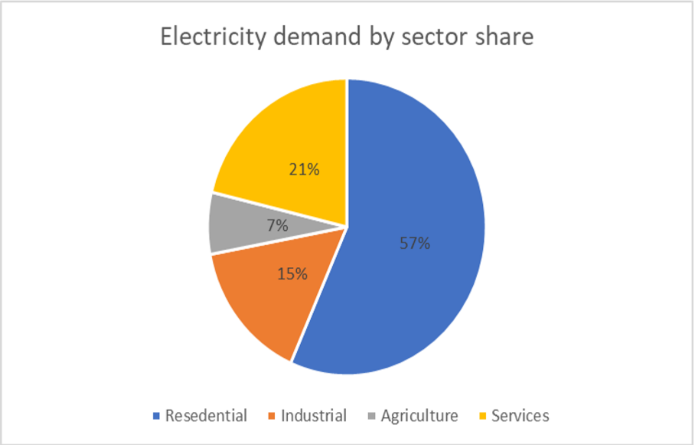


Figure 3.4 - Electricity demand share by sector in 2019.
Source: own elaboration from [21]

The demand profile in Sudan is very much like the other Sub-Saharan African countries where it peaks in the summer period due to the heat waves and harsh summer which leads to excessive usage of HVAC appliances for the grid connected users. In the summer, the demand for electricity doubles, leading to substantial power disruptions. During the hottest times of the year in Sudan, June and July, load shedding may affect up to 40% of the electrical consumption according to the World bank [8]. The largest concern for electricity users is probably load shedding, which also causes them to overuse electricity while it is available. Figure 3.5 shows the demand profile of electricity. The hourly profile is retrieved from the PLEXOS database for 2015 [22] and an assumption that the same load profile is sustained during the study period is made.

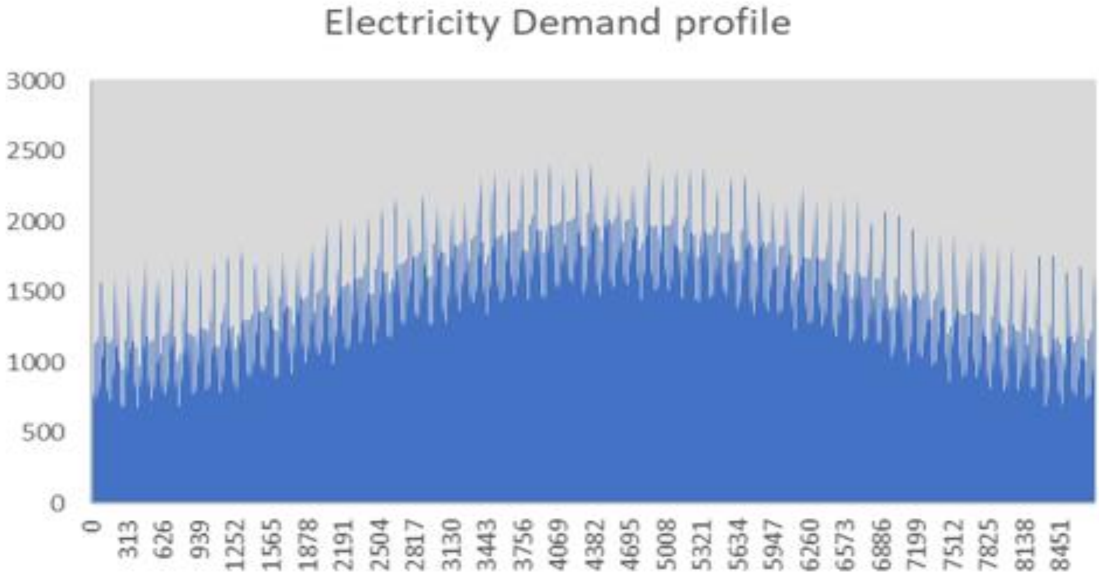


Figure 3.3 - Sudan electricity demand profile. Source: own elaboration from [22]

3.2.2 Supply

Currently the electricity supply in Sudan is divided into thermal power generation from conventional power plants, which use mostly oil products as energy resource, and hydropower plants exploiting dams and the river Nile basin. The installed capacity in 2018 shows that hydropower has a slightly more installed capacity compared to thermal generation. The generation mix also shows that hydropower generation contribution in the produced electricity is higher than thermal power generation however, and that the share of thermal power generation had experienced a rise in the latest years reaching almost 48% in 2018 and is expected to grow even higher [8].

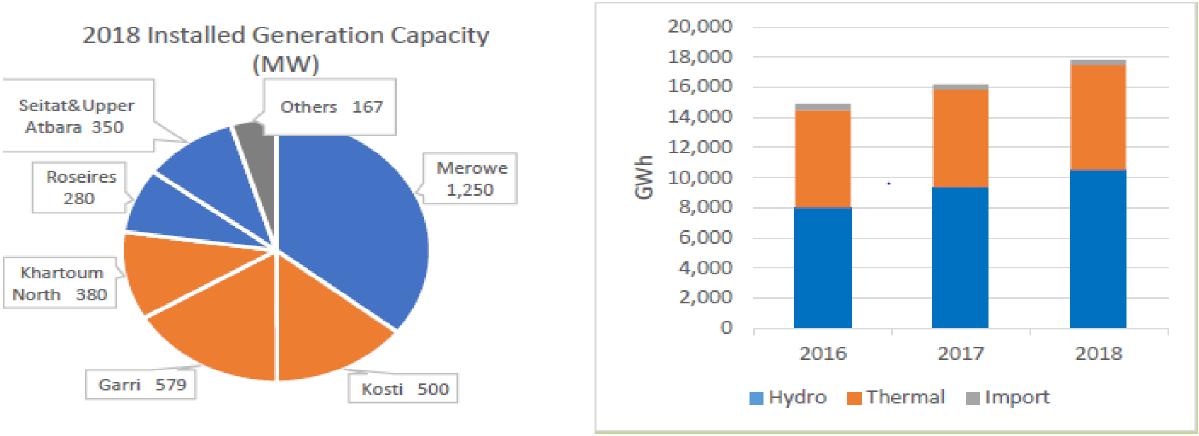
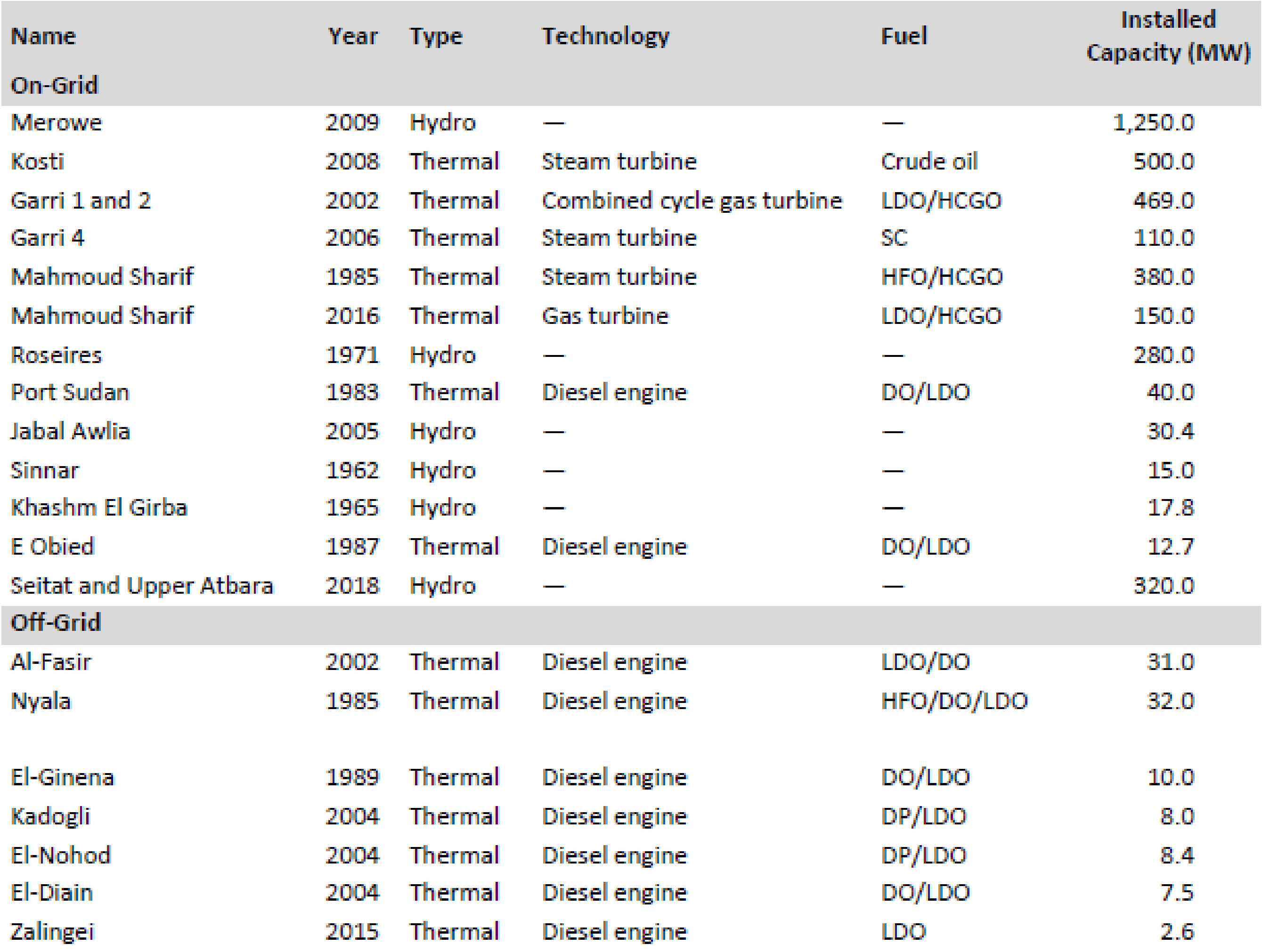


Figure 3.4 - Sudan Installed Generation Capacity 2018. Source [8]

A list of the Sudanese power plants that are currently in operation is shown below Figure (3.7). Although the list is for the power plants that were available in 2018, nothing has changed regarding supply given the instability brought by the end of 2019 that toppled the previous government and caused political instability. It is important to note that although most of Sudan's installed power plants are old and have outlived their technological lifetime, they continue to function well. This may be because there are many highly skilled Operation and Maintenance (O&M) workers in the area, and because American sanctions encouraged the preservation of the country's existing infrastructure.



Name	Year	Type	Technology	Fuel	Installed Capacity (MW)
On-Grid					
Merowe	2009	Hydro	—	—	1,250.0
Kosti	2008	Thermal	Steam turbine	Crude oil	500.0
Garri 1 and 2	2002	Thermal	Combined cycle gas turbine	LDO/HCGO	469.0
Garri 4	2006	Thermal	Steam turbine	SC	110.0
Mahmoud Sharif	1985	Thermal	Steam turbine	HFO/HCGO	380.0
Mahmoud Sharif	2016	Thermal	Gas turbine	LDO/HCGO	150.0
Roseires	1971	Hydro	—	—	280.0
Port Sudan	1983	Thermal	Diesel engine	DO/LDO	40.0
Jabal Awlia	2005	Hydro	—	—	30.4
Sinnar	1962	Hydro	—	—	15.0
Khashm El Girba	1965	Hydro	—	—	17.8
E Obied	1987	Thermal	Diesel engine	DO/LDO	12.7
Seitat and Upper Atbara	2018	Hydro	—	—	320.0
Off-Grid					
Al-Fasir	2002	Thermal	Diesel engine	LDO/DO	31.0
Nyala	1985	Thermal	Diesel engine	HFO/DO/LDO	32.0
El-Ginena	1989	Thermal	Diesel engine	DO/LDO	10.0
Kadogli	2004	Thermal	Diesel engine	DP/LDO	8.0
El-Nohod	2004	Thermal	Diesel engine	DP/LDO	8.4
El-Diain	2004	Thermal	Diesel engine	DO/LDO	7.5
Zalingei	2015	Thermal	Diesel engine	LDO	2.6

Figure 3.5 - Operating Powerplants in Sudan. Source [8]

3.3 Institutional structure and Guiding energy policies

Sudan's electrical market ecology is monopolized, and all power producing facilities are owned and run by government-owned corporations (hydroelectric plants and thermal power plants). The state-owned companies that oversee energy generation are all governed by the Electricity Regulatory Authority, which was formerly known as the Ministry of Water Resources, Irrigation, and Electricity (MWRE). However, following the successful civil revolution uprising in December 2018, the newly established transitional government abolished the previous MWRE, and all electricity-related matters are now within the purview of the Ministry of Energy and Mining. In addition to regulatory bodies, there is a National

Energy Research Centre that focuses mostly on renewable energy for its research activities [8]. The government of Sudan placed several polices to guide the electricity sector toward its growth:

- Sudan National Development Strategy. (2007-2031)

Present the national development goals across the electricity sector. Goal 3 – Sustainable development: features several objectives related to the electricity sector, including loss reduction, interconnection with East Nile Basin countries, energy efficiency, data management, and capacity building

- Power sector development framework. (2015-2020)

The framework presents the list of priority investments for the electricity sector. The list of projects includes the development of thermal generation to meet growing demand, acceleration of the rehabilitation and strengthening of the distribution system and addressing the fuel storage issue for thermal plants. The sector framework is built on long- and medium-term power system plans for 2012–2031 prepared by an international consulting firm in 2012. The plan was built on system modelling for generation and electrical network expansion based on a least-cost approach.

- Universal access to electricity by 2031.

The Sudanese Electricity Distribution Company (SEDC) had expressed its intention toward universal electricity access by 2031.

- Private sector involvement in power generation.

The Sudanese Holding Electricity Company (SHEC) is looking forward to easing the procedure of private sector investment in the electricity production sector by defining new transparent codes and by gradually lifting the subsidy.

Chapter 4 MODELS SETTING

The main feature of bottom-up energy systems models is their capacity expansion feature. They assist in providing an insight to the future possible scenarios to achieve certain well-defined targets under clearly listed assumptions. As mentioned in section 1.3 the three investigated models in this study are open-source, bottom-up models that provide the possibility to refine time and space as indicated by the user. However, the required computational power to reach a stable solution is clearly different depending on the resolution decided by the user. Also, it is worth mentioning that Calliope, unlike OSeMOSYS and Hypatia relies on snapshot logic rather than capacity deployment, as will be further explained. In this chapter the models set up to analyze the Sudanese electricity system are elaborated together with the definition of the working methodology of the different models by presenting their main objective function and balancing equations. The main exogenously defined parameters (e.g., Resource potential, demand, techno-economic data, and transmission lines parameters) are defined and explained to understand the underlying assumptions. The Chapter then proceeds with explaining the different scenarios and the main differences and assumptions made.

4.1 Model Functioning

4.1.1 OSeMOSYS

OSeMOSYS energy model is a widely used and well-established energy systems optimization model developed by KTH university. It is written in various programming languages where it was originally developed in GNUMathProg language however, later versions are available in both Python and GAMS languages. A model based on OSeMOSYS is structured in a systematic multi-layer organization. OSeMOSYS model is written in the most famous LP format where Sets are defined then parameters are defined as functions of multiple sets followed by variables definition, Objective function format and Constraints definition. Figure 4.1 illustrates How a model defined in OSeMOSYS is structured. To provide the exogenously defined parameters and sets OSeMOSYS offers different possibilities from uploading a .dat file Structured in a defined manner up to the usage of Graphical User Interface (GUI) such as Momani and ClicSand. The input parameters are then processed by OSeMOSYS code after an instant is created and sent to the backend which is Pyomo that consequently transform the data from to a Pyomo Concrete model. The LP file is then solved by a solver either commercial or open solvers. The results are then reconstructed into pandas format and lastly reported as CSV files

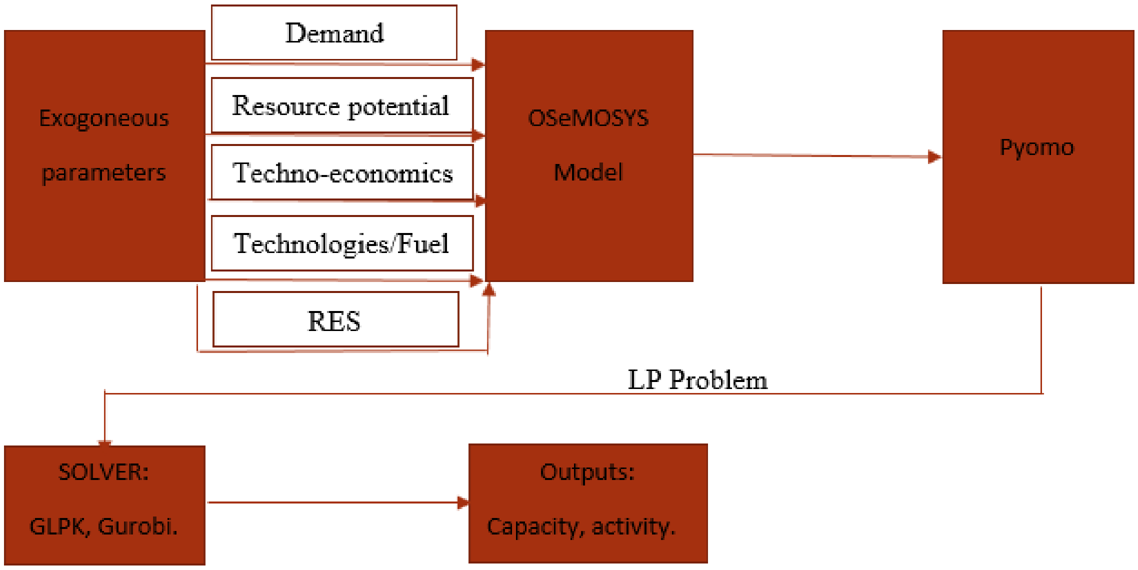


Figure 4.1 - OSeMOSYS Structure

In this Study instead of using the lengthy .dat files or the available GUIs due to their limited capabilities since only GLPK solver is available to be used with GUIs. A software developed by SESAM Group was used. The GUI software prompts the user to select the required sets according to the studied case then generate a readable excel sheet to define both the sets and parameters. The software then asks the modeler to choose the solver and directly communicate with OSeMOSYS Pyomo to produce the results and output them again in .xlsx format. Since OSeMOSYS allows for multi-regional approach the five prescribed regions were modelled. Even though the time resolution can be arbitrarily defined OSeMOSYS like most bottom-up capacity expansion planning energy systems models that covers a long range usually is defined with coarse time slices because of the enormous computing and solving capabilities required to solve, for instance, an hourly model. Therefore, four time slices throughout the year are defined according to seasonal division (Table 4.1). The Four seasons are further subdivided by day and night operation to account for the variable renewable energy production specially from Solar PV systems, where the Day time is (6:00 - 17:00) and Night time is (18.00 – 5.00).

Table 4.1 - Seasonal division of time slices: OSeMOSYS.

Season	Period
Winter	December – March
WD	(6.00 – 17.00)
WN	(18.00 – 5.00)
Spring	April – May
SPD	(6.00 – 17.00)
SPN	(18.00 – 5.00)
Summer	June – September
SD	(6.00 – 17.00)
SN	(18.00 – 5.00)
Fall	October - November
FD	(6.00 – 17.00)
FN	(18.00 – 5.00)

4.1.2 Calliope

Calliope Model is one of the emerging energy models that works best with VRES due to its high resolution. Calliope is currently available only in python language. It is characterized by a very high learning curve and few interactions between the code and the modeler without compromising the transparency of the code. A model based on Calliope is structured in a clear manner (Figure 4.2): the modeler provides the exogenous parameters describing the available locations, technologies and their techno-economic characteristics, demand, and constraints in a.YAML and .CSV format. YAML files are associated with the main blocks building the model while CSV files are associated with time series data that fluctuates with time. Calliope allows the categorization of technologies into different classes by defining technologies' parent. It also defines the resource of a certain technology that represents the resource assessment using different approaches (e.g., Capacity factor, Available production potential, Available installation area). Fuels in Calliope are called carriers and technologies are defined by listing the carrier in/out, to/from the technology. Demand in Calliope is defined as a technology of the class demand unlike OSeMOSYS that defines demand as a fuel. Locations are defined by simple geographic coordinates (latitude and longitude) and the distances between locations are calculated accordingly. Costs in Calliope are also categorized into classes the main class is the monetary class which defines the economic valuation of technologies however other cost classes such as CO2 or any other emissions can be defined this feature is mainly helpful in the weighted objective function of Calliope where different cost classes can be assigned arbitrarily different weights according to the modeler choice. The exogenous parameters passed to Calliope are firstly restructured to Xarray data set readable by Pyomo backend. The data passed to Pyomo are then constructed into a LP that is solved by a solver (e.g., CPLEX, Gourbi, etc...). Results are then collected in Xarray format and transformed to the more readable CSV format for further analysis.

In this study Calliope multi-nodal feature was exploited dividing the country into the previously discussed regions. To represent the regions the most Populous city in each region was chosen (Table 4.2). The time resolution in Calliope, which is in terms of hours is beneficial and a one-hour time slice was used. However, unlike OSeMOSYS Calliope is a snapshot logic model and thus only the year 2030 is modelled.

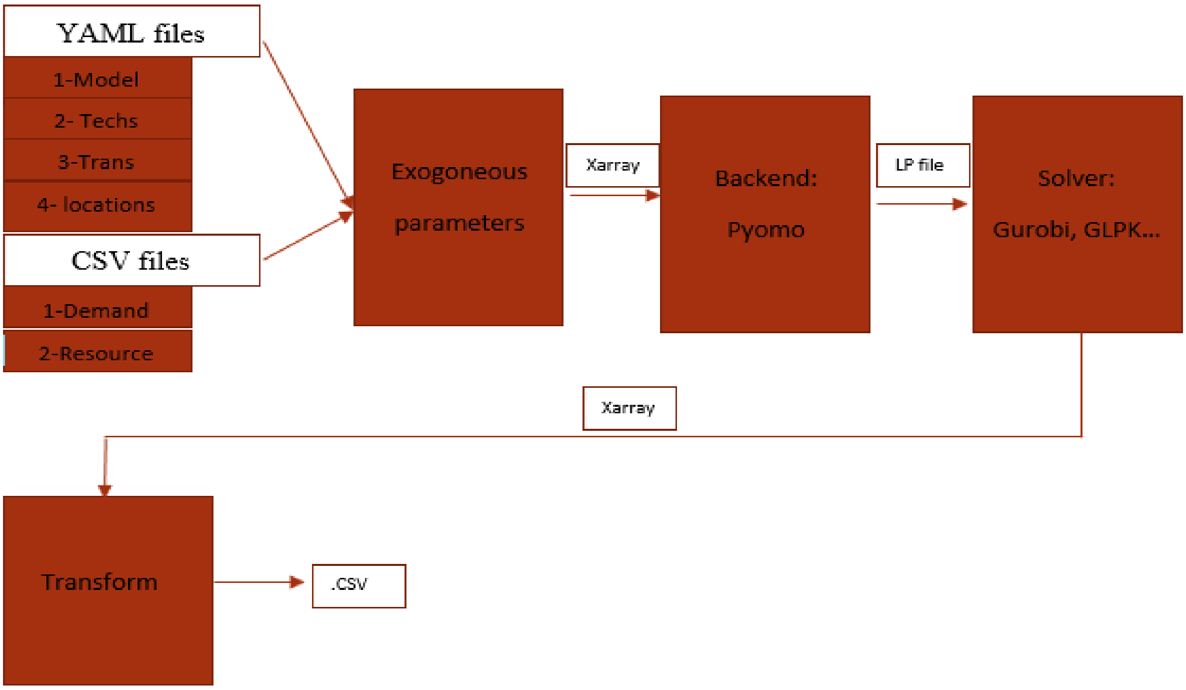


Figure 4.2 - Calliope Structure.

Table 4.2 - Representing City for each region: Calliope

Region	City
Khartoum	Khartoum
West Sudan	El-Obeid
North Sudan	Dongola
East Sudan	Port-Sudan
Central Sudan	Wd Madani

4.1.3 Hypatia

Hypatia is the newest of the models used in this benchmarking study, it was developed by the efforts of the SESAM group in Politecnico di Milano (POLIMI). In fact, the model is still under development and this study serves as one of the basic studies to elaborate on the model functionality. Hypatia is a capacity expansion planning, energy systems optimization model with the capability to perform both planning and operational modes. The model is constructed to be user friendly and easily accessible and readable to allow for a transparent model environment. The model is based on the domain specific language CVXPY to generate the LP file that is solved by a solver unlike the common energy systems optimization models that use Pyomo environment. The main pros to CVXPY when compared to Pyomo is the ability to express the problem in a mathematical sense. For instance, two dimensional variables are a possibility using CVXPY which significantly cut down the required computation time to pass the LP file to the solver due to the absence of long iterative loops. Hypatia in essence was inspired by both OSeMOSYS, and Calliope models and it is presenting itself as a future possible candidate to overcome the shortcomings of the two models. The structure of Hypatia is explained in Figure 4.3. The model interacts with the modeler by producing an easily readable and updatable excel file in which the modeler defines the sets and parameters. The model then reads the excel files and convert them to CVXPY linear programming format. The instance is then solved using a wide range of solvers (e.g., Gourbi, SciPy, CPLEX, etc.…). Hypatia has the ability to perform multi-nodal analysis with no upper limit on the regions. It also possesses the capability to refine the time resolution up to hours level. The model generates a distinct excel file for each region as well as a global excel file where global (i.e., region independent) parameters can be defined. Transmission lines for the different fuels between any two regions are defined in a distinct excel file.

In this study two multi-regional models for time resolution similar to OSeMOSYS and Calliope are developed to emphasize the importance of time resolution on the outcomes.

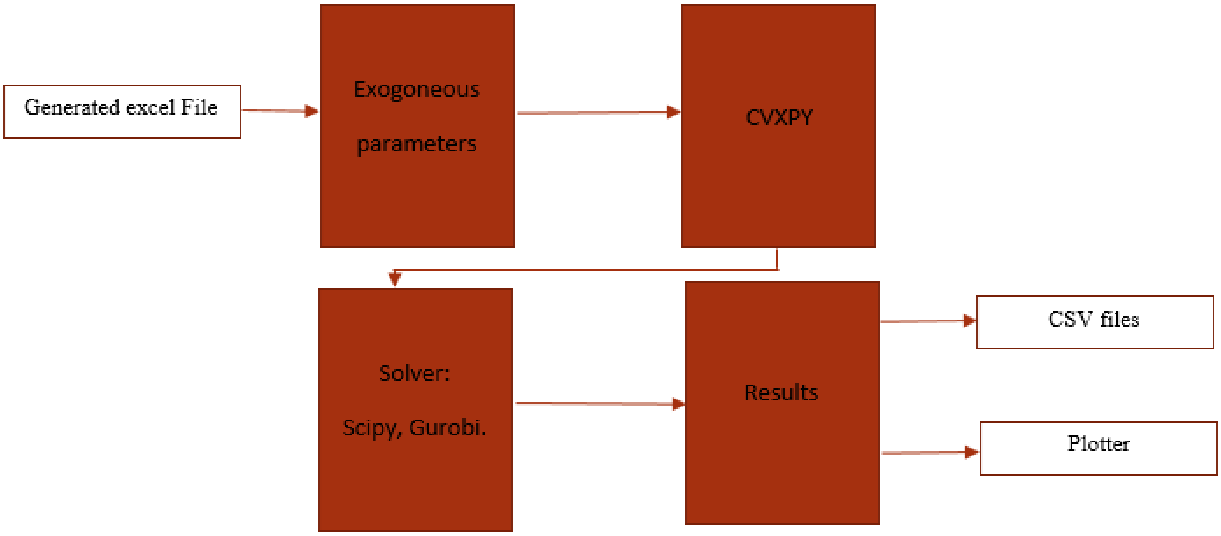


Figure 4.3 - Hypatia Structure

4.2 Resource Assessment

Sudan is the third largest African Country expanded across four Koppen climate groups. This large area distributed among different climate conditions from desertic to heavy-savannah rain forests allowed Sudan to have a huge energy resource whether it is coming from Fossil fuels or renewable energy systems. Sudan is well-known to be a home to a high untapped renewable energy resource due to its geographical location and the different terrain throughout the country promoting air circulation. Also, Sudan is one of the downstream countries to the river Nile accompanied by the enormous hydro-electric power production potential. The resource potential for the different sources in the country is assessed below. The CSP resource potential was not assessed however due to the different capacity factors of different CSP technologies; instead, an average value provided by [23] was used for the entire country since the Direct Normal Irradiance (DNI) in Sudan is fairly constant [24]. The potential was set to be infinite.

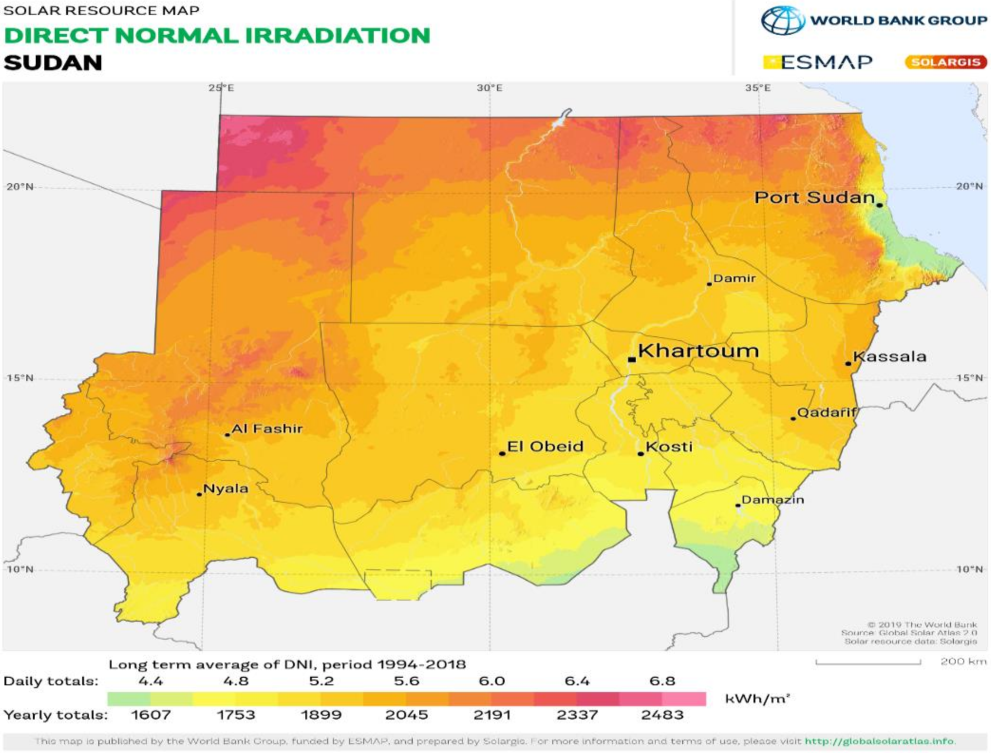


Figure 4.4 - Direct Normal Irradiation in Sudan. Source [24]

4.2.1 Solar PV and Wind

As mentioned in the IRENA report [18] both solar PV and wind energy potential are extremely high in Sudan due to the high solar insolation and coastal regions moving currents respectively, in this study to assess the potential of the two energy sources a GIS based analysis mimicking the method used by the National Renewable Energy Laboratory (NREL) [25] is developed. The step-by-step elaboration of the analysis is as follow:

1- Technical potential area assessment: Technical potential of an energy technology is defined as the installable capacity of the technology considering technical constraints on the theoretical potential such as: exclusion of protected areas, agricultural areas, and water bodies as well as proximity of the installed system to the transmission grid [25]. To assess the technical potential area a GIS based analysis is required to calculate the available area to install both PV and wind systems. In this part Google earth software was used to investigate the areas available for the installation with the following restricting conditions:

A- Exclusion of agricultural areas.
B- Exclusion of protected areas.
C- Exclusion of water bodies.
D- The maximum distance between the installed system and the transmission grid is 25 km.

This method ensures that the calculated area considers only places where the transmission lines are close by and thus neglecting far potential that is inaccessible in the short term. Figure 4.5 Shows on the map the available area for PV and Wind installation (white) and the subtracted area (blue) which is the river Nile area. We can notice that the technical potential area is mainly distributed on the riverbanks as the transmission lines follow the Nile because most of the cities and villages are located on the riverbanks as well. The assessed area for the different regions is tabulated below and provided as an upper limit for the constrained optimization problem.

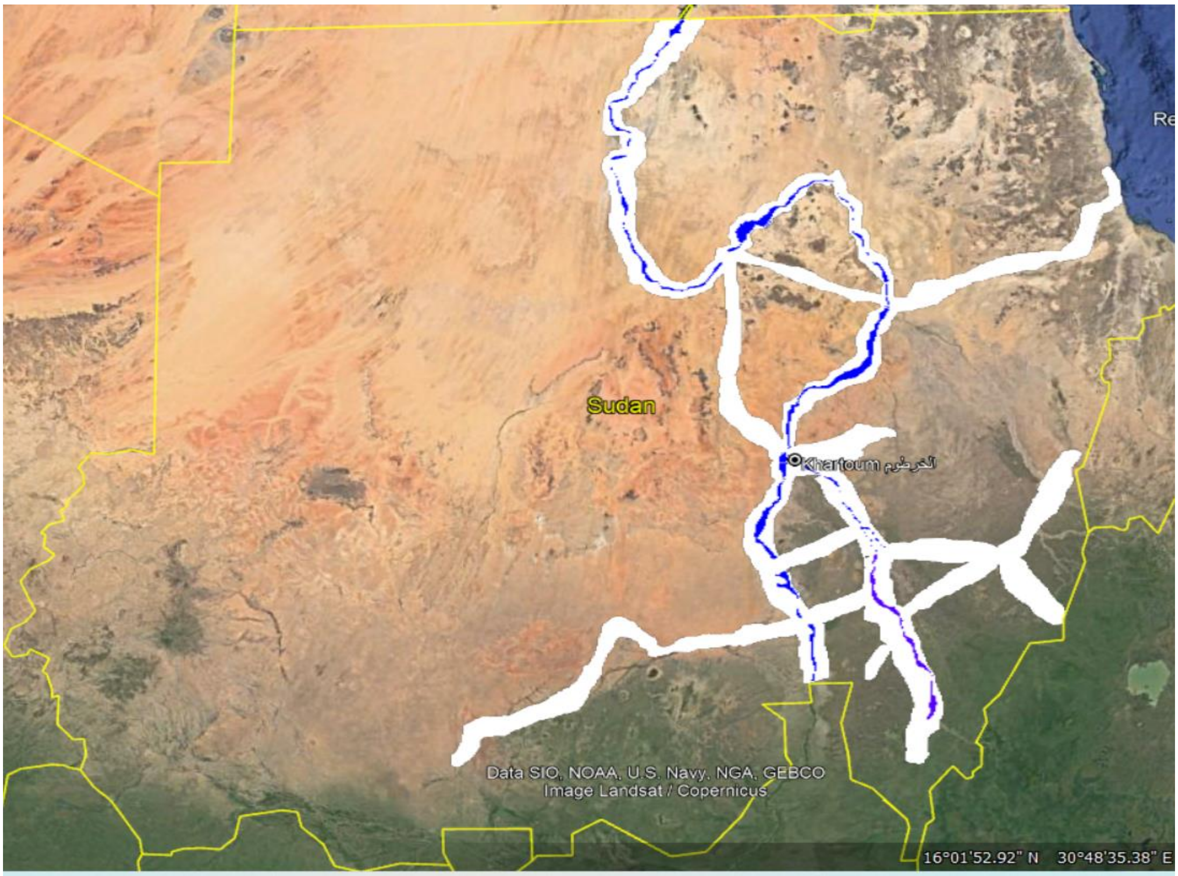


Figure 4.5 – Available PV and wind technical potential map

Table 4.3 – PV and Wind technical potential area.

Region	Technical potential Area (km^2)
N_SUDAN	43046
KRT	12854
C_SUDAN	38137
E_SUDAN	28234
W_SUDAN	13485

2- Capacity factor assessment: To assess the capacity factor of solar PV and wind energy systems the online simulation tool renewables.ninja (Renewables.ninja, 2015) was used [26]. The simulation was carried for points on the available technical potential area at the halfway distance for every 100 kms resulting in a total of 188 simulation. The simulated systems specifications are tabulated below (Table 4.4). Renewable. ninja outputs the hourly capacity factor throughout a year for each point in a CSV format.

Table 4.4 - System Specifications in Renewable. Ninja Simulation tool.

Solar PV	On-Shore wind Turbine
Capacity = 1 kW	Model: Vestas V90 2000
No tracking	Capacity = 1 kW
Tilt angel = 15, Azimuth angle = 180	Hub height = 80 m

3- Lastly, to express the available potential in units of power rather than available effective area. The land usage of a normative PV farm and wind park were retrieved from literature [27] [28]. The retrieved land usage takes into consideration the spacing between PV panels such that mutual shadowing is avoided and clear passages for maintenance vehicles also for wind turbines it considers the spacing such that the back flow turbulence created by the upstream turbine is not felt by the downstream turbine. Finally, the actual installable capacity was calculated according to equation 3. However, due to OSeMOSYS and the seasonally divided Hypatia representation of time slices the average capacity factor in the previously defined time slices were computed using a C++ program Appendix I. The program takes the average hourly value for the capacity factor in the region and outputs the average capacity factor value in the time slices defined in section 4.1.1.

(Eq. 3)

$$Available\ resource_{i,j} = effective\ area_{i,j} \times land\ usage_j$$

4.2.2 Geothermal

In the last few decades, the potential of geothermal energy production was studied closely in Africa, leading the authorities to explore possible geothermal wells mainly to be used in the electricity production sector. At the time being the government of Sudan has just launched a partnership with the Egyptian government to investigate and draw a map of the entire available potential [29]. However, in this study only the proven wells with electricity capacity production of 400 MW were considered. The geographic distribution of the wells [30] is outlined in Figure 4.6.

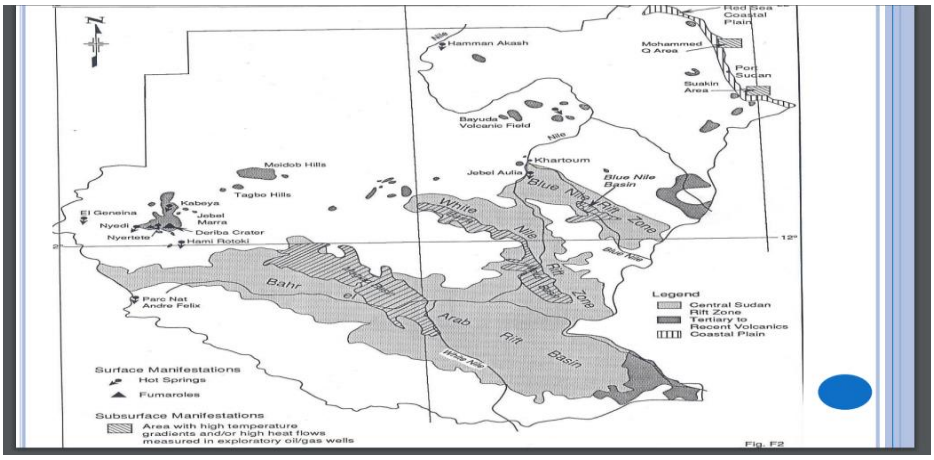


Figure 4.6 - Geothermal potential distribution in Sudan. Source [30]

4.2.3 Hydropower

Sudan currently heavily relies on the production of electricity from hydropower utilizing the river Nile basin which is a cross-country river shared by most of the eastern African countries. However, almost 50% of the practical potential is used currently by the existing hydropower plants. The total estimated potential in Sudan is 4860 MW for large hydropower plants accounting for river Nile flow rate and Sudanese share of the Nile. As we can see in Figure 4.7 retrieved from IRENA report [18]. The candidate hydropower plants are merely focused around the central and northern regions of the country. To account for hydropower capacity factor a 15-year monthly average of the capacity factor in Sudan was retrieved from PLEXOS database [22].

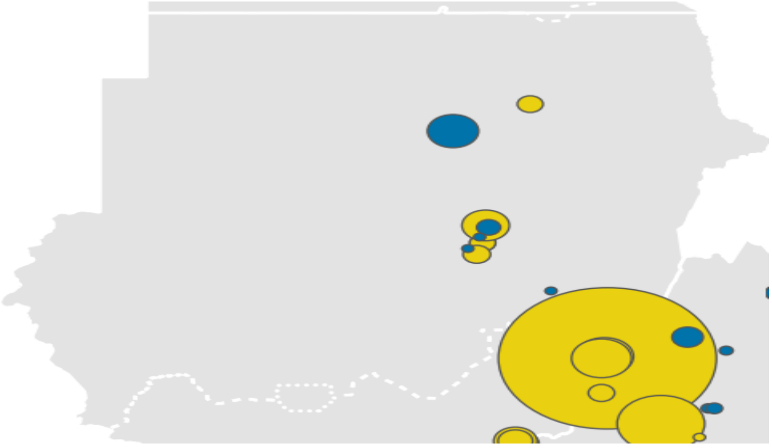


Figure 4.7 - Existing and future candidate hydropower plants in Sudan
Source [18]

4.2.4 Fossil fuels and Biomass

Sudan is a country that has a relatively high proven oil and gas reserve. It is the 23rd country in terms of proven oil reserves worldwide with five billion barrels. And almost three trillion m^3 Natural gas reserves [31]. Figure 4.8 elaborates that the currently producing oil and gas wells are concentrated in the southwestern part of the country however investigation of potential reserves is fairly distributed around the country [32].

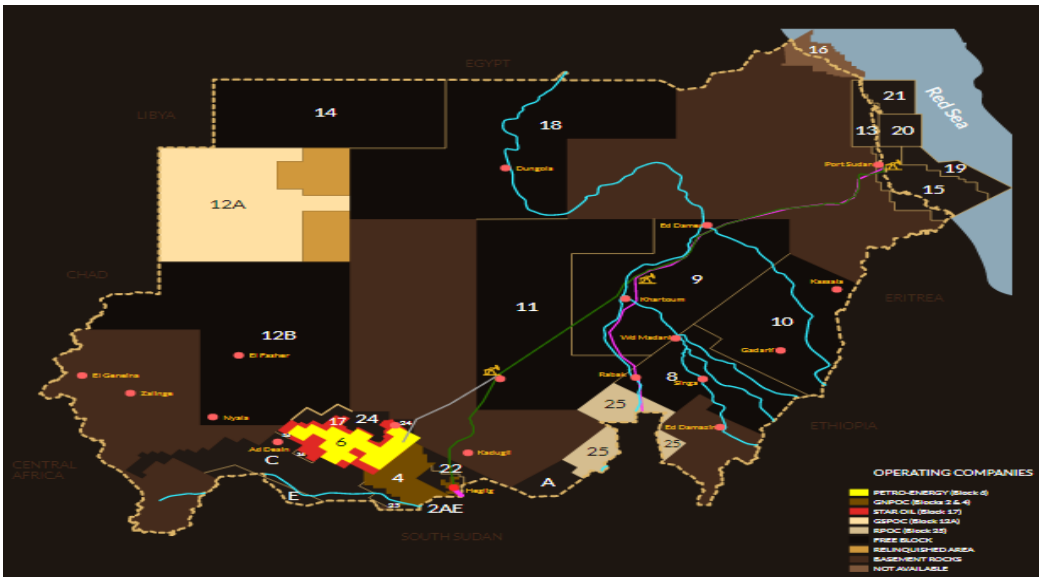


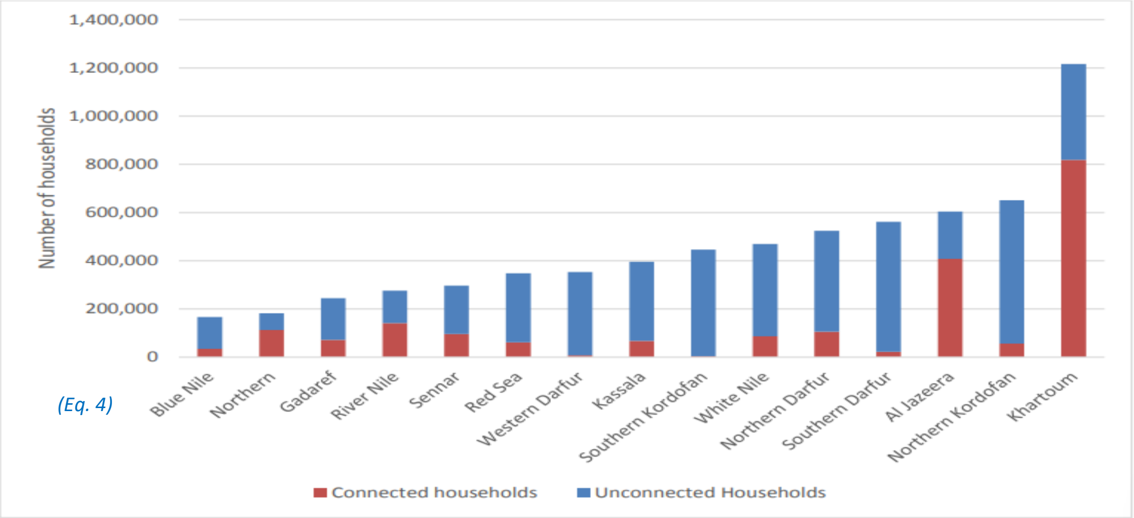
Figure 4.8 - Oil and gas wells distribution in Sudan. Source [32]

For the biomass potential the UN report [33] estimates the potential including only rain-fed sugarcane bagasse as a biomass, given that Sudan is one of the largest sugar cane exporters worldwide a 2 GW potential is available.

4.3 Estimation of Demand Evolution

Electricity demand in Sudan had been experiencing a continuous growth over the last decades with an accelerated rate in the last few years. Demand increase is related mainly to the connection of new users instead of digitalization of home appliances or changing behavior of the customers. In this study, the electricity demand is divided based on a sectoral approach to enhance the representation of reality. The four main covered sectors are: residential, services, agriculture and industrial. A necessity for optimization energy systems models is to provide exogenously the forecasted demand toward the last year of the study. Keeping in mind that the main objective of this study is to provide guidance to officials toward universal access, a particular interest was given to forecasting the future demand that would ensure this target.

The First step is to regionally divide the current demand taken from [8]. Due to lack of actual data many assumptions to achieve the regional distribution for different sectors were implied. For the residential demand, a unique approach relying on the ratio of the number of connected households in each region to the total connected households (Figure 4.9) is followed. The service sector demand is regionally distributed using the same ratios of connected households in each region underlying an assumption that the services distribution across the country is linked to the distribution of power. This approach highly reflects the real conditions.



Source: SEDC, World Bank analysis

Figure 4.9 - Connected household for each state in Sudan. Source [8]

$$Residential\ demand\ (region) = \frac{Connected\ households\ (region)}{Total\ connected\ households} \times Total\ residential\ demand$$

The industrial demand regional distributions relies on making the discrepancy between two industry types:

1. Large industries: heavy industries with high energy consumption such as: metal alloy in factories, sugar production factories, manufacturing factories, etc.…
2. Small industries: low energy consumption industries such as: food canning and processing facilities, cigarette production factories, car repair industrial areas.

The two industries are assumed to equivalently share the industrial demand of the country. Regarding the large industries demand, the list of factories meeting the criteria for large industries was retrieved from [34] Table 4.5 indicates the number of large factories in each region. The small industries are assumed to be equally divided between the northern and central regions i.e., the two regions with the highest share of GDP in the country.

(Eq. 5)

$$Industrial\ demand\ (region) = 0.5\ \times small\ industries\% + 0.5\ \times \frac{Large\ factories\ (region)}{Total\ large\ factories}$$

Table 4.5 - Large factories distribution in Sudan

Region	Number of large factories
Khartoum	1
Western Sudan	0
Central Sudan	9
Eastern Sudan	1
Northen Sudan	5

The agricultural demand was divided following the agricultural area for each region in Sudan. The currently used land for agricultural purposes are represented by points in

Figure 4.10 retrieved from [35]. The demand is then divided according to the ratio of points in each region.

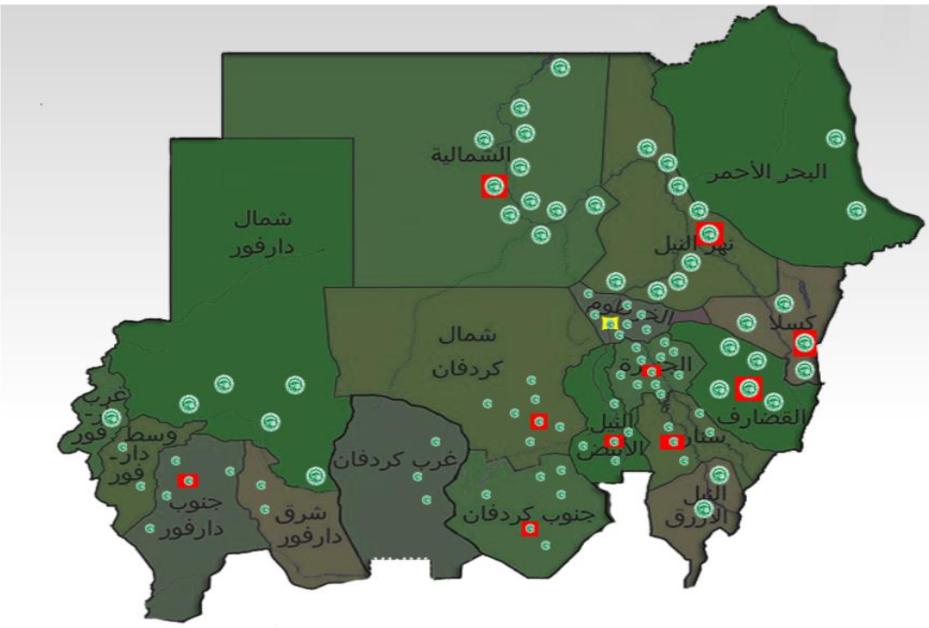


Figure 4.10 - Agricultural areas distribution in Sudan. Source [35]

The second step included forecasting the demand starting from 2017 (the last year of available data) up toward 2030. Again, the sectroal division of demand proved significant allowing for different approaches to be followed on extrapolating the future demand. In particular, the industrial and agricultural demand were allowed to grow according to their historical growth rate. However, since full access of electricity to resedential cutsomers is seeked a different approach is suggested where the future demand is calculated as follow:

(Eq. 6)

$$\begin{aligned} &Residential\ demand(\,t) \\ &\quad = connected\ household\ consumption\ (t) \times number\ of\ households\ (\,t) \\ &\quad \times electricity\ access\ \%\ (t) \end{aligned}$$

Electricity consumption per connected household in Sudan amounted to 3825 kWh/year which is above the world average (Figure 4.11) in fact it is higher than some of the most developed countries around the world. One might argue that this is due to many reasons but closely related to the harsh weather conditions during summer which promotes the usage of HVAC appliances and also due to the poor efficiency of used appliances. To stay in track with the SDGs the electricity consumption per connected household is assumed to be constant during the modelled period. The population growth is assumed to continue its current high levels and the population is allowed to grow according to the mean growth rates for the years 2009-2018 [36]. Lastly, the electricity access percentage is computed from Figure 4.11 for 2017. Whilst the access is maintained constant for the period 2017- 2022 it has linearly increased ever since toward 2030 to allow for full access. The services demand followed the same exact technique.

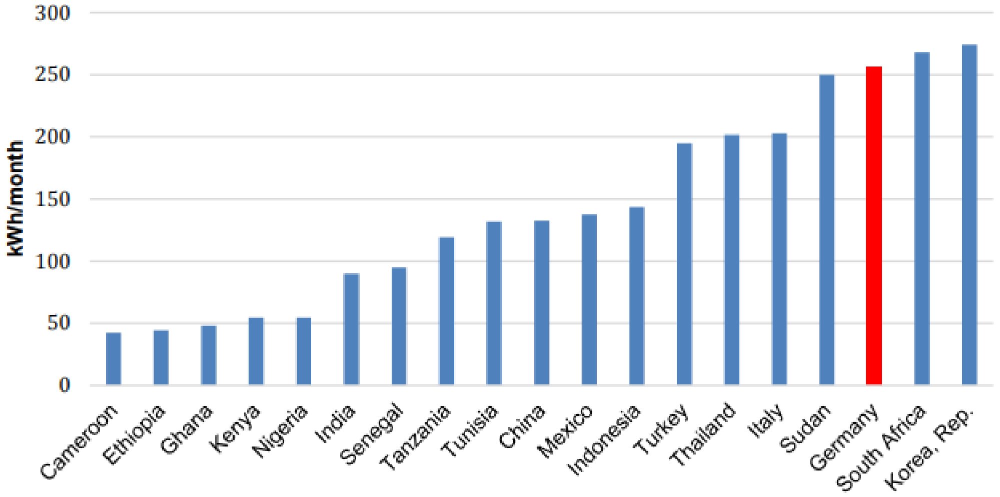


Figure 4.11 - Per household electricity consumption in selected countries. Source [8]

4.4 Reference Energy System

Reference Energy System is a widely used analytical tool to simplify the flow of energy from supply to demand passing through conversion processes. It is the backbone of energy system analysis from which the complex multi-layered system can be simplified into building blocks. To develop the RES a modeler needs to define the conversion technologies included in his study and their consumed/produced fuels. Table 4.6 provides the list of conventional power plants included in this study. Fossil fuel-based technologies are divided into currently existing conventional technologies and future candidate technologies the inclusion of future candidate technologies is to provide the possibility of shifting the dirtier current technologies with more efficient and less pollutant configurations and to explore the possibility of benefiting from the huge gas reserve available (i.e., Gas technologies). Also, to explore the possibility of introducing cheap coal technology. Table 4.7 lists the renewable energy technologies considered in this study.

Table 4.6 - Fossil fuel-based power plants included in the study

Existing Conventional Technologies			
Technology type	**ID**	**Prime mover**	**Fuel**
Crude Oil steam Turbine	CROST	Steam Turbine	Crude Oil
HFO Steam Turbine	HFOST	Steam Turbine	HFO
LFO Simple Cycle Gas Turbine	SCGT2	Gas Turbine	LFO
LFO Combined Cycle Gas Turbine	CCGT2	Combined Cycle	LFO
Diesel Generator	Gen-Set	Generator	LFO
Future Candidate Technologies			
Technology type	**ID**	**Prime mover**	**Fuel**
NG Simple Cycle Gas Turbine	SCGT1	Gas Turbine	Natural Gas
NG Combined Cycle Gas Turbine	CCGT1	Combined Cycle	Natural Gas
Coal Steam Turbine	COST	Steam Turbine	Coal

Table 4.7 - Renewable energy technologies included in the study.

Renewable Energy Technologies			
Technology type	**ID**	**Prime mover**	**Fuel**
Grid Connected PV systems	PV_UTL	-	-
Large Hydro Power Plants >100 Mw	LHYD	-	-
Small Hydro Power Plants <100 Mw	SHYD	-	-
Concentrated Solar Power	CSP	-	-
Biomass Power Plant	BMPP	Gas Turbine	Biomass
Geothermal Steam Turbine	GEOST	Steam Turbine	-
On-Shore Wind Turbines	WIND	-	-

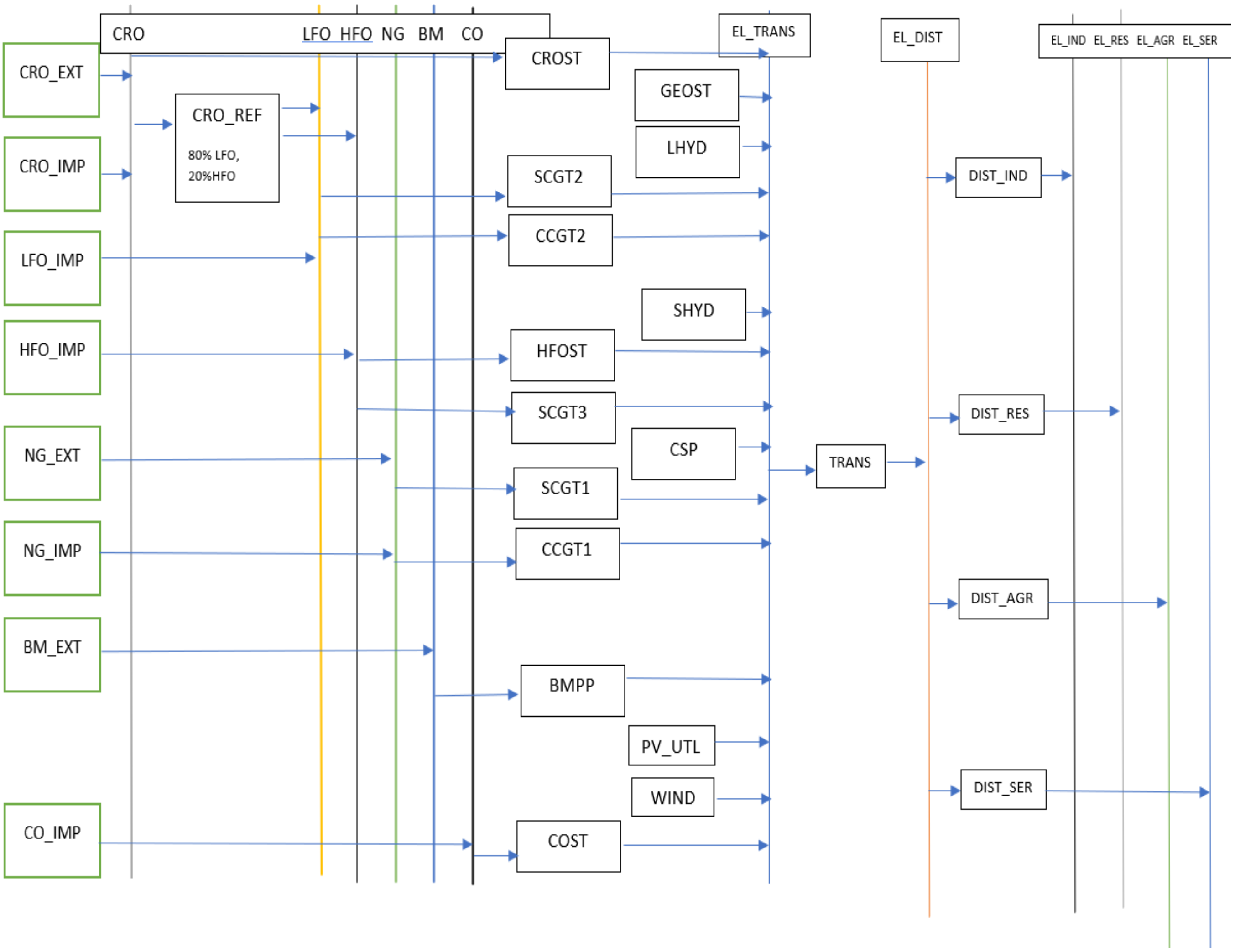


Figure 4.12 - Reference Energy System of one region in Sudan.

4.5 Techno-economic Data

The techno-economic data represents the economic and technical parameters associated with power production plants as the name implies. Table 4.8 represents the techno-economic data for the technologies that will experience no change in their capital cost in the foreseen future. Capital, fixed, and variable Operation and Maintenance (O&M) costs were retrieved from [18]. The variable O&M costs here do not include fuel costs.

Table 4.8 - Techno-economic data for conventional conversion technologies.

Technology	Capital Cost (M$/Gw)	Fixed O&M (M$/Gw)	Variable O&M (M$/PJ)	Efficiency	Lifetime (years)
CROST	2500	75	1.03	0.37	35
HFOST	2500	75	1.03	0.37	35
SCGT1	700	20	0.75	0.33	25
CCGT1	1200	35	0.583	0.48	30
SCGT2	1450	45	0.75	0.35	25
CCGT2	1200	35	0.583	0.48	30
COST	2500	78	1.03	0.37	35
GEOST	4000	120	0.861	-	25
BMPP	2500	75	1.03	0.35	30
LHYD	3000	90	0.917	-	50
SHYD	2500	75	0.917	-	50
GEN_SET	750	23	0.5	0.30	10

Regarding the VRES, the capital cost of system installation had been falling and is expected to keep falling in the future (Figure 4.13). To account for that IRENA estimates of VRES capital cost in Africa [37] were collected the original data are presented every five years for the period 2015-2050 and a linear reduction rate was assumed between the points. Meanwhile, variable, and fixed costs are assumed to remain constant during the modelled period (Table 4.9).

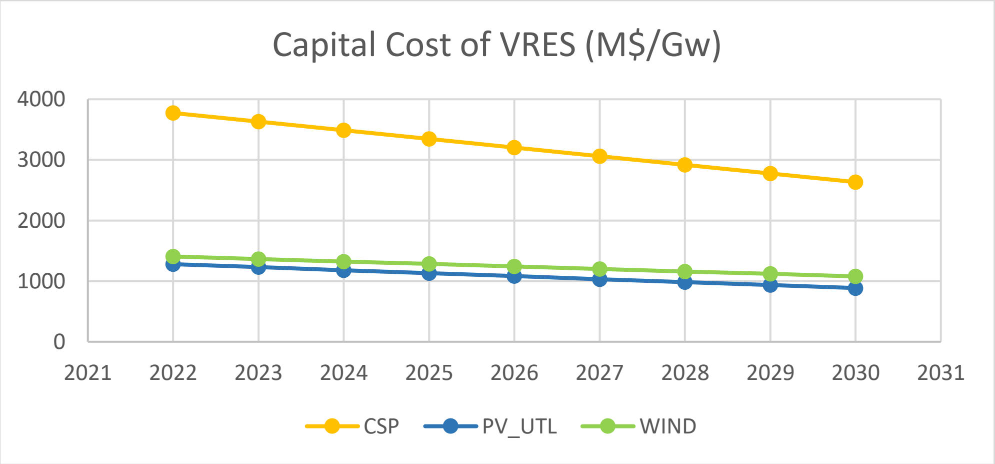


Figure 4.13 - Forecast of Capital Cost for variable renewable energy systems.

Table 4.9 - Techno-economic data for variable renewable energy systems.

Technology	Capital Cost (M$/Gw)	Fixed O&M (M$/Gw)	Variable O&M (M$/PJ)	LifeTime
CSP	2634	40.58	1.03	30
SCSP	3763	75.79	1.03	30
PV_UTL	886	17.91	0.0556	24
PV_DIST	2700	86.4	0.0556	24
WIND	1078	59.56	1.03	25

fuel prices represent the forecasted international prices. Imported fuel prices were raised by 10% to account for transportation. For crude oil price forecast is produced by the US energy information agency [38]. HFO and LFO prices were calculated by multiplying the crude oil price by 0.88 and 1.33 respectively following the TEMBA method [39]. Natural gas and coal prices to 2030 were retrieved from [37] applying linear transition between data points.

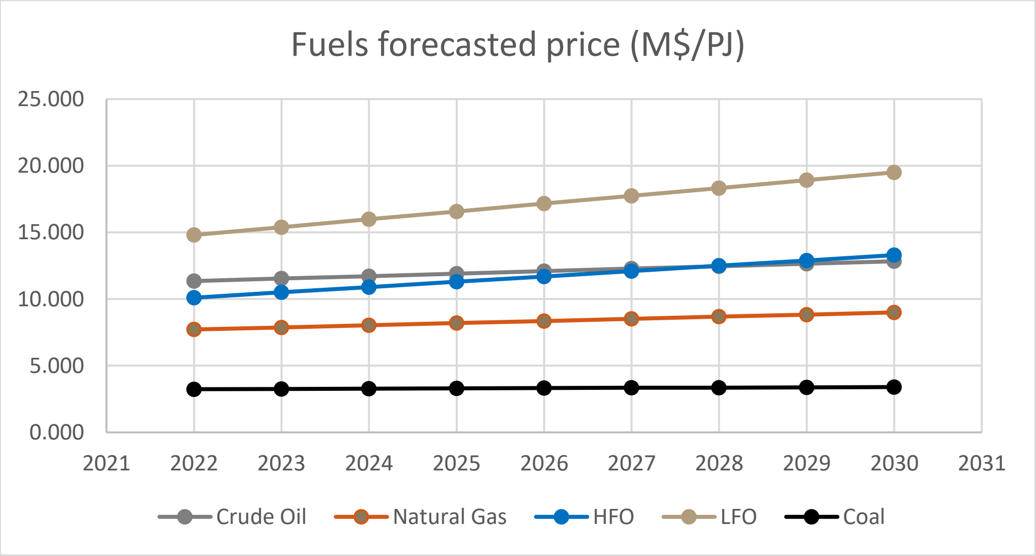


Figure 4.14 - Forecast of fossil fuels prices.

4.6 Transmission lines Modelling

Modelling of transmission lines is of essential importance to obtain robust and realistic insights into the opportunities and risks of expanding the capacity in a country. For a multi-nodal approach, it becomes an essential feature to include the transmission grid expansion costs as a decision variable to obtain the overall least cost plan. Hypatia and Calliope both enable the modeler to neatly model the cross-border transmission lines by exogenously defining parameters related to their performance (e.g., installed capacity, capital cost, operational costs, efficiency, etc.…). On the other hand, OSeMOSYS has no direct way of modelling the transmission lines and the transmission of power between regions is hence assumed to be free of charge, this might result in accumulation of capacity in regions that have better capacity factor for spatially variable technologies. In this study the investment cost of cross-border transmission lines was taken from [18] amounting to 800 $/kW. The variable O&M costs were adopted from [40]. The current transmission network shown in Figure 4.15 is characterized by its old infrastructure. However, an assumption that 250 MW of capacity exists between the connected regions is made. The operating efficiency of both the transmission and distribution networks are 0.95 and 0.85 respectively according to [8]. The cross-countries transmission lines between Sudan and its neighboring countries namely Egypt and Ethiopia here are considered due to their plans to expand the transmission lines capacity with Sudan, were treated the same way as the inter-regional transmission lines assuming the same techno-economic parameters.

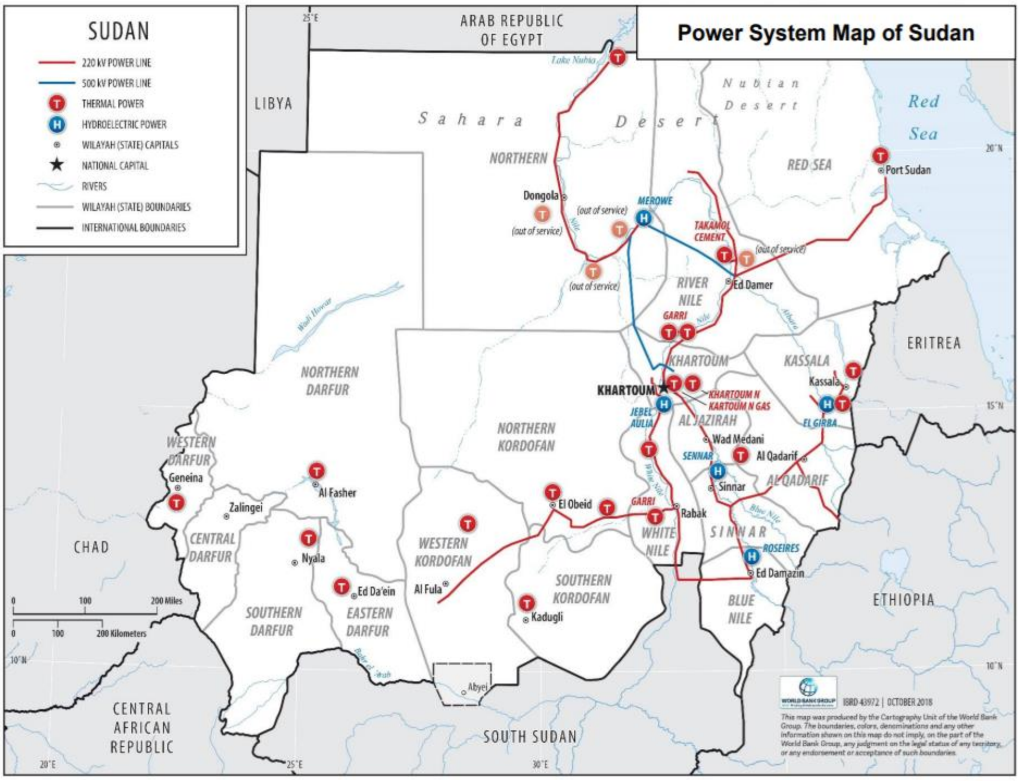


Figure 4.15 - Sudan Power Transmission. Source [8]

4.7 Scenarios Definition

Energy systems optimization models are used here to analyze different scenarios representing different futures and answering what-if questions. A scenario in energy modelling is defined by a set of parameters and assumptions representing a possible reality, providing policy makers a range of possible options. Scenarios analysis is also usually used to informally assess the sensitivity of model outputs to changes in the inputs, checking the model robustness. Three distinct scenarios are investigated here: the first scenario is the reference scenario for the study called Business as Usual (BAU) and the other two scenarios are compared to it. The second scenario is a capacity expansion planning scenario that considers free trade with neighbors. The third scenario is closely related to the second scenario but with limiting on the imports from Egypt and Ethiopia.

4.7.1 Business as Usual (BAU)

Business As Usual (BAU) is the reference scenario where the models are freely allowed to plan the future based on the previously described data. This scenario results represent the least cost plan merely motivated by economic concerns with no regards to any specific policies, BAU scenarios are usually the starting point for energy planning, driving optimization by minimizing costs and working with reduced constraints and no policies in act. In the BAU Scenario the existing power plants were assumed to be functioning at the same current condition toward the end of modelling period. In theory, most of the existing power plants have exceeded their operational lifetime. However, the government has no declared intentions of decommissioning those power plants. It is worth mentioning though that most of the plants are operating in a good condition due to regular maintenance.

4.7.2 Free Trade Scenario

This scenario introduces transitional electricity trade between Sudan and its neighbors. It investigates the possibility and worthiness of importing electricity rather than domestically generate it, considering the cost of importing electricity and the cost of expanding the capacity of the transmission lines as decision variables to reach the optimized solution without posing any constraints. In this context and given the current energy system of Sudan only importing electricity from neighbors is considered as concurrent to national production power plants. Future studies may consider exporting options, too.

International connections with Ethiopia and Egypt were considered in this scenario not only because there exists a connection between the countries but because of their future agenda to start exporting to Sudan. The Egyptian cross-border transmission line capacity is as small as 70 MW. However, Egypt is a country with a high electricity generation surplus and plans to act as a regional hub of electricity is promoting the expansion of transmission lines capacity at its southern border toward Sudan. In Fact, according to an Egyptians official [41] interviewed by Egypt today newspaper on February 2022 the capacity is expected to raise to 300 MW by early 2023 and even beyond in later years to reach almost 1 GW. On the other hand, Ethiopia is expected to have a huge surplus of electricity after the completion of the Grand Ethiopian Renaissance Dam (GERD) that has a total capacity of 5150 MW planned to be achieved by 2025. The under-development dam is intended not only to act as the baseload supply entity nationally, but also to promote Ethiopia as a power supplier across the eastern part of the African continent. Yet, the Ethiopian government faced rigours opposition from Sudanese and Egyptian officials since the announcement of its intentions to start building the dam (lately, reaching the UN security council). The huge dam and accordingly its enormous reservoir of 74×10^9 m^3 is being built on one of the main two tributaries of the river Nile (Blue Nile) which raised concerns in the two downstream countries regarding their water share. However, regardless of the opposition the dam is progressing according to the plan and two fillings of its reservoir is already done. Currently the installed capacity of the electricity transmission line between Sudan and Ethiopia is 200 MW. Nevertheless, the Ethiopian government expressed its willingness to expand this capacity if an agreement with the Sudanese government regarding the GERD is reached. The cost of the imported electricity was taken as the price of electricity for industrial consumers in the two countries retrieved from [42] [43] and amounted to 0.047 USD/kWh in Egypt and 0.023 USD/kWh in Ethiopia.

4.7.3 Limited Trade Scenario

This Scenario puts a cap on the capacity of the international transmissions lines thus limiting the imported electricity from both Egypt and Ethiopia. For the Egyptian border transmission line, the expansion follows the expansion strategy addresses by the Egyptian official in [41] of increasing the capacity to 300 MW in 2023 and linearly increase then to reach 1 GW by 2030. the Ethiopian side transmission line is projected to reach 4 GW by 2030 According the Program for Infrastructure Development in Africa PIDA [44]. The relevance of this scenario is to not overestimate the reliance of the Sudanese electricity sector on imports. Since the growing demand in Sudan must be met always the inclusion of this scenario is expected to promote domestic generation in the country for the years where imports can’t exceed the assigned cap.

Chapter 5 RESULTS AND BENCHMARKING

In this chapter the results obtained by running the different scenarios using the different modelling frameworks will be presented, commented on, and benchmarked. Primarily, for each scenario the results prevailed from the three frameworks will be presented; since the logic followed by OSeMOSYS and Hypatia on one hand and Calliope on the other is different, the presented results will likely differ as well. Specifically, the two capacity expansion planning models (i.e., Hypatia and OSeMOSYS) allow for the visualization of the path toward the desired end state throughout the modelling time horizon (2022-2030), therefore the detailed outlook for: capacity expansion, electricity production mix, fossil fuel consumption, investment and operating costs, and the electricity trade will be obtained. On contrast, Calliope only provides a snapshot for the end state (2030), but its hourly resolution also allows tracking of plants dispatching and system overall balance in a detailed manner. The plant's dispatch, system balance for the different regions as well as investment and operating cost in 2030 will be noted. Secondarily, a comparison between the results generated by the different models for the same scenario will be conducted to highlight how sensitive the suggested policies are to the model characteristics (i.e., model logic, temporal resolution, transmission lines modelling capabilities, etc.…). To carry out the benchmarking the following results will be compared:

1. Regionally divided total installed capacity in 2030.
2. Sudan total installed capacity mix in 2030.
3. Sudan Electricity production mix in 2030.
4. Total investment cost and operating cost in 2030.

The Second part of the chapter includes a comparison of the different scenarios. In this part the model will be fixed while comparing how the different scenarios previously defined in section 4.7. present different realities.

5.1 Business as Usual (BAU) Scenario

The BAU scenario, which is the reference scenario that presents the future from a merely economic best practice strategy results are assessed in this section for the different models. Unfortunately, the hourly Hypatia model that used a time resolution of one-hour experienced difficulties being solved and the solver crashed and was unable to solve the optimization problem. This is expected as the number of variables included exceeds 5×10^6 due to the high geographical and temporal resolution for a time horizon of nine years. Nevertheless, the CVXPY proved to be highly functional as the LP problem regardless of its huge dimension was quickly constructed from the imported excel files and provided to the solver. GLPK, SciPy and Gourbi solvers were all used in this study.

5.1.1 OSeMOSYS BAU Results

Results for OSeMOSYS are reported here for each region. The eight time slices used to set the model temporal resolution are prescribed in section 4.1.1. As mentioned earlier the yearly expansion of the capacity for the different regions is obtainable.

Western Sudan

The western part of the country is the least fortunate in terms of both electricity supply and access percentage. Currently, it relies mainly on off-grid diesel generators to supply the main governmental institutions and basic-need services in the large cities. The electricity grid reaches only El-Obeid, the capital of North Kurdufan state with a small distribution network across the main city. The small agriculture demand is also met by distributed diesel generators. The wind and solar PV capacity factors across the region are not the highest around the country. The river Nile does not pass across the region therefore no relevant hydroelectric production is available whatsoever. In the meantime, the operative oil & gas wells are clustered around the southernmost part of the region and due to its large area, a huge reserve of the two fuels is available.

Figure 5.1 shows the expansion of the generation capacity in the region. As the model was not restricted to start expanding the capacity from a certain year (i.e., free expansion of capacity), Natural Gas based Combined Cycle Gas Turbines (NG-CCGT) are installed as early as 2023 with a capacity of approximately 0.8 GW. The Figure presents no further expansion of the capacity from any other technology. Consequently Figure 5.2 shows the electricity production from the installed plants in the region. While the production strictly follows the capacity outlook a noticeable decrease in the production from NG-CCGT in the last year is observed. This indicates that the operating costs of the installed plants roses beyond the total cost (investment and operating costs) of other technologies in other regions. One needs to remind that OSeMOSYS allows the electricity to be freely traded thus the incentive to continue using the already installed capacity diminishes. Also, due to the high cost of importing LFO or internally produce it using local refineries the diesel generators are discarded since the first year. The total locally produced electricity is low compared to the increasing residential and services demand in the region that increases by more than twenty times toward 2030. As a result, Figure 5.3 shows that the region imports almost all of the electricity needed to supply the demand throughout the years with a linearly increasing imports. The only exception is 2023 when the NG-CCGT is installed, and the total demand has not yet outgrown the production, showing that a certain level of energy independence is still required to the region.

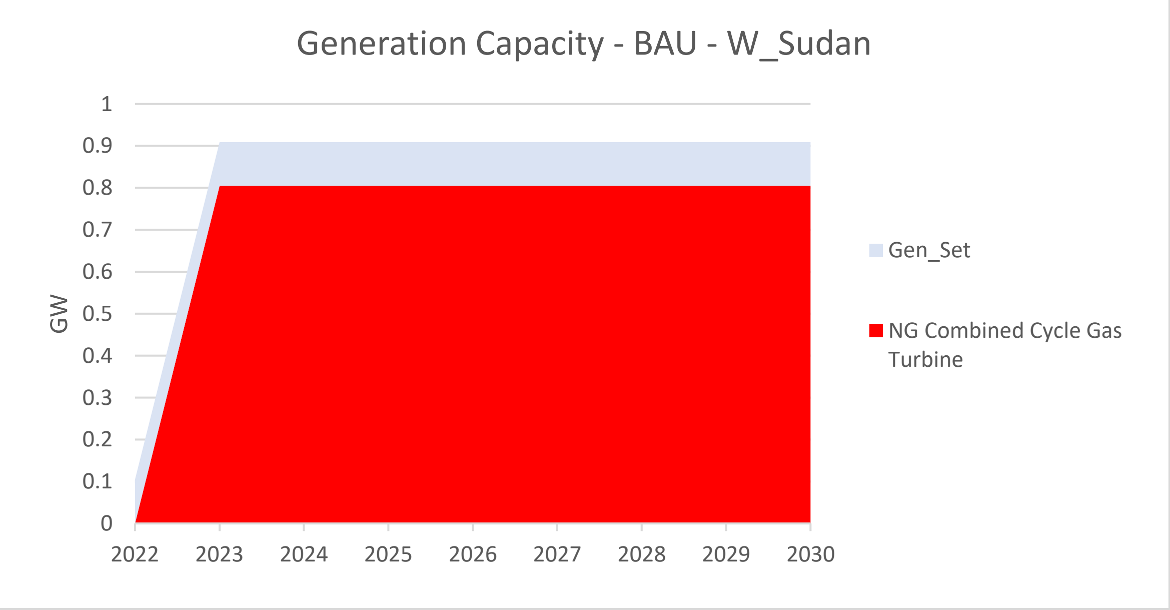


Figure 5.1 - Western Sudan Total installed capacity outlook, BAU, OSeMOSYS.

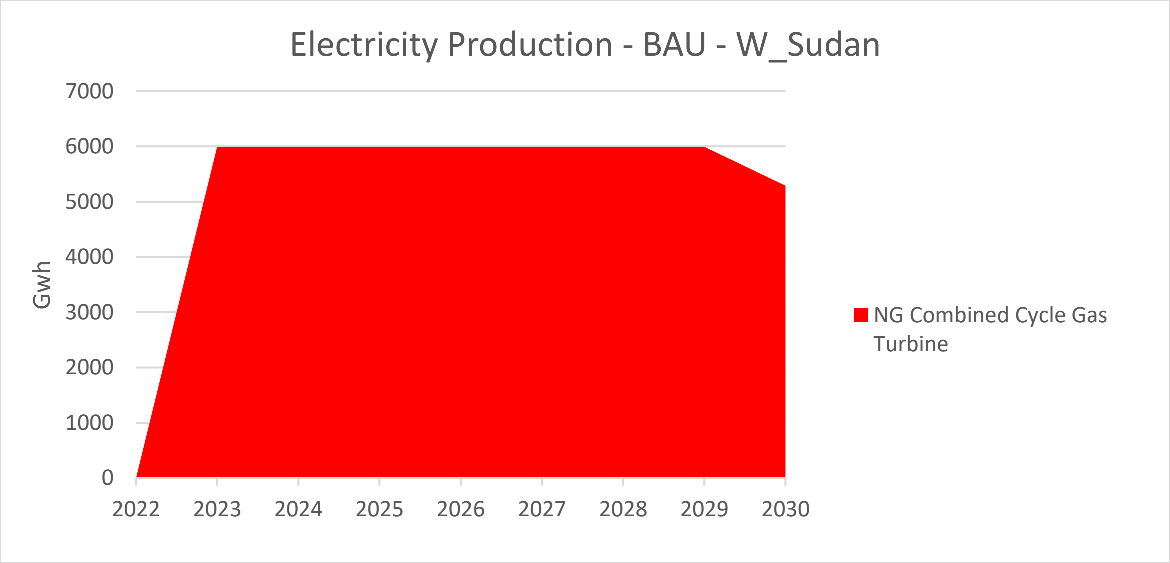


Figure 5.2 - Western Sudan electricity production outlook, BAU, OSeMOSYS.

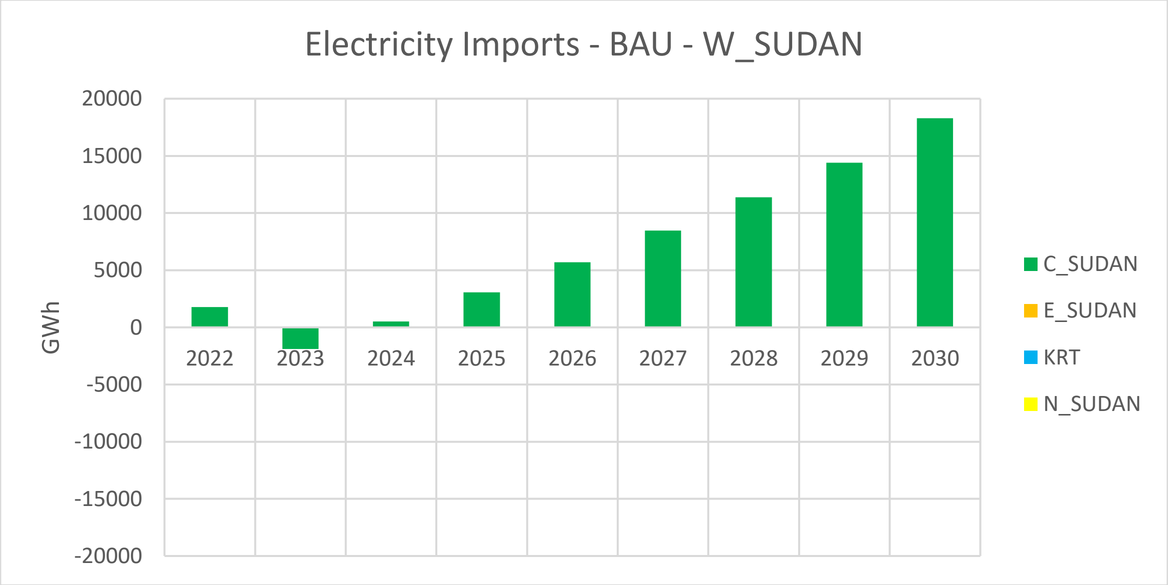


Figure 5.3 - Western Sudan electricity trade, BAU, OSeMOSYS.

Northern Sudan

The northern region in Sudan is the least populous region and presents the largest hydroelectric power plant (Merowe) of the country. Currently, hydroelectric power is the only technology used for energy supply, despite the Solar PV capacity factor average value being the highest amongst the regions. The region has the second highest electricity access percentage in the country (48%) leading to a moderate increase in the residential and services demands; the industrial and agricultural demands are relatively high. Figure 5.4 shows a small addition of NG-CCGT in the first two years to the existing large hydroelectric power plant. In 2024 a huge NG-CCGT capacity is added resulting in a total capacity of 1.75 GW after which the technology capacity stands still. Starting from 2027 when the solar PV capital cost drops making it the technology with the lowest LCOE in the region an exponential increase of utility scale PV systems is noticed toward 2030 amounting to a total of 10.5 GW, given that the Northern area has the highest capacity factor compared to the other regions, increasing the capacity of utility scale PV in north Sudan and then exporting the excess electricity generated to other regions is a more practical and reliable option found by the model to overcome the increasing demand of electricity across the country. Placing restrictions on the maximum capacity a technology can install each year may be a way to avoid increasing the capacity in particular areas. Figure 5.5 Shows the resulting electricity produced from the installed capacities. Production is consequent with the available capacity. A smaller share of solar PV systems in the electricity production is apparent and anticipated compared to the share in capacity due to the low overall capacity factor of PV systems. The produced electricity in the region is always higher than the total demand thus, the region is a net exporter of electricity (Figure 5.6).

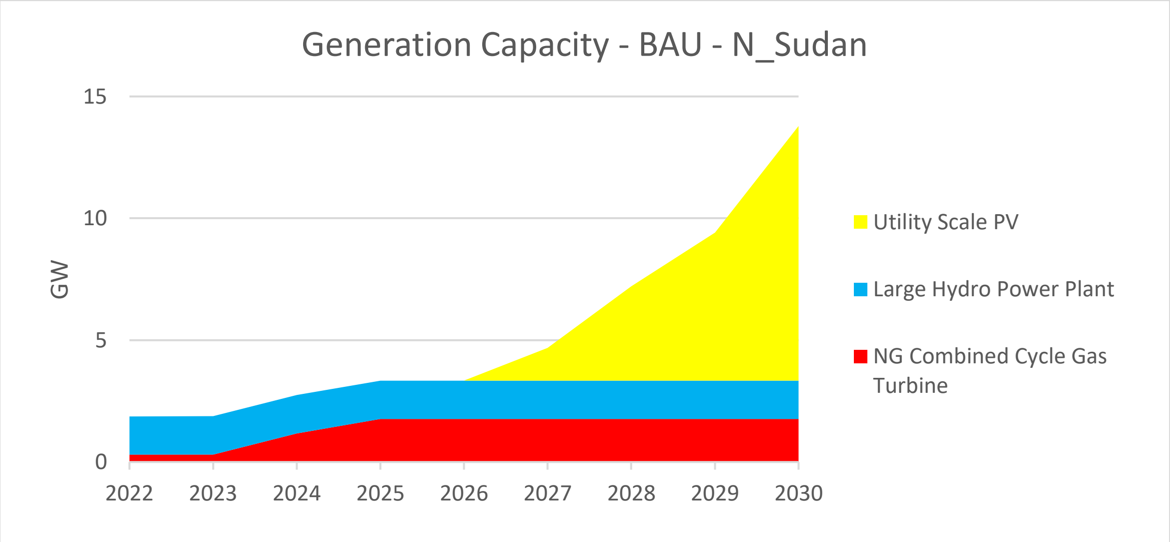


Figure 5.4 - Northern Sudan Total installed capacity outlook, BAU, OSeMOSYS.

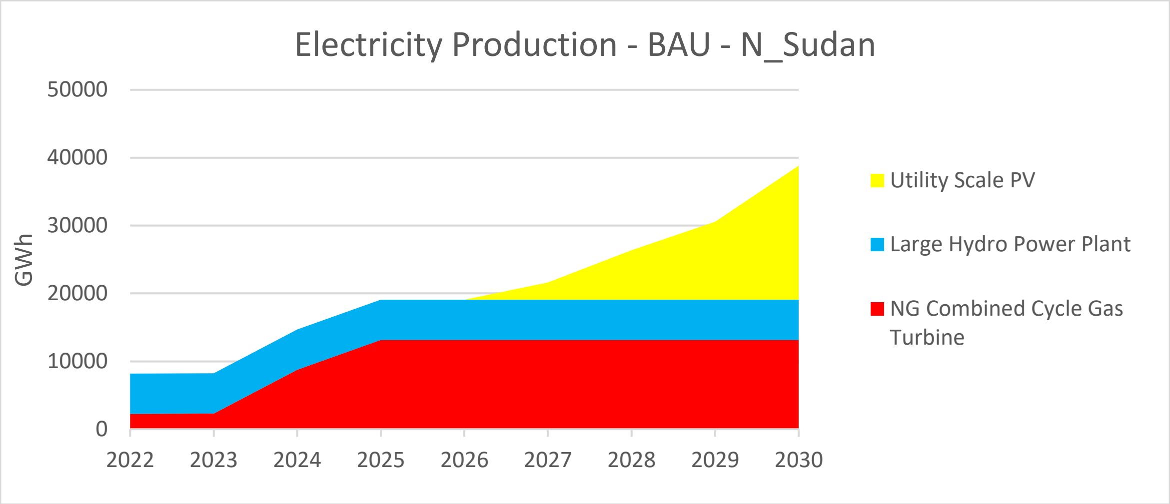


Figure 5.5 - Northern Sudan electricity production outlook, BAU, OSeMOSYS.

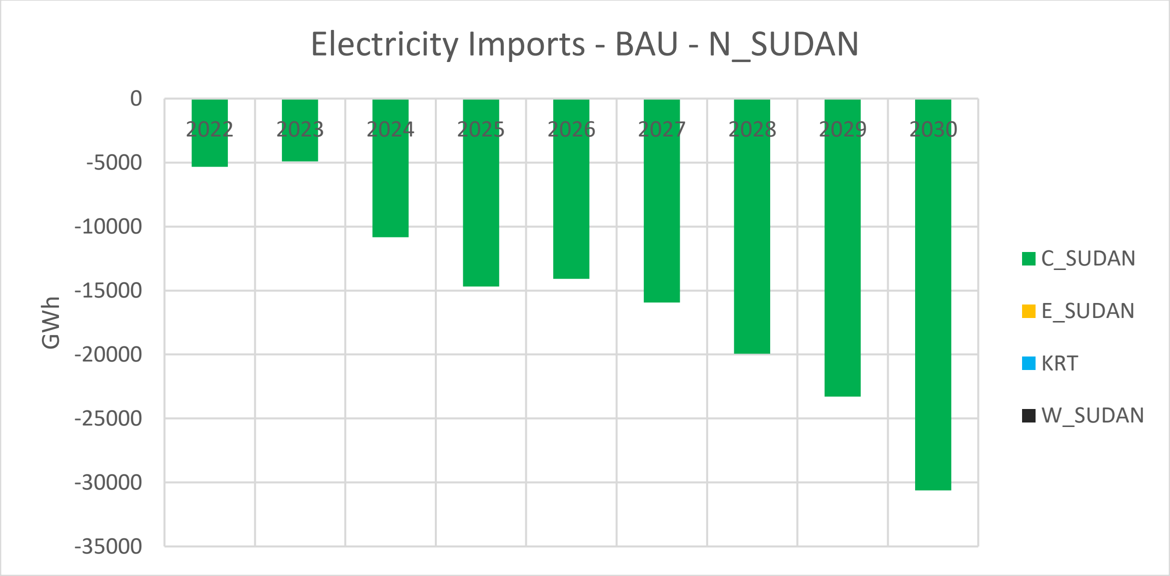


Figure 5.6 - Northern Sudan electricity trade, BAU, OSeMOSYS.

Khartoum

The capital of the country and its economic and political center is the most served region regarding electricity system infrastrucuture and other services. Most of the existing fossil-fuel power plants are distributed around the region also, the supply centers outside the capital mainly serves the capital demand and only distributing the electricity for the cities on the transmission line way to the capital. Although in pure numbers the region is not the most populus however, it has the highest population density. The region has the highest wind energy average capacity factor around the country and the second highest solar PV capacity factor. In terms of electricity access percentage it leads the country with more than 67% of the households connected to the national grid. The residential and services demand thereofre are increasing in a moderate rate. Figure 5.7 outlines the capacity expansion in Khartoum. The capacity is excpected to experience no expansion up to 2027 when wind turbines cost falls considerablly. From that point the installed wind turbines capacity linearly increase by a rate of 1.5 GW/year reaching a total of 6 GW in 2030. The electricity production outlook (Figure 5.8) shows that up to 2027 when the wind capacity is deployed the existing Heavy Fuel Oil Steam Turbine (HFOST) is dispatched producing around 2 TWh/year meanwhile, the Light Fuel Oil CCGT (LFO-CCGT) is barely fired producing less than 0.5 TWh/year in average. In the later years however this reality is flipped where LFO-CCGT contribution to the power production reaches 1.5 TWh in 2029 and HFOST falls to zero in the last year. This can be traced back to the fact that in the earlier years it is cheaper to import HFO than LFO. However, as the years passes producing LFO domestically using the crude oil reserve and the crude oil refinery is cheaper than importing HFO. Since the exisiting installed capacity is not enough to meet the region demand the shortcoming is imported. With the exception of the last year khartoum is always a net-importer of electricity (Figure 5.9).

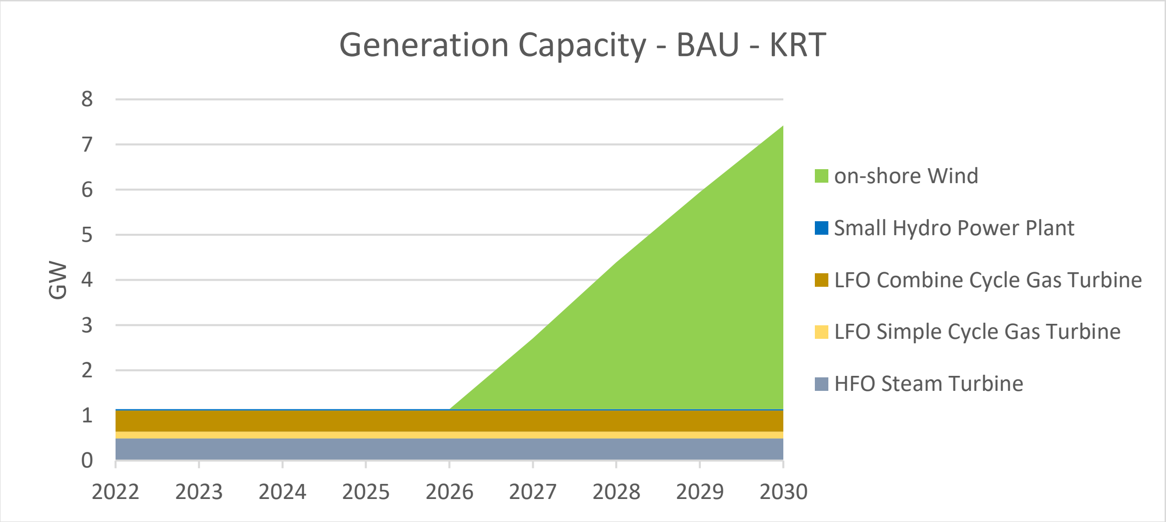


Figure 5.7 - Khartoum Total installed capacity outlook, BAU, OSeMOSYS.

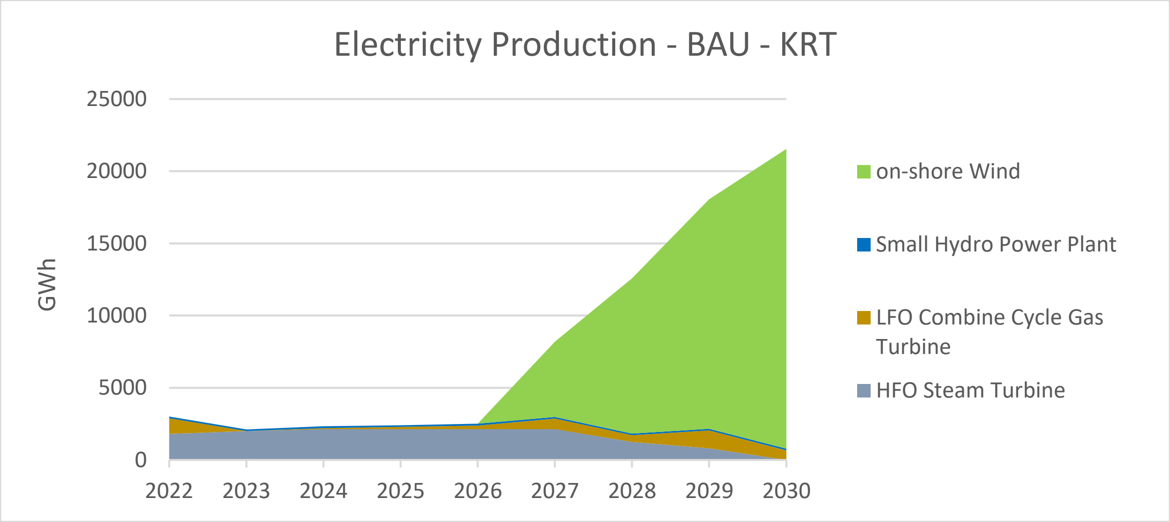


Figure 5.8 - Khartoum electricity production outlook, BAU, OSeMOSYS.

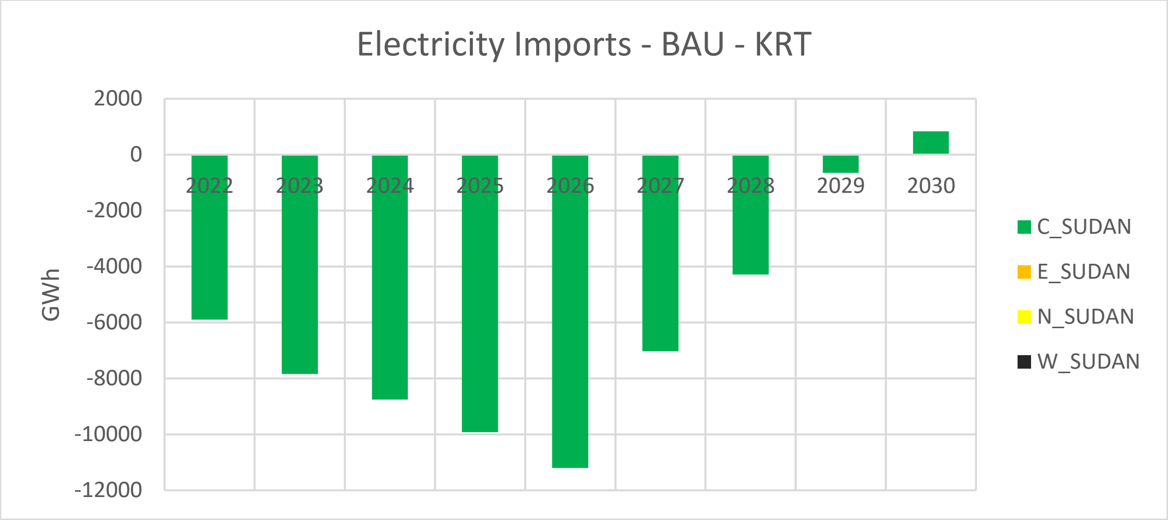


Figure 5.9 - Khartoum electricity trade, BAU, OSeMOSYS.

Eastern Sudan

The Eastern region that consists of three states is the second poorest region in terms of electricity access percentage, since less than 20% of the population are granted a grid connection. Even though it has the main Sudanese port (Port-Sudan) the distributed cities are relying either on small hydro power plants or diesel engines. The demand accordingly is expected to experience a high increase. Figure 5.10 clarifies that up to 2025 no additional supply is added, and the region satisfies its growing demand by importing electricity (Figure 5.12). In 2026 through a 1 GW NG-CCGT capacity is deployed allowing the region to export electricity until 2028 where the demand again exceeds the production, and the region starts importing. The electricity production outlook (Figure 5.11) follows the installed capacity with the diesel generators being turned off.

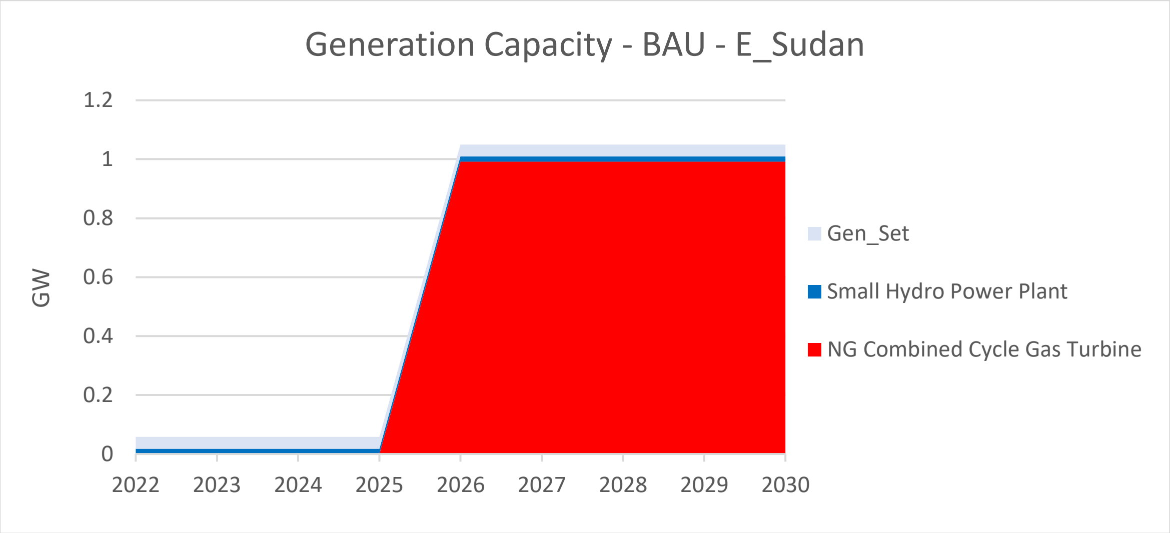


Figure 5.130 - Eastern Sudan Total installed capacity outlook, BAU, OSeMOSYS

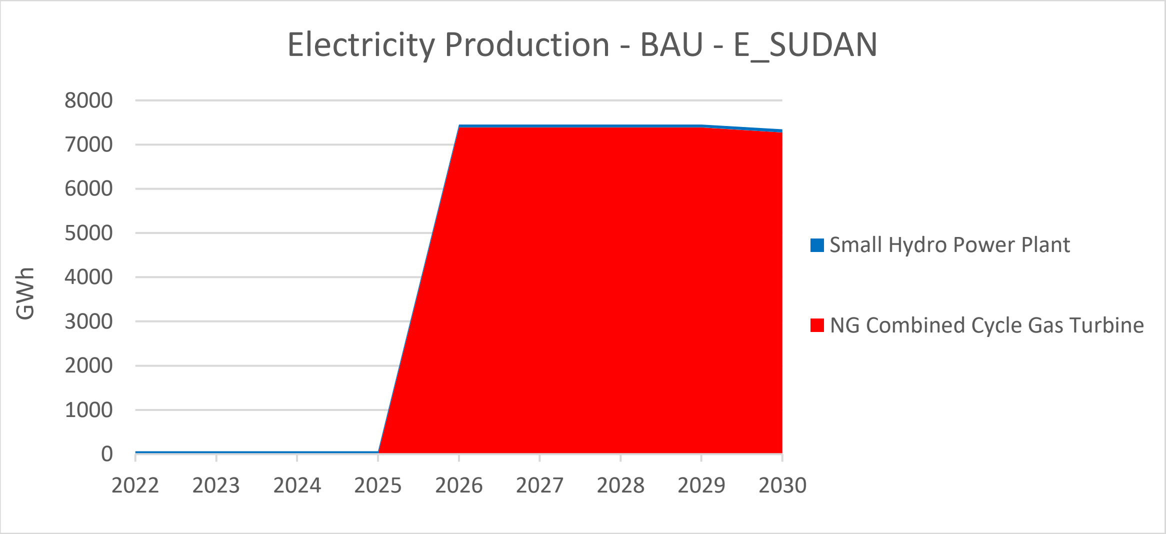


Figure 5.14 - Eastern Sudan electricity production outlook, BAU, OSeMOSYS

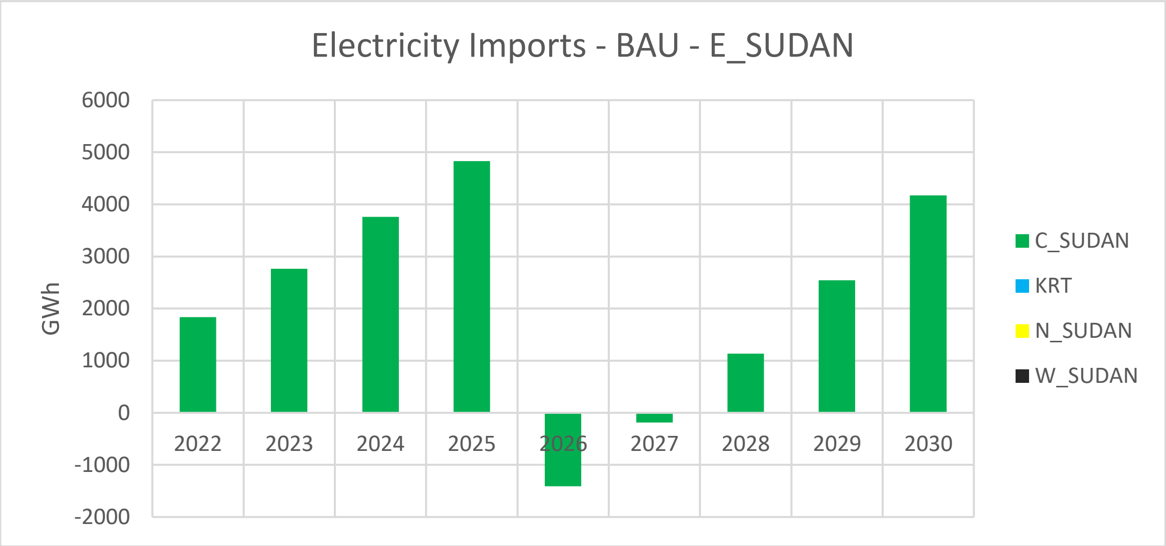


Figure 5.15 - Eastern Sudan electricity trade, BAU, OSeMOSYS.

Central Sudan

Central states of Sudan are the second most contributors in the Sudanese economy due to the large agricultural areas and the associated transitional industries. The two main tributaries of the river Nile i.e., Blue Nile and White Nile cross the region promoting electricity production from hydropower plants. In fact, some of the oldest supply plants are constructed in this region. Electricity access percentage in the region is relatively moderate at 38%. The demand accordingly shows a relatively moderate increase. The solar PV and wind energy capacity factors are the lowest in this region. The capacity expansion path (Figure 5.13) shows that the model decided to immediately add 1.4 GW of NG-CCGT from 2022 to the existing large hydroelectric power plants and the Crude Oil Steam Turbine (CROST). This added capacity meets the local demand with a surplus that is exported. Another addition of less than 0.5 GW from NG-CCGT is also noticed in 2025. The electricity production outlook (Figure 5.14) closely follows the installed capacity with CROST contribution increases toward 2025 to meet the growing demand then decreases when the region begins importing electricity. In Figure 5.15 it's obvious that the Central region is treated as a distribution point of power between the regions it imports the surplus produced by Northern Sudan and rarely other regions and distributes it to the other regions. It is worth mentioning though this is not related to the geographic positioning of the regions or to minimize the distance of transmission lines since transmission lines are not modelled whatsoever in OSeMOSYS.

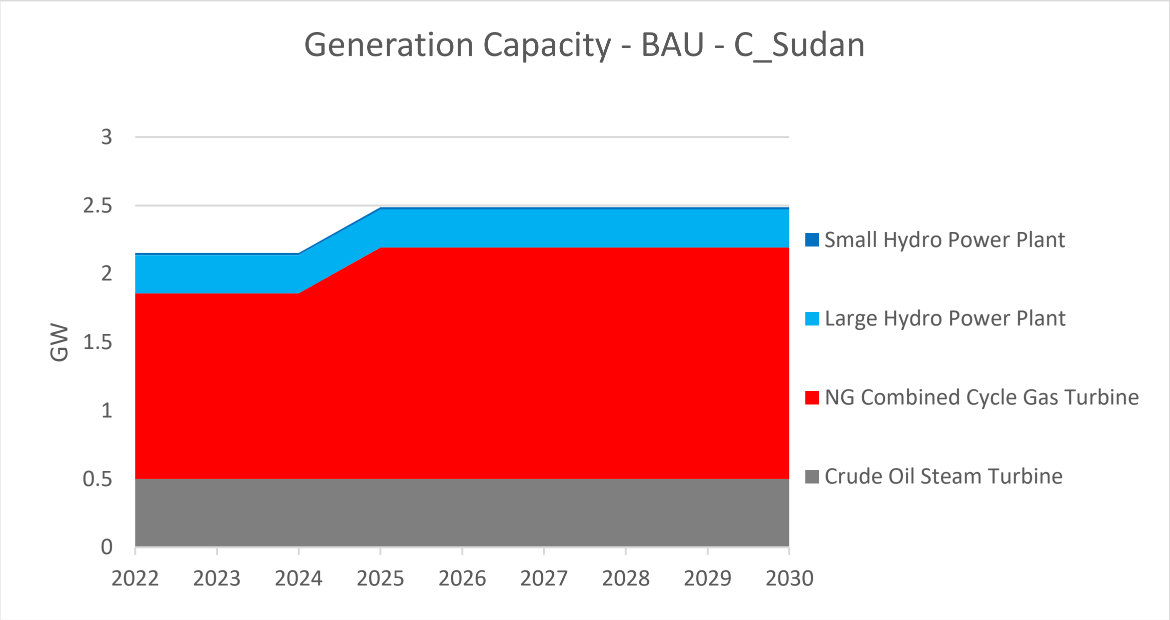


Figure 5.16 - Central Sudan Total installed capacity outlook, BAU, OSeMOSYS.

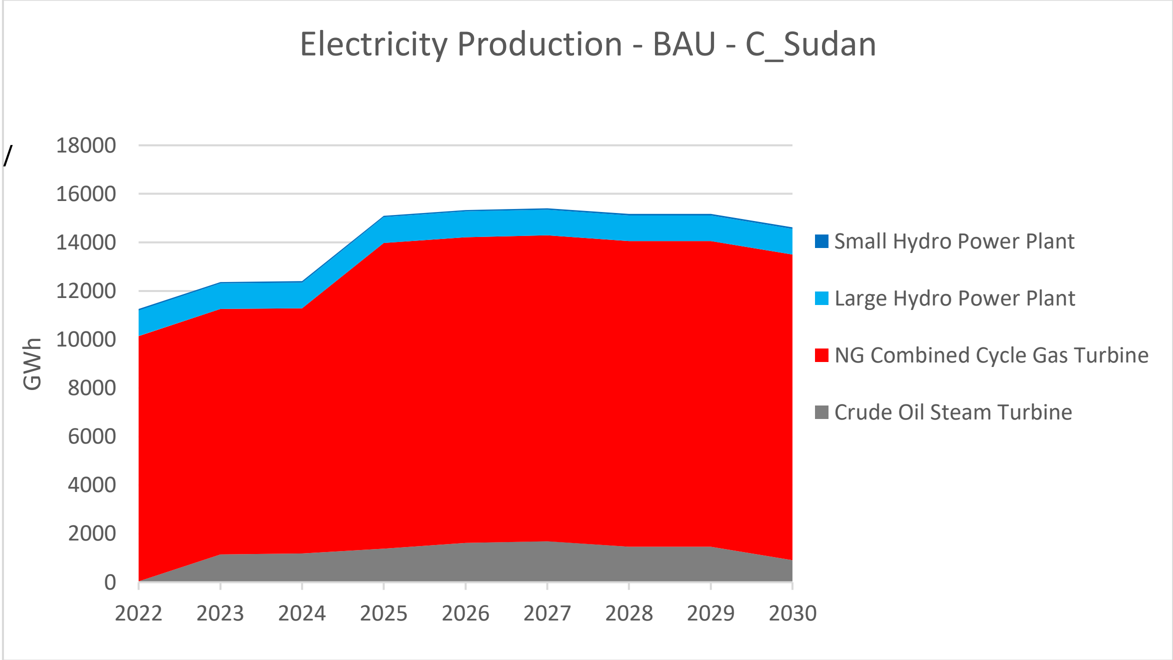


Figure 5.17 - Central Sudan electricity production outlook, BAU, OSeMOSYS.

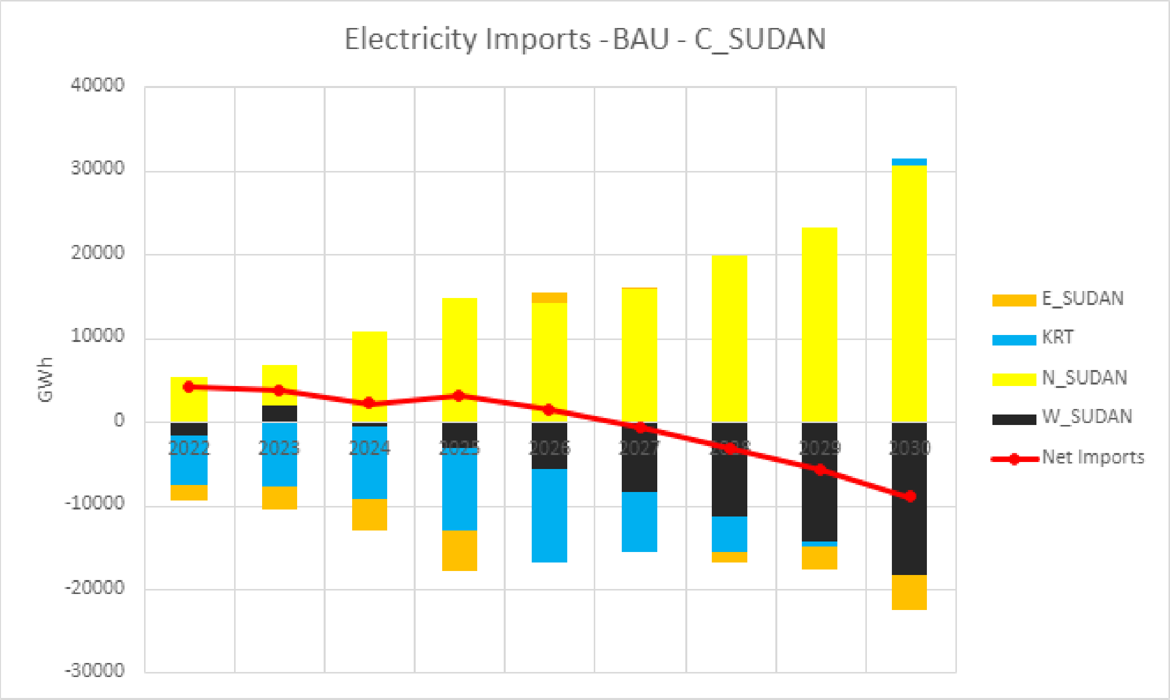


Figure 5.18 - Central Sudan electricity trade, BAU, OSeMOSYS.

The yearly investment and operational costs distributed among the different technologies are presented in Figure 5.16 and Figure 5.17, respectively. Up to 2026 the investments are devoted to building new NG-CCGT power plants, it is not until 2027 where the LCOE of both Solar PV and Wind turbine systems falls below other technologies. The total investment costs amounted to 23.3 billion USD. Operational costs are dominated by the extraction of fossil fuels and natural gas in particular use to power the newly installed NG-CCGT power plants. The operational costs of the power plants only amount to a small percentage. The total operational costs through the years amounted to 28.5 billion USD and 4.1 billion USD in 2030.

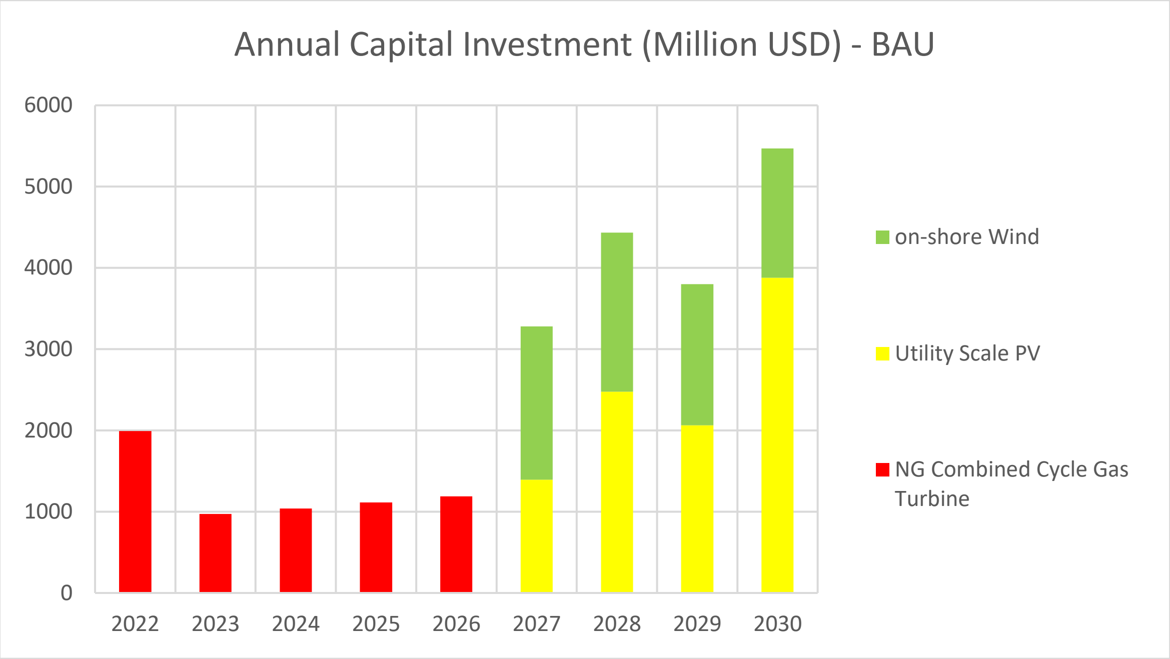


Figure 5.19 - Annual capital investment, BAU, OSeMOSYS.

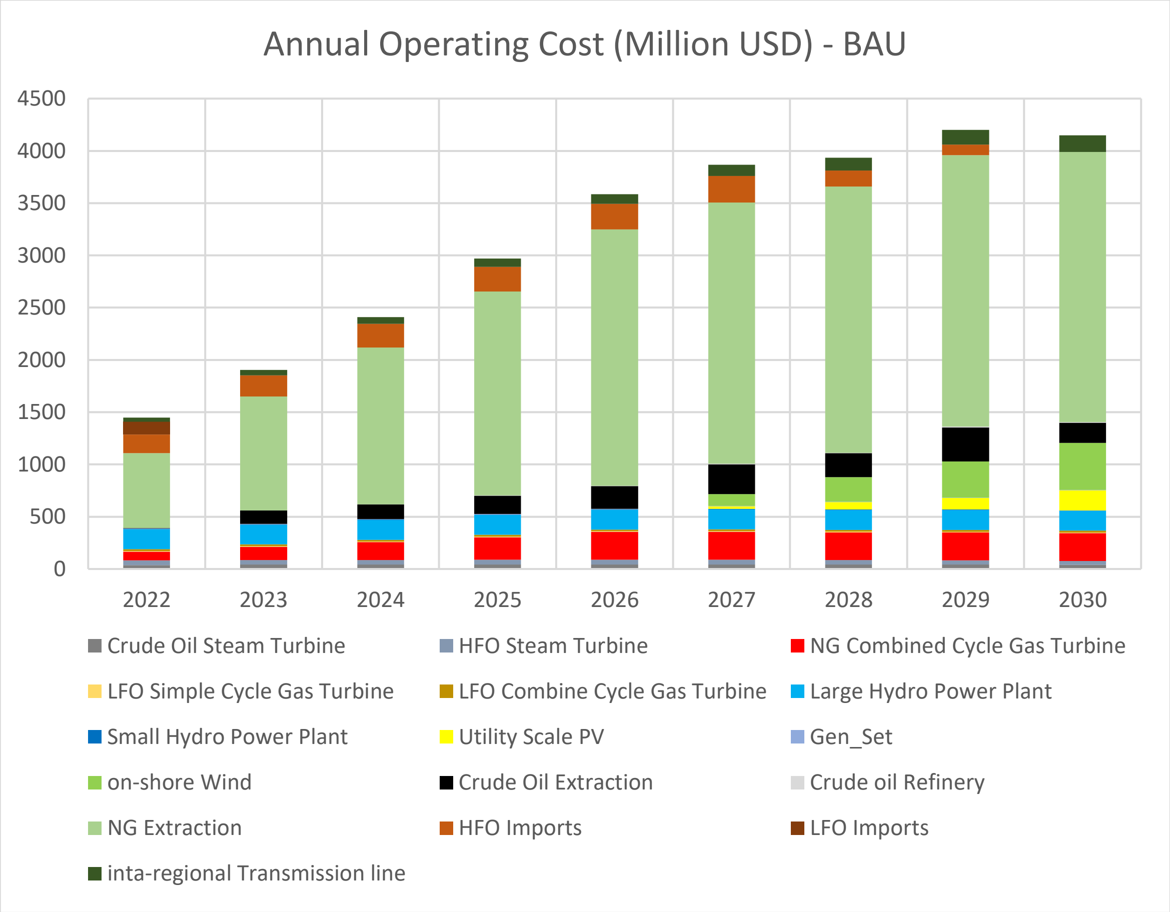


Figure 5.20 - Annual operating cost, BAU, OSeMOSYS.

Figures 5.18 and 5.19 presents the cumulative consumption of fossil fuels in the country toward 2030. Natural gas as anticipated from the results is the most used fuel.

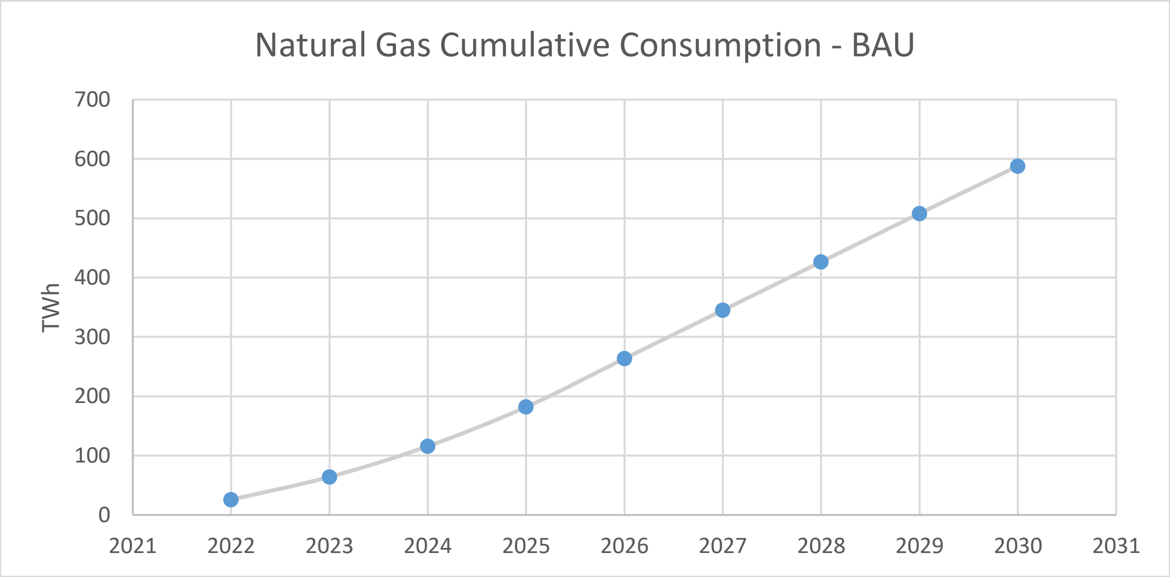


Figure 5.21 - Cumulative Natural gas consumption , BAU, OSeMOSYS.

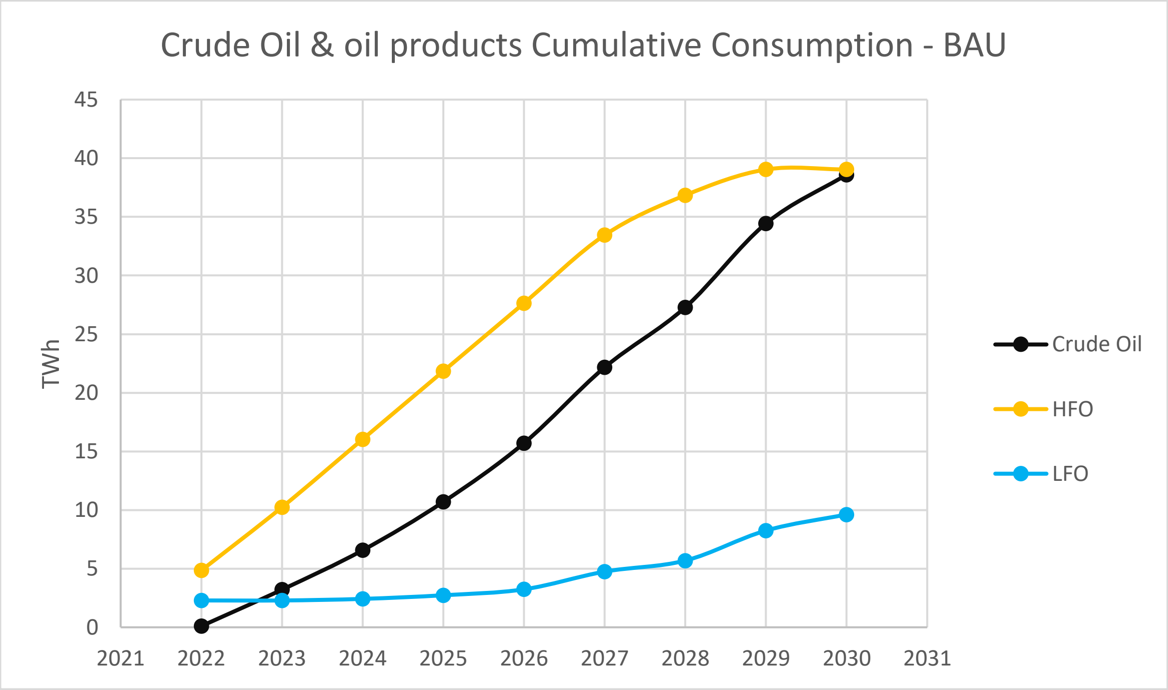


Figure 5.22 - Cumulative Crude oil and Oil products consumption , BAU, OSeMOSYS

5.1.2 Hypatia BAU Results

Hypatia energy modelling framework was intended to be used to construct two models having different time resolution to further investigate how fine time slices highly influence the results especially of VRES. However, as mentioned in section 5.1 the hourly model did not converge using different solvers, given the huge computational effort and the to-the-date solving structure of the software. Therefore, the same time slices as in OSeMOSYS were used. One key difference is that Hypatia allows for modelling the cross-border transmission network enhancing the nodal analysis performance.

Western Sudan

Figure 5.20 presents the generation capacity outlook in the region. Once again, the model was not restricted to start expanding the capacity from a certain year. The expansion starts as early as 2022 linearly increasing the NG-CCGT capacity to 2.2 GW in 2027 after which further expansion is coming from the exponentially increasing solar PV systems reaching 3.6 GW in 2030. Figure 5.21 shows that the electricity production strictly follows the capacity outlook while diesel generators are again not utilized. The total produced electricity is still lower than satisfying the demand yet considerably higher than OSeMOSYS. This is clear looking at Figure 5.22 where even though the region is net importer in almost all of the years the imported electricity is lower by two orders of magnitude compared to OSeMOSYS.

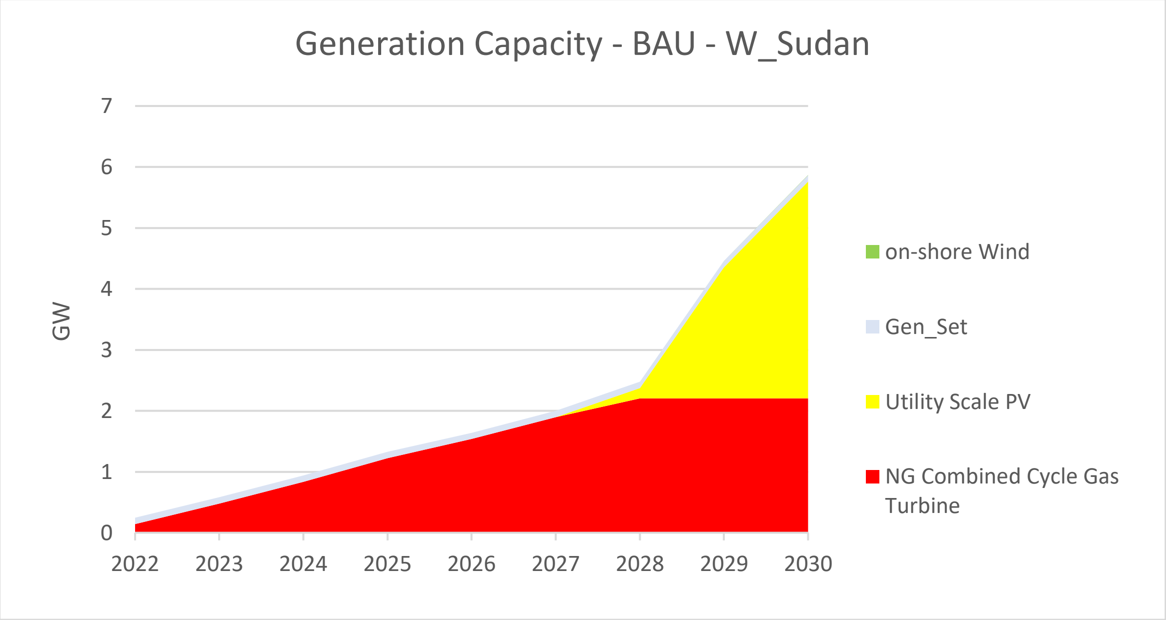


Figure 5.23 - Western Sudan Total installed capacity outlook, BAU, Hypatia.

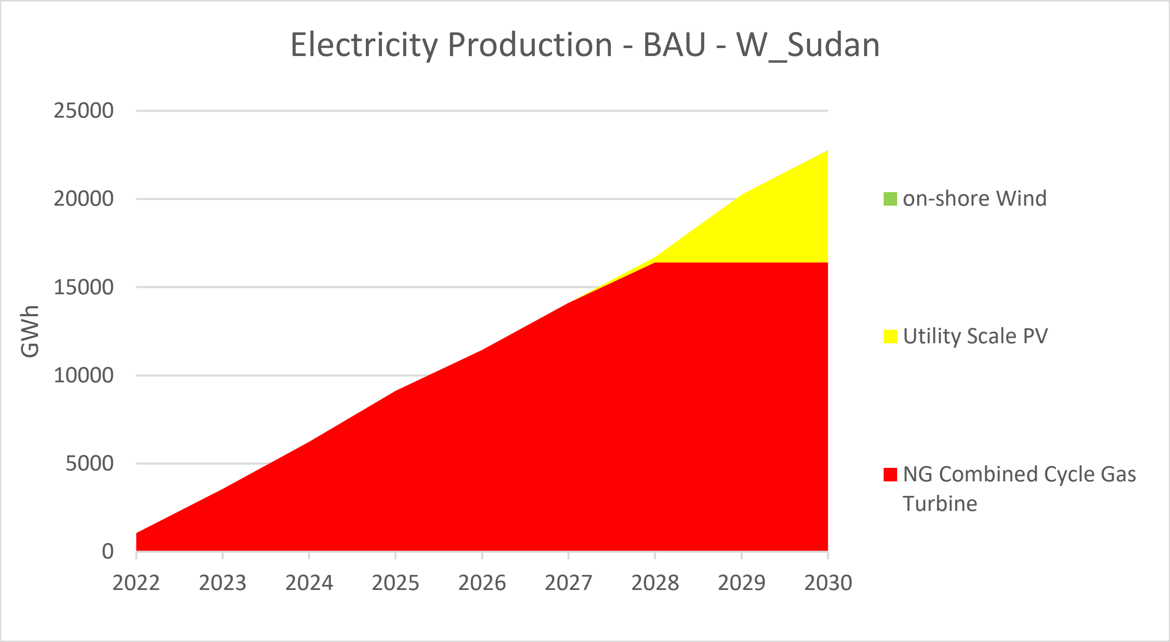


Figure 5.24 - Western Sudan electricity production outlook, BAU, Hypatia.

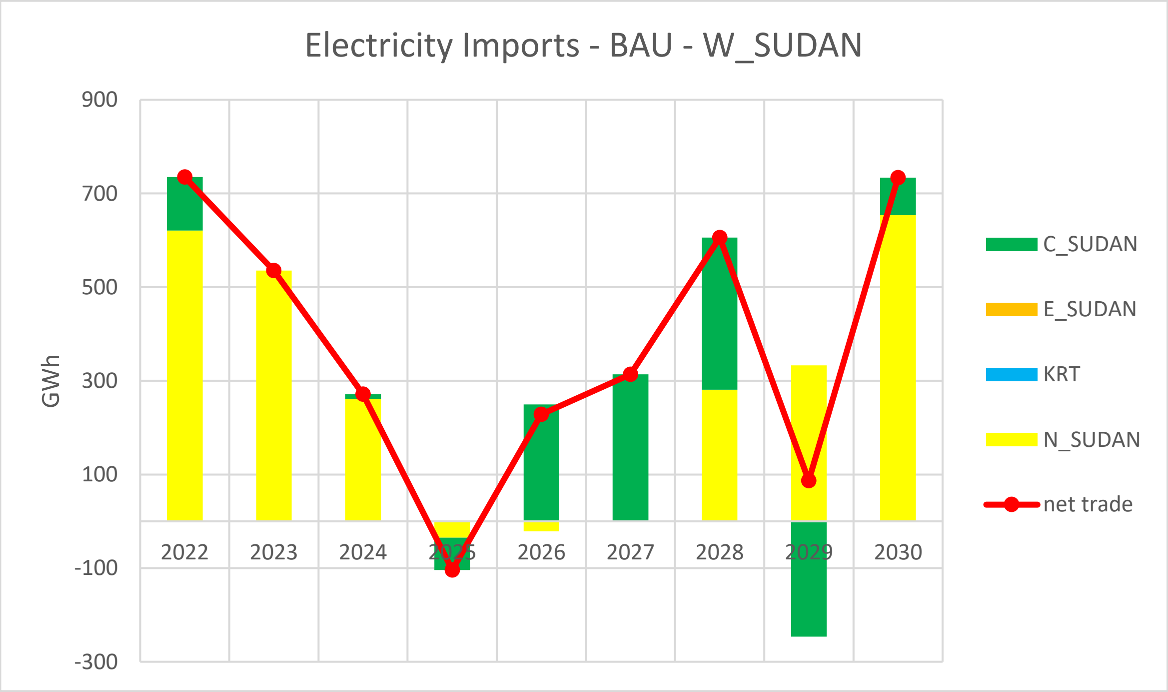


Figure 5.25 - Western Sudan electricity trade, BAU, Hypatia.

Northern Sudan

Figure 5.23 shows that unlike OSeMOSYS the northern region experiences no addition of NG-CCGT in fact up to 2026 no additional capacity of any technology is noticed. This might be referred to the fact that production in the northern region is higher than the demand and since Hypatia considers the transmission lines investments cost exchange of power between regions is kept to minimum. Starting from 2026 the region shows a linear increase of utility scale PV systems toward 2030 amounting to a total of 1.3 GW accompanied with a small additional 0.4 GW wind turbines. Electricity production mix in the region is dominated by the existing large hydroelectric powerplants as shown in Figure 5.24. The region is once again acts as a net exporter of electricity however with lower values (Figure 5.25).

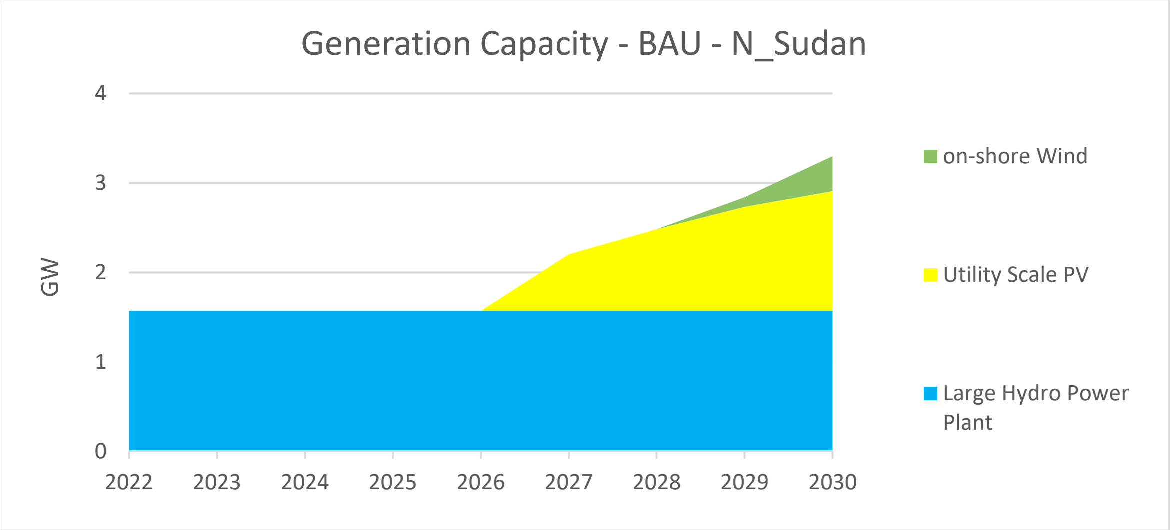


Figure 5.26 - Northern Sudan Total installed capacity outlook, BAU, Hypatia.

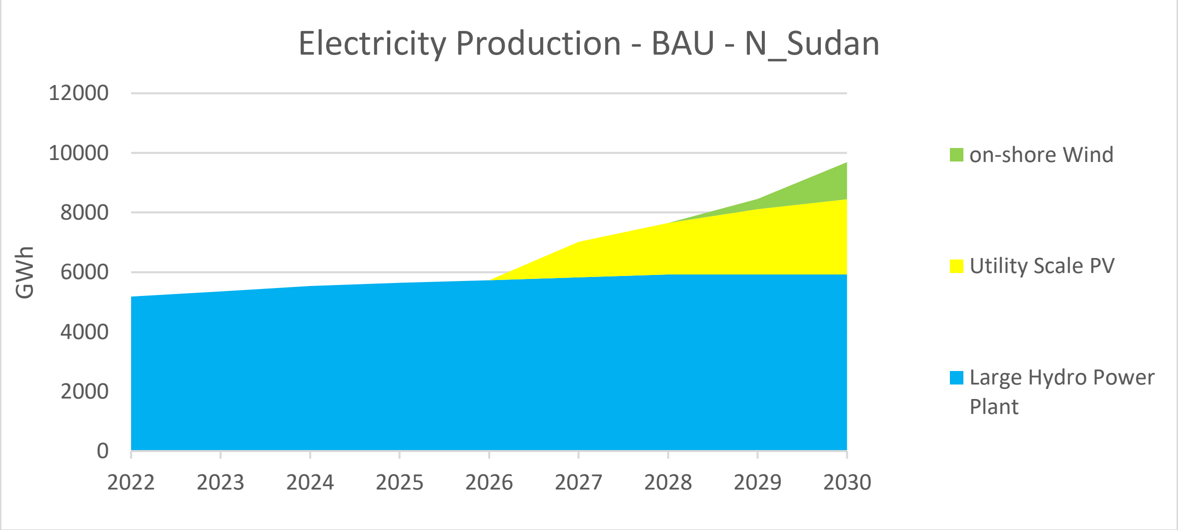


Figure 5.27 - Northern Sudan electricity production outlook, BAU, Hypatia.

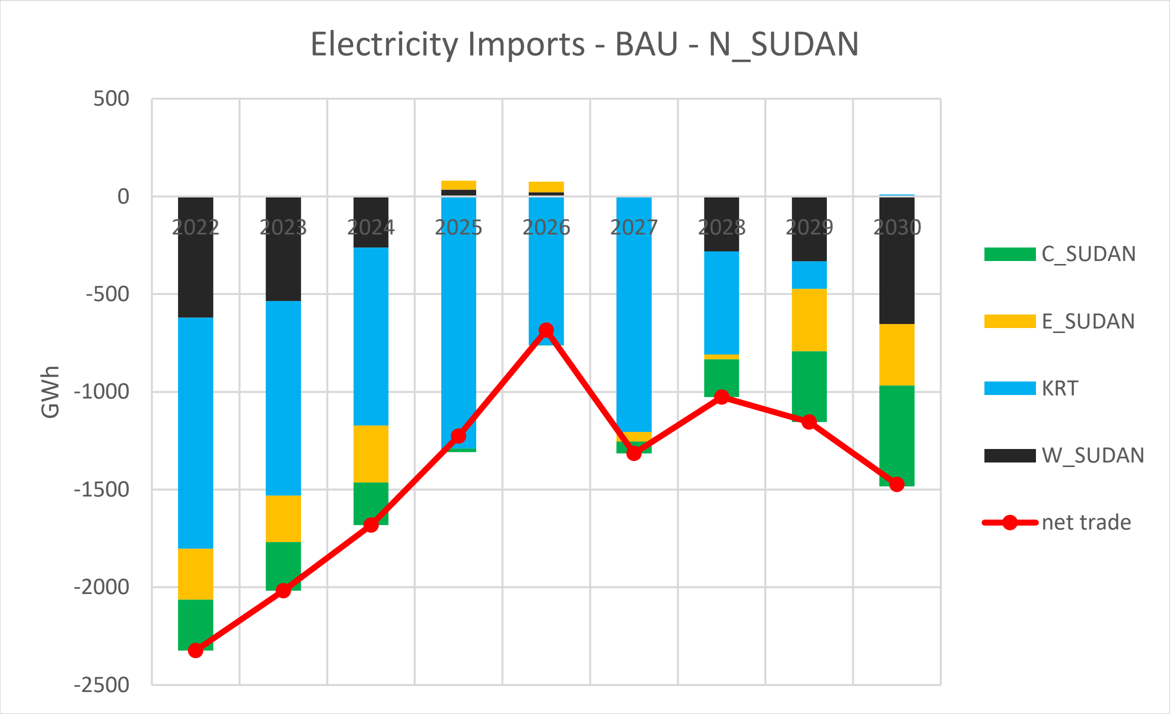


Figure 5.28 - Northern Sudan electricity trade, BAU, Hypatia.

Khartoum

Figure 5.26 outlines the capacity expansion in Khartoum. The capacity experiences continuous expansion throughout the years to meet the regional demand along with the imported electricity mostly from the northern region. The period 2022-2025 shows curtailing capacity from NG-CCGT to reach almost 1 GW. Starting from 2025 wind and solar PV systems costs fall considerably and they are deployed in the region to reach 3 GW and 2.4 GW respectively. The electricity production outlook (Figure 5.27) shows a similar trend to the total installed capacity however the operation of HFOST and LFO-CCGT power plants is slightly different than OSeMOSYS where they follow the demand in the early years increasing their production to counter-attack the demand growth however, from 2026 when PV and wind emerges their contribution decreases. Up to 2029 Figure 5.28 Shows that Khartoum is a net importer of electricity mainly importing from the northern region. It is not until PV and wind penetration increases then Khartoum starts to export.

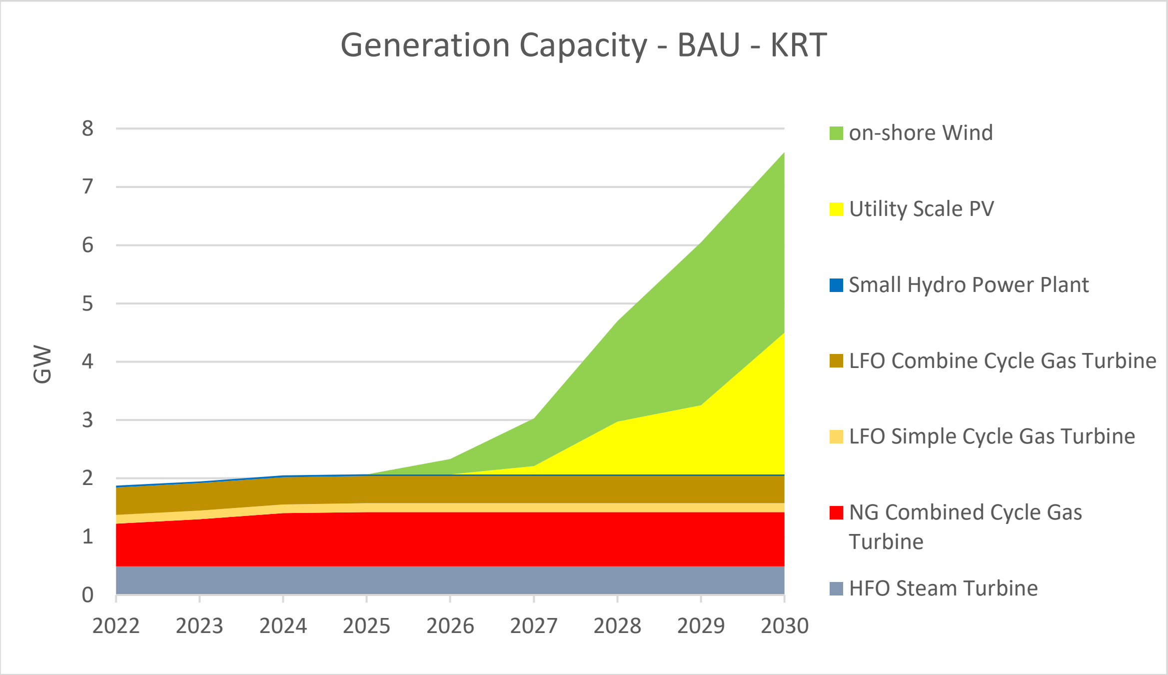


Figure 5.29 - Khartoum Total installed capacity outlook, BAU, Hypatia.

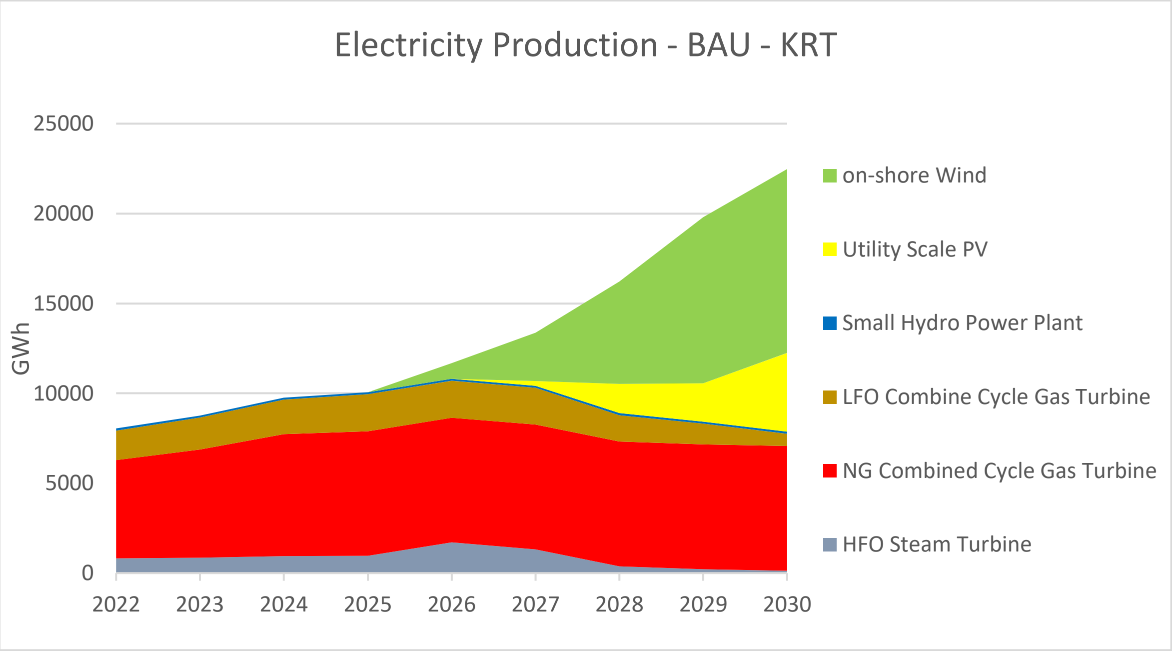


Figure 5.30 - Khartoum electricity production outlook, BAU, Hypatia

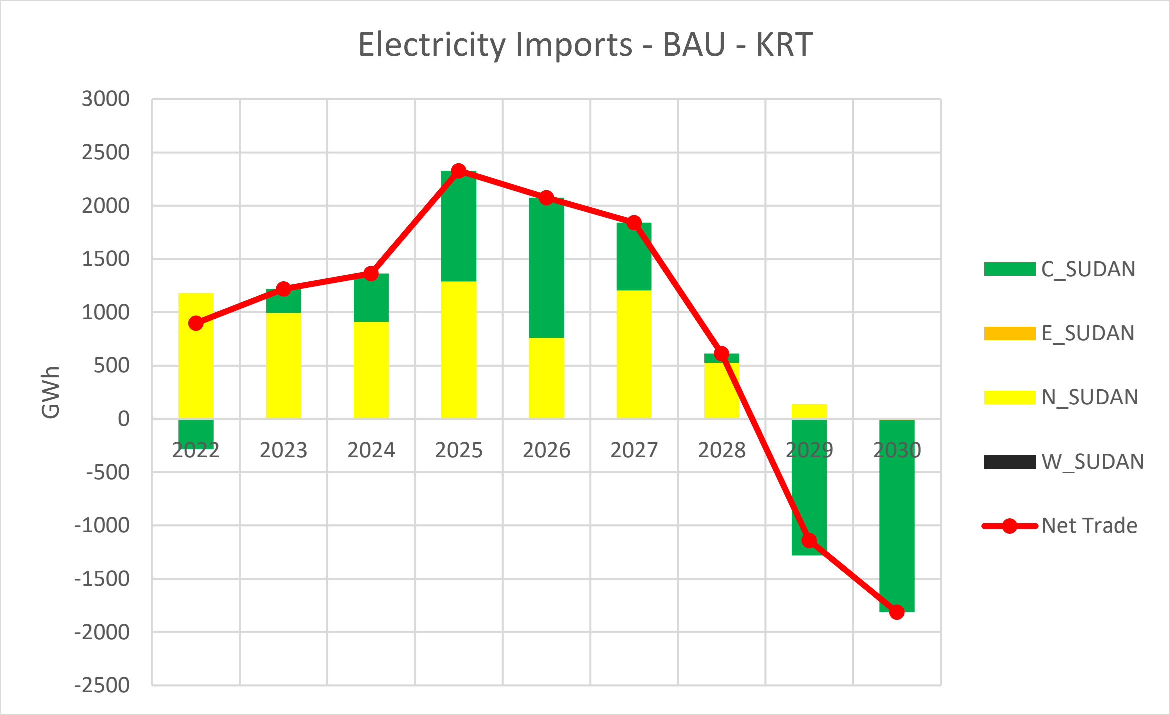


Figure 5.31 - Khartoum electricity trade, BAU, Hypatia

Eastern Sudan

Figure 5.29 Solidifies the conclusion that Hypatia promotes the development of regional supply rather than the exchange of power between regions. Unlike OSeMOSYS, the eastern region capacity expands to minimize electricity imports and avoid the installation of new capacity for transmission lines. Thus, decreasing the imports (Figure 5.31). The electricity production outlook (Figure 5.30) follows the installed capacity with the diesel generators being turned off.

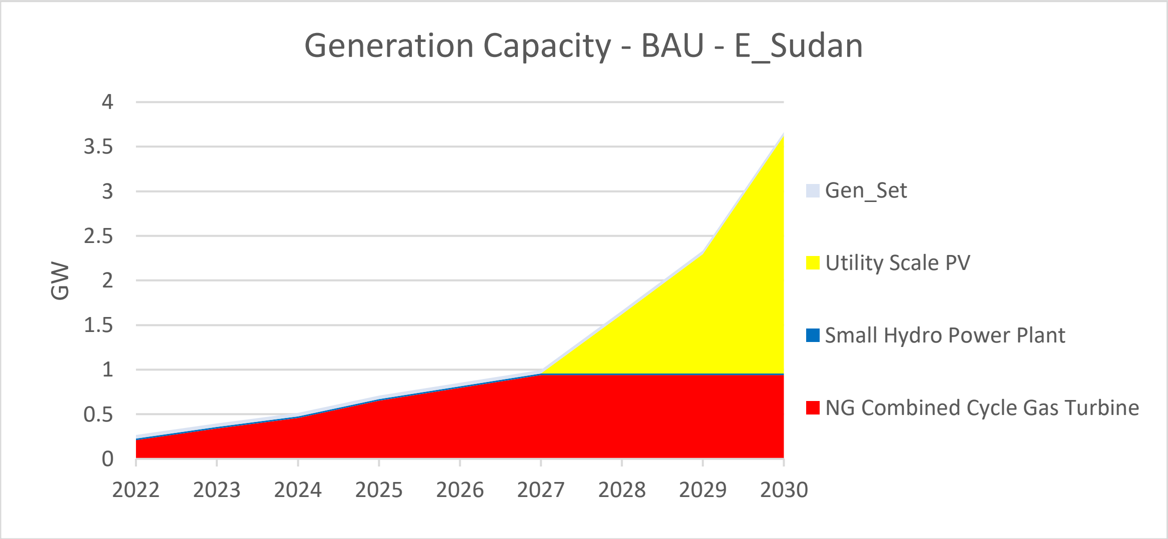


Figure 5.32 - Eastern Sudan Total installed capacity outlook, BAU, Hypatia.

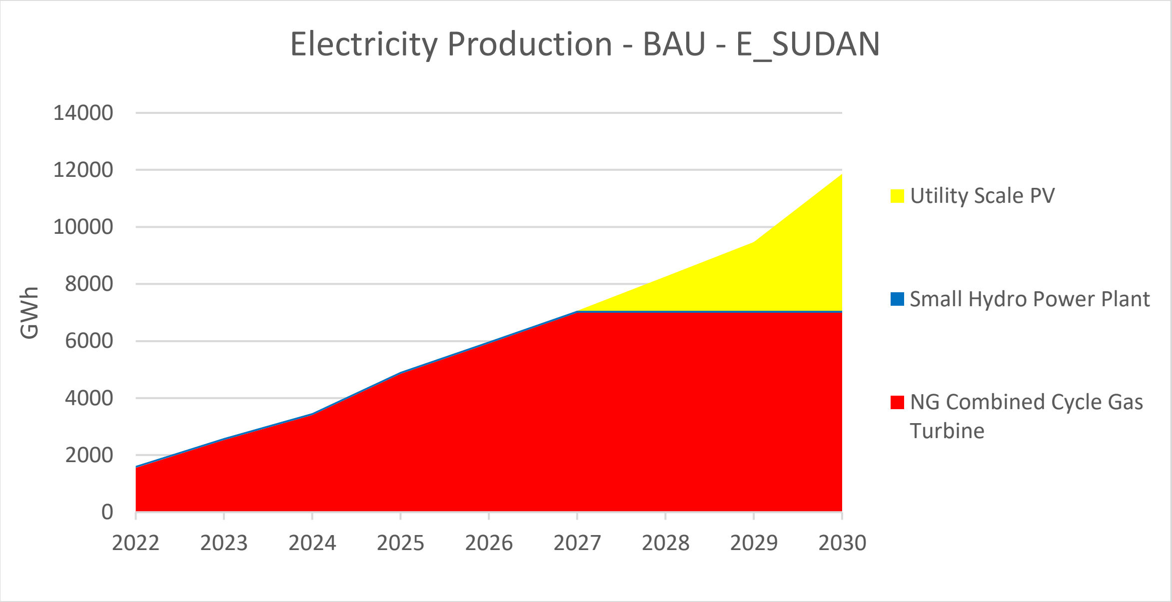


Figure 5.33 - Eastern Sudan electricity production outlook, BAU, Hypatia.

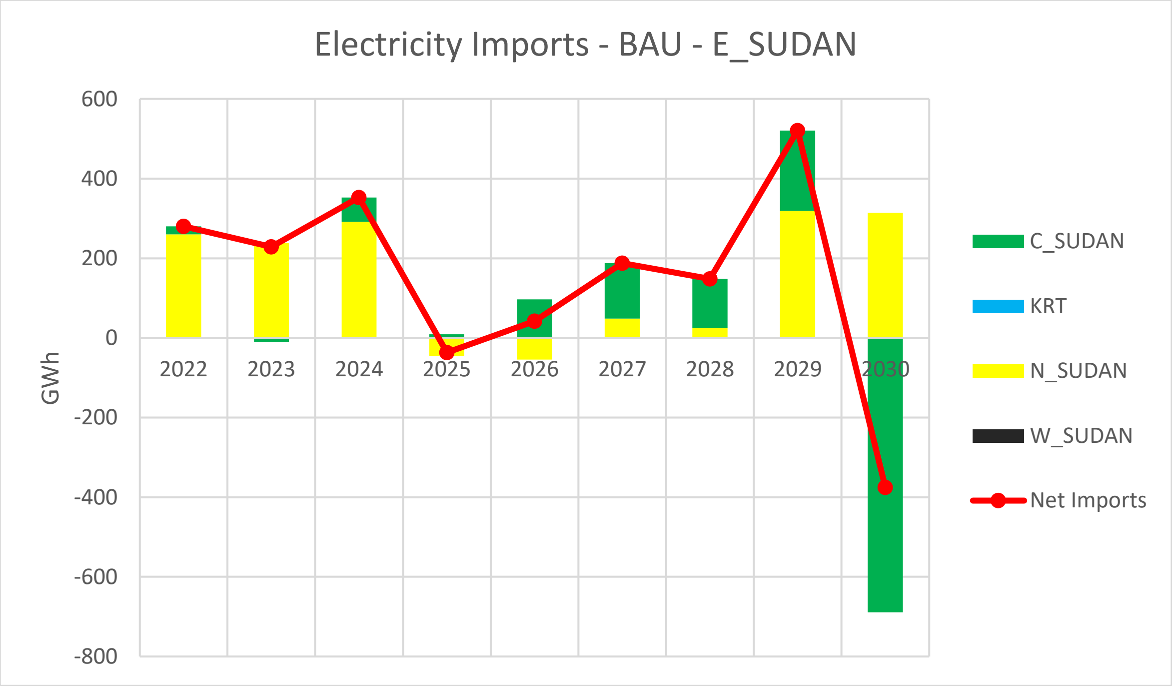


Figure 5.34 - Eastern Sudan electricity trade, BAU, Hypatia.

Central Sudan

As mentioned earlier in section 5.1.1 central region is the region with worst solar PV and wind capacity factors, this is clear in Figure 5.32 where even though promoting local generation Hypatia did not suggest the addition of the two technologies except in 2030 where a 1.3 GW PV system is deployed. Instead, the capacity is expanded using NG-CCGT growing linearly to follow the demand growth up to 2028 when importing electricity from other regions where electricity production from VRES is much cheaper turns out to be more profitable (Figure 5.34).

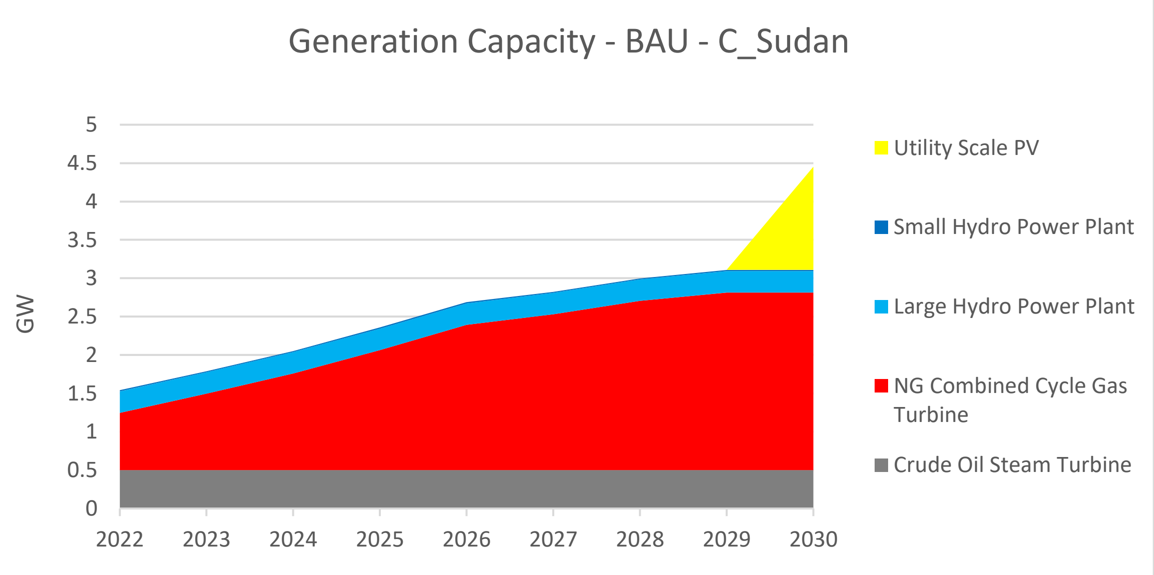


Figure 5.35 - Central Sudan Total installed capacity outlook, BAU, Hypatia.

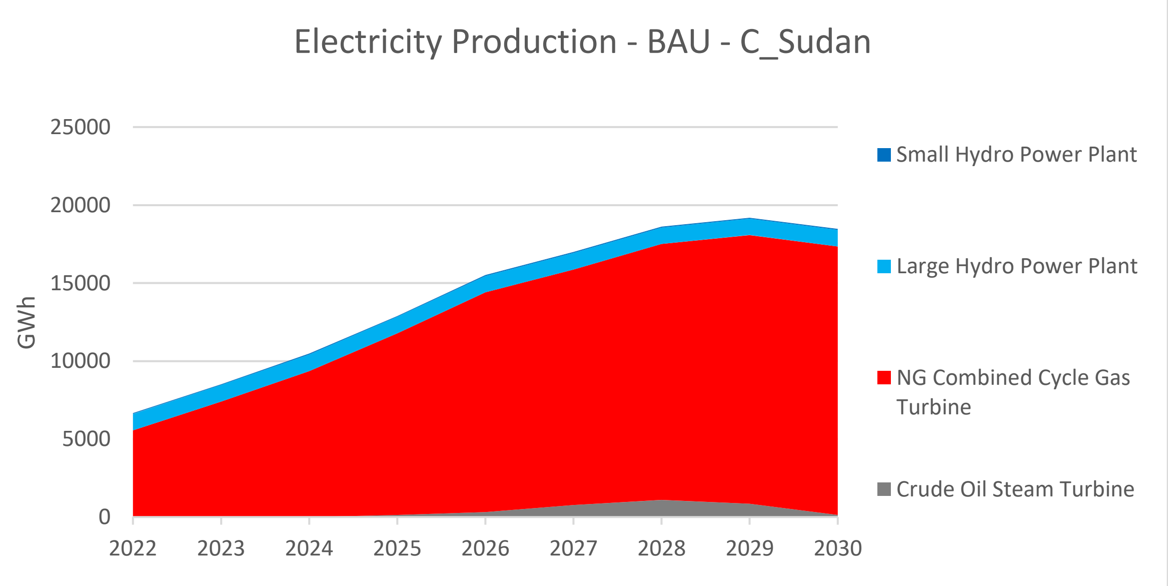


Figure 5.36 - Central Sudan electricity production outlook, BAU, Hypatia.

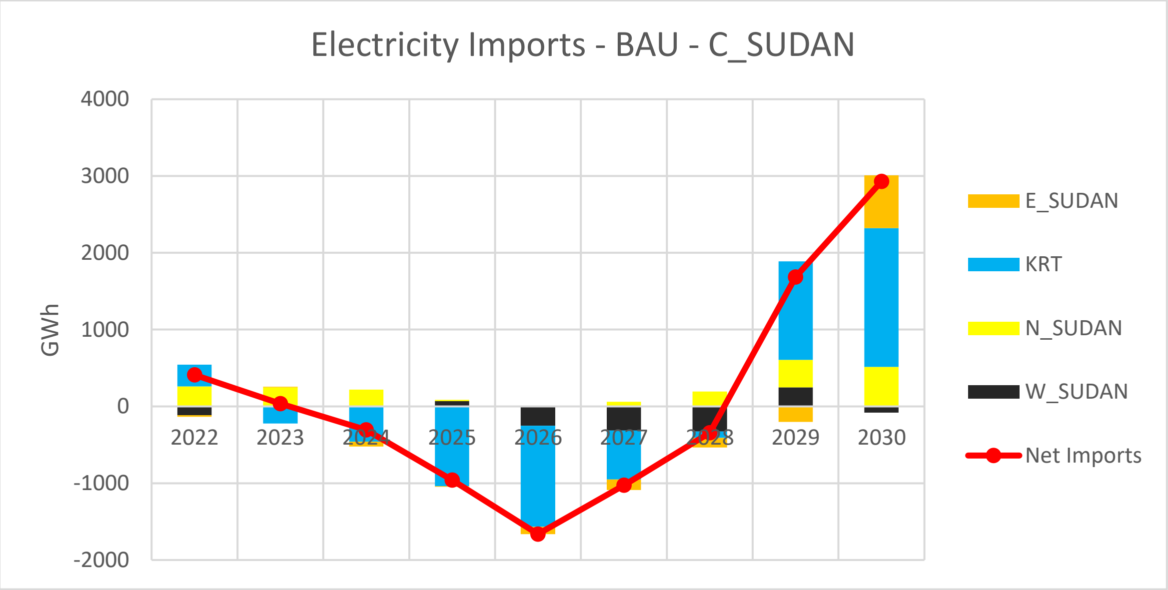


Figure 5.37 - Central Sudan electricity trade, BAU, Hypatia

Obviously, the main differences between Hypatia and OSeMOSYS are related to the modelling of the transmission grid in Hypatia which motivates the regions to reach self-sufficiency limiting power trade to be within the existing network capacity. This is noticeable looking at:

1- Supply capacity was expanded in all regions in Hypatia.

2- Existing power plants were utilized more (i.e., LFO-CCGT and HFOST in khartoum, CROST in Eastern Sudan, etc…).

3- Electricity trade magnitudes reduced by orders of magnitudes.

However, looking at the capacity expansion of the entire country for the two cases one notices how the share of different technologies is similar, (Figure 5.35 and Figure 5.36).

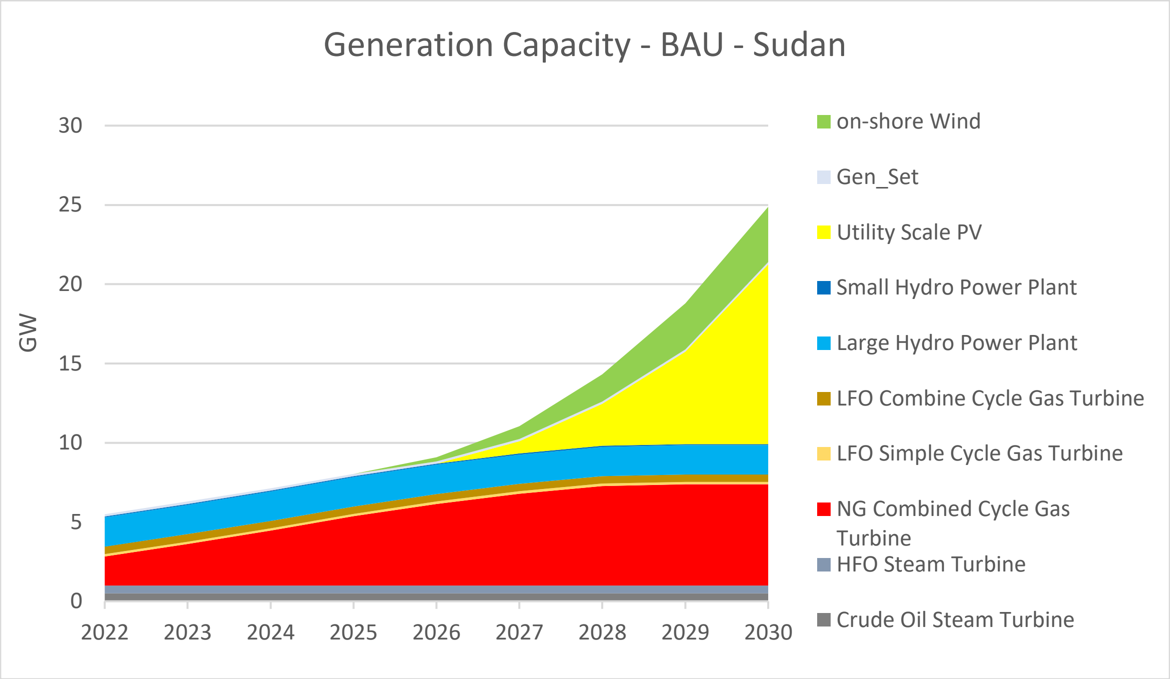


Figure 5.38 - Sudan Total installed capacity, BAU, Hypatia.

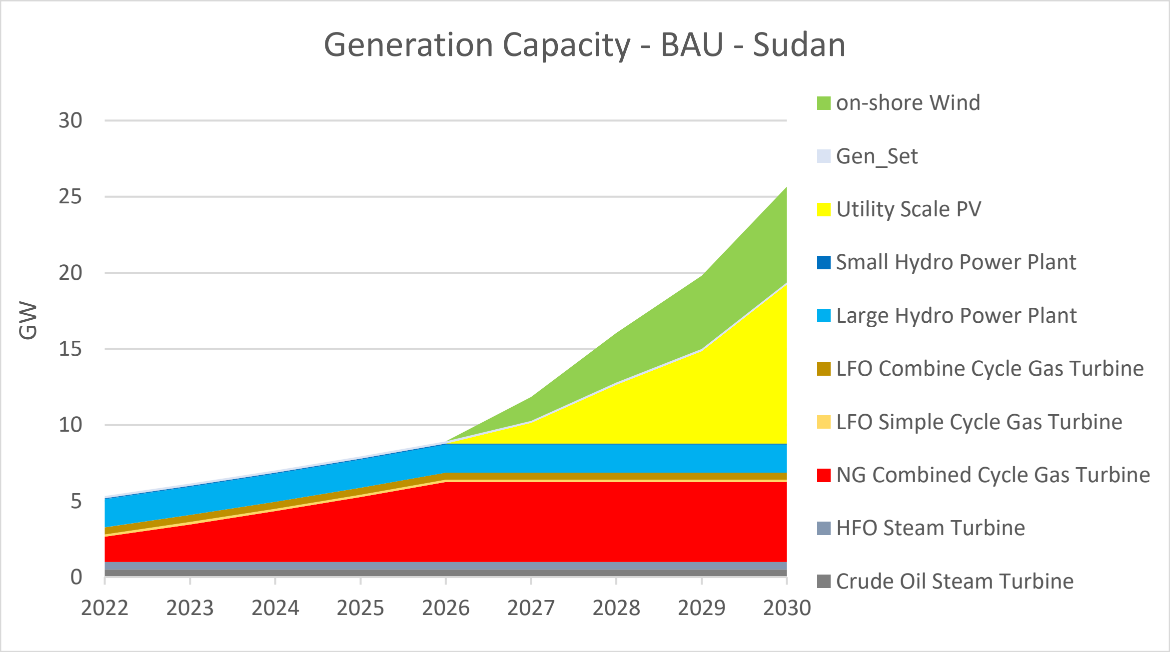


Figure 5.39 - Sudan Total installed capacity, BAU, OSeMOSYS.

The total investment and operation costs in this case are reported below (Figure 5.37) and (Figure 5.38). As expected, the overall cost in Hypatia is higher since OSeMOSYS provides the least cost plan with no regard to transmission costs.

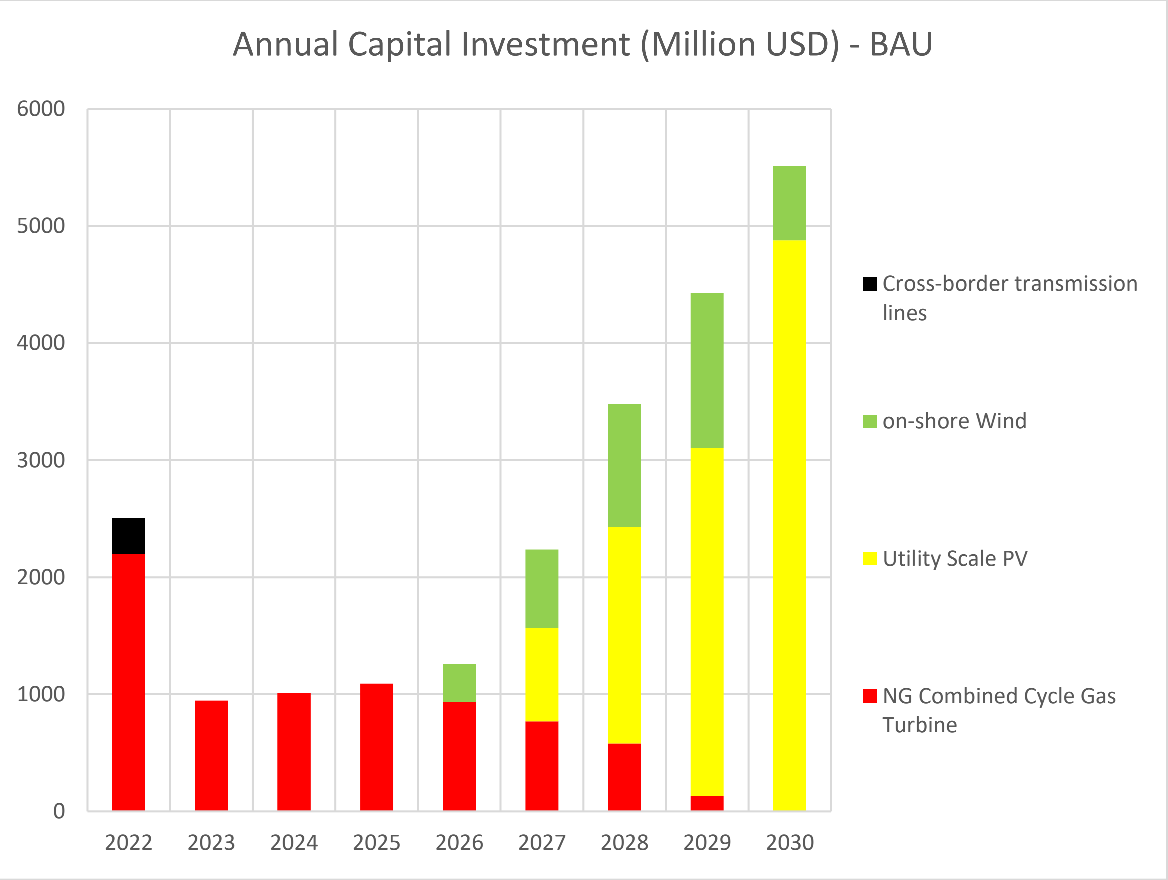


Figure 5.40 - Annual capital investment, BAU, Hypatia.

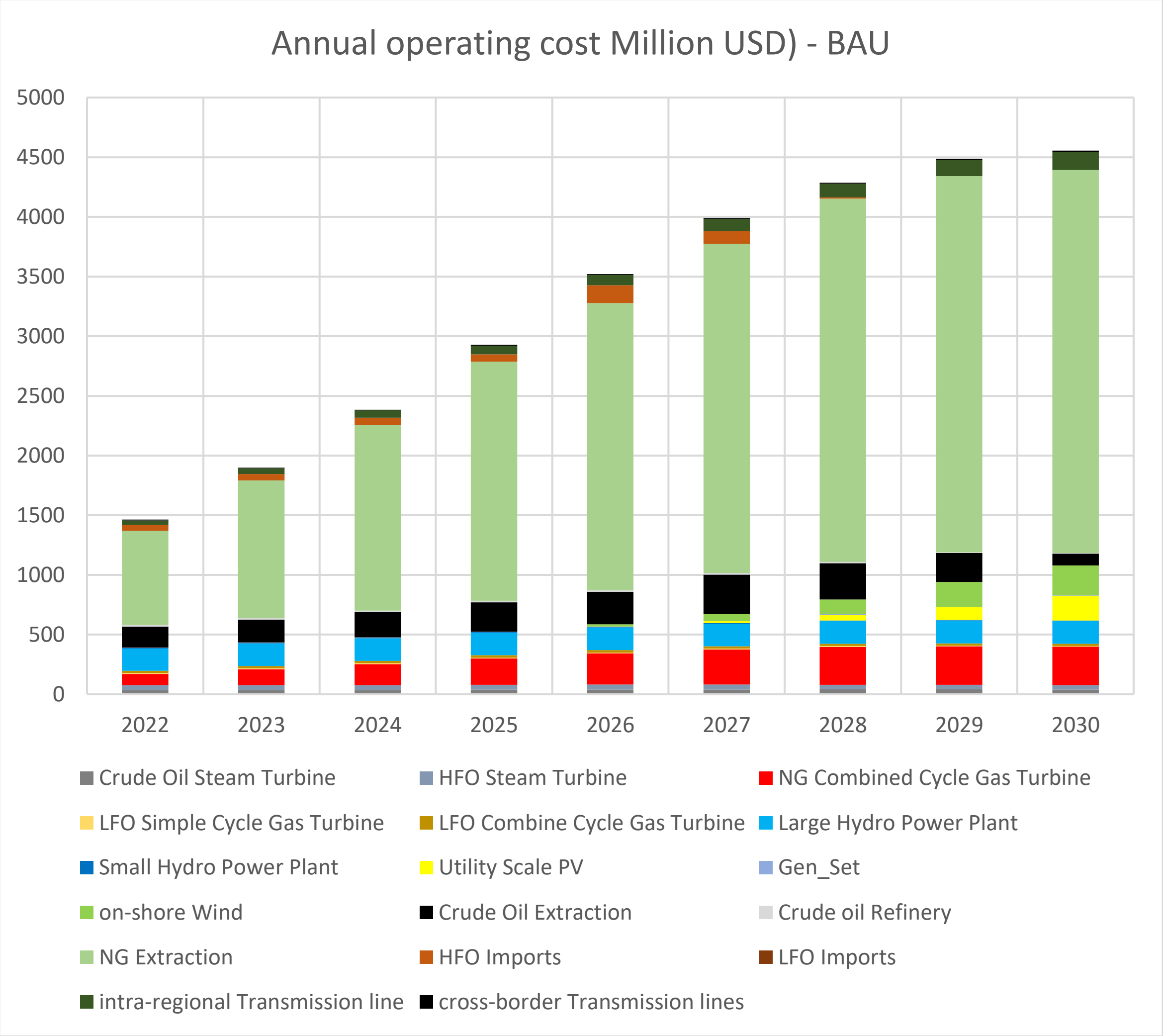


Figure 5.41 - Annual operating cost, BAU, Hypatia.

Figures 5.39 and 5.40 presents the cumulative consumption of fossil fuels in the country toward 2030. Natural gas as anticipated from the results is the most used fuel. Compared to OSeMOSYS fossil fuels are slightly more consumed.

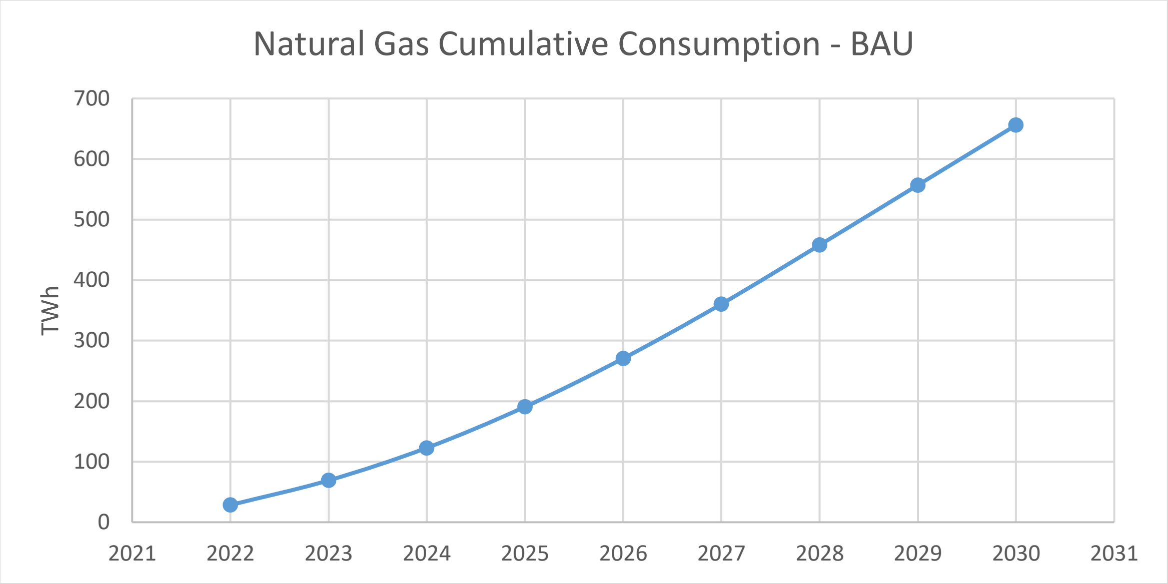


Figure 5.42 - Cumulative Natural gas consumption , BAU, Hypatia.

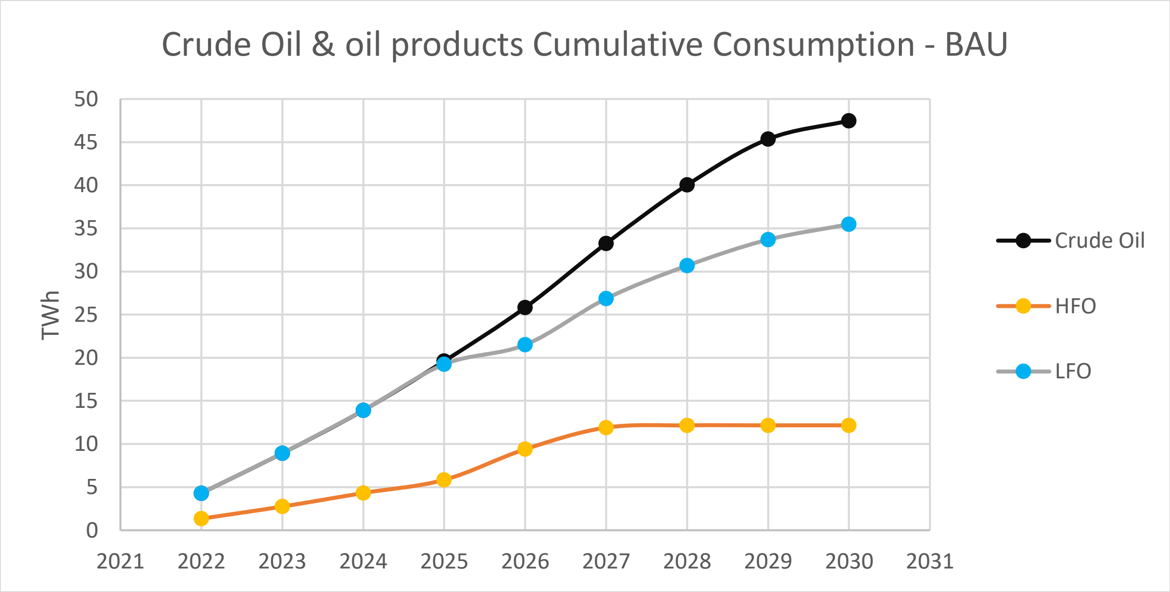


Figure 5.43 - Cumulative Crude oil and Oil products consumption , BAU, Hypatia.

5.1.3 Calliope BAU Results

Among the three used models, Calliope was the only one that converged when solved hourly this is closely but not totally related to the fact that Calliope gives a snapshot of the last year. In any sense, Calliope results allow quantitatively describe how time representation matters when high VRES contribution is sought reported. For the same reason however, plotting the annual progress of outputs is not possible. Still, some useful and insightful results can be analyzed from Calliope Such as:

1- The dispatch of different power plants throughout the year.
2- System balance indicating production/consumption and electricity trade in each region.

To visualize the system balance for the different regions two days from summer (02/06 12:00 – 04/06 12:00) were investigated. The days were chosen from summer since the demand peaks at that time and to be as representative of balance as possible.

Western Sudan

Figure 5.41 presents how the different technologies are dispatched hourly. Geothermal Steam Turbines (GEOST) in a smaller manner and onshore wind turbines function as baseload technologies. Even though wind is an intermittent power production technology its available throughout the year with a capacity factor ranging between (0 - 0.93) and a mean of 0.32 however one statistical value of interest when categorizing wind energy systems is the standard deviation of capacity factor in this case the low standard deviation of 0.2 allowed the wind to dominate the baseload. On the contrary, solar PV systems having higher fluctuations and standard deviation 0.3 acted basically as a peak load technology. We can also see small spikes of NG-CCGT and NG-SCGT to compensate for the low production from VRES specially at nighttime where solar power is not available and wind production falls below the demand. The dispatch of GEOST is also a direct result of the high time resolution because of the at demand dispatchability GEOST is favored

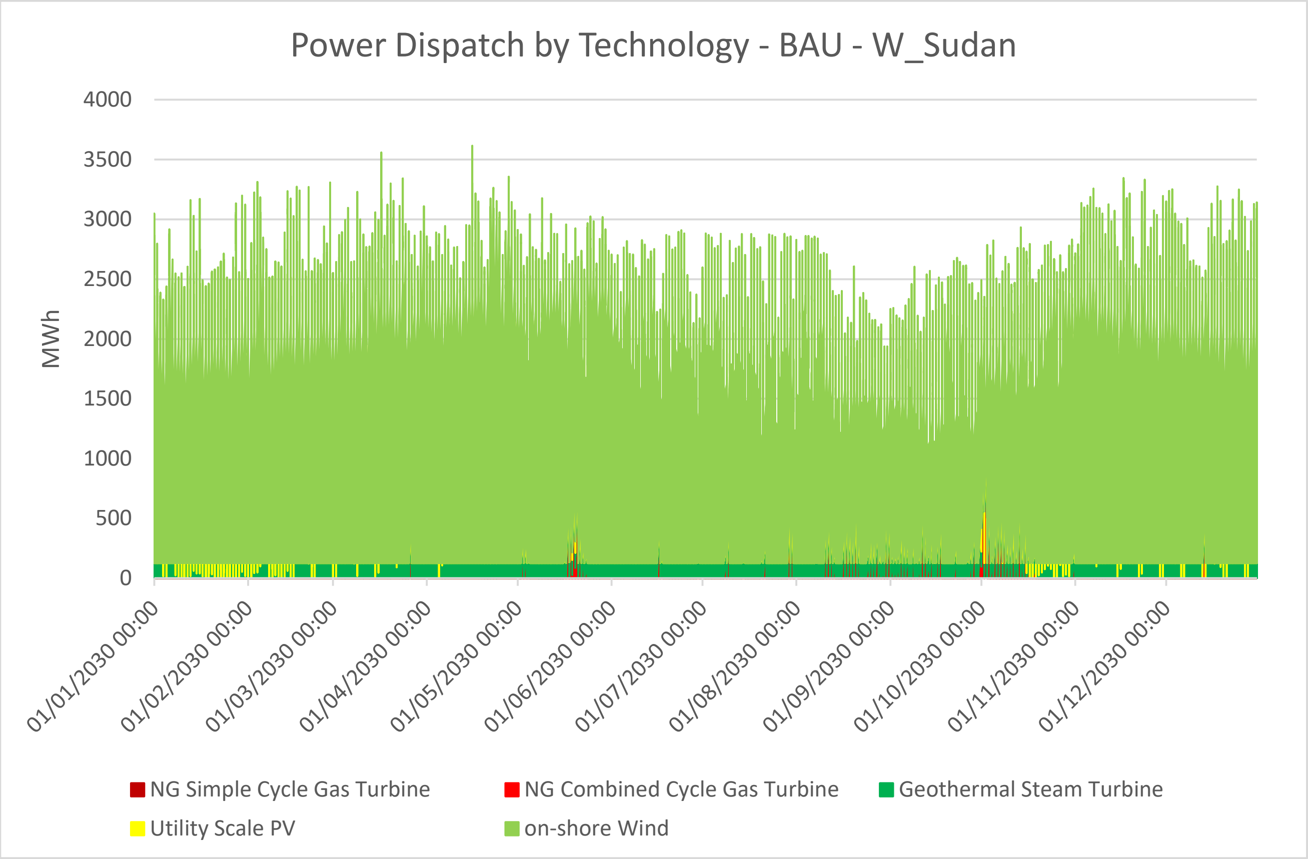


Figure 5.44 - Western Sudan electricity production by technology, BAU, Calliope.

Like Hypatia, Calliope models the transmission lines and integrates them into the objective function therefore, electricity trade is expected to be kept as low as possible. System balance (Figure 5.42) across the western region shows that the region is always importing electricity in the period defined in section 5.1.2, the net electricity trade throughout the year in the region is around 530 GWh of imported electricity which is comparable to the 700 GWh found by Hypatia and significantly lower than OSeMOSYS.

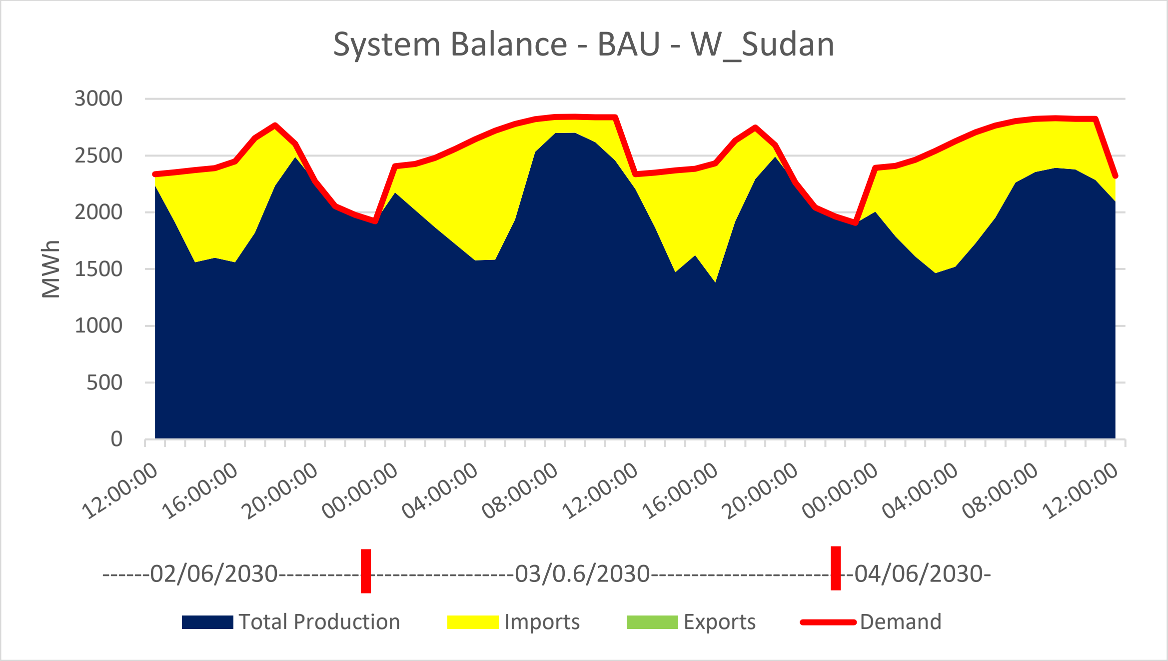


Figure 5.45 - Western Sudan system balance, BAU, Calliope.

Northern Sudan

In the northern region the existing large hydroelectric power plant and wind turbines covers the baseload, meanwhile a higher contribution of solar PV systems is noticeable thanks to the high-capacity factor.

System balance of the region coincides with Hypatia and OSeMOSYS and Hypatia in the essence that the northern region acts as a net exporter of electricity with the yearly magnitude of exports close to Hypatia. Appreciation of the hourly resolution stems as the balance is examined in detail. Clearly, at night times the region stops exporting and the production is equivalent to the local demand.

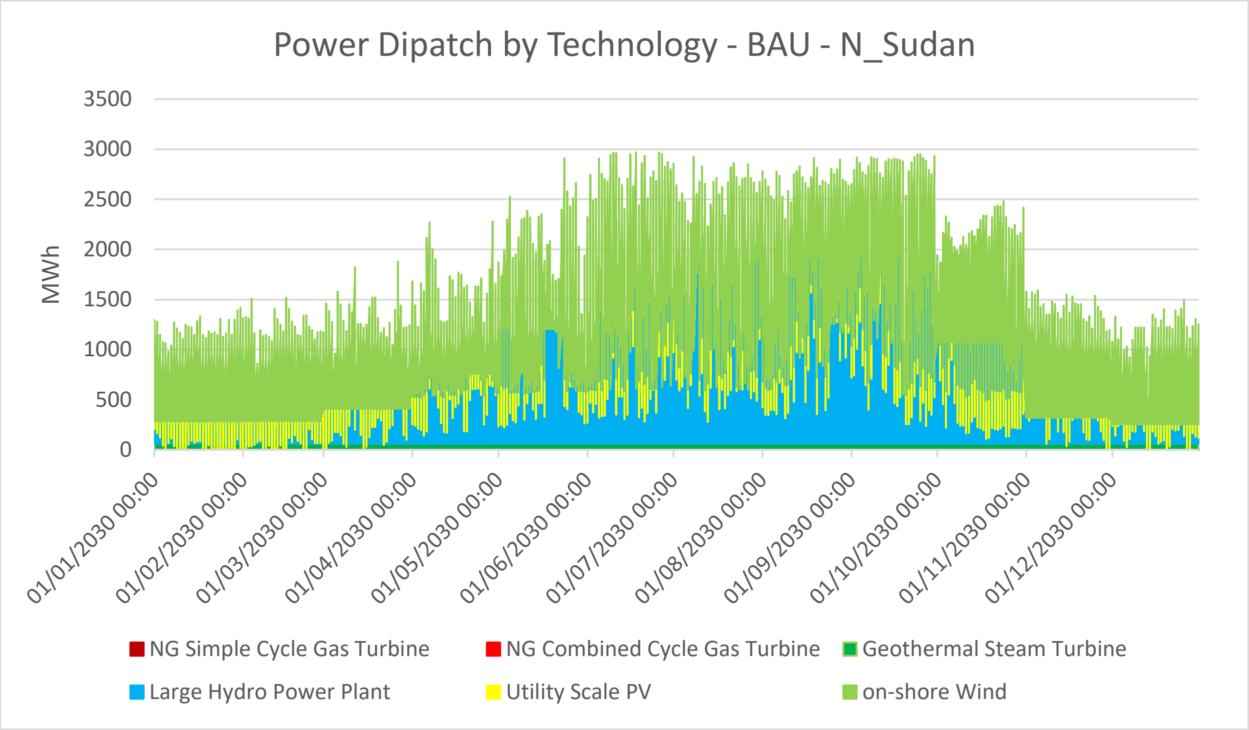


Figure 5.46 - Northern Sudan electricity production by technology, BAU, Calliope.

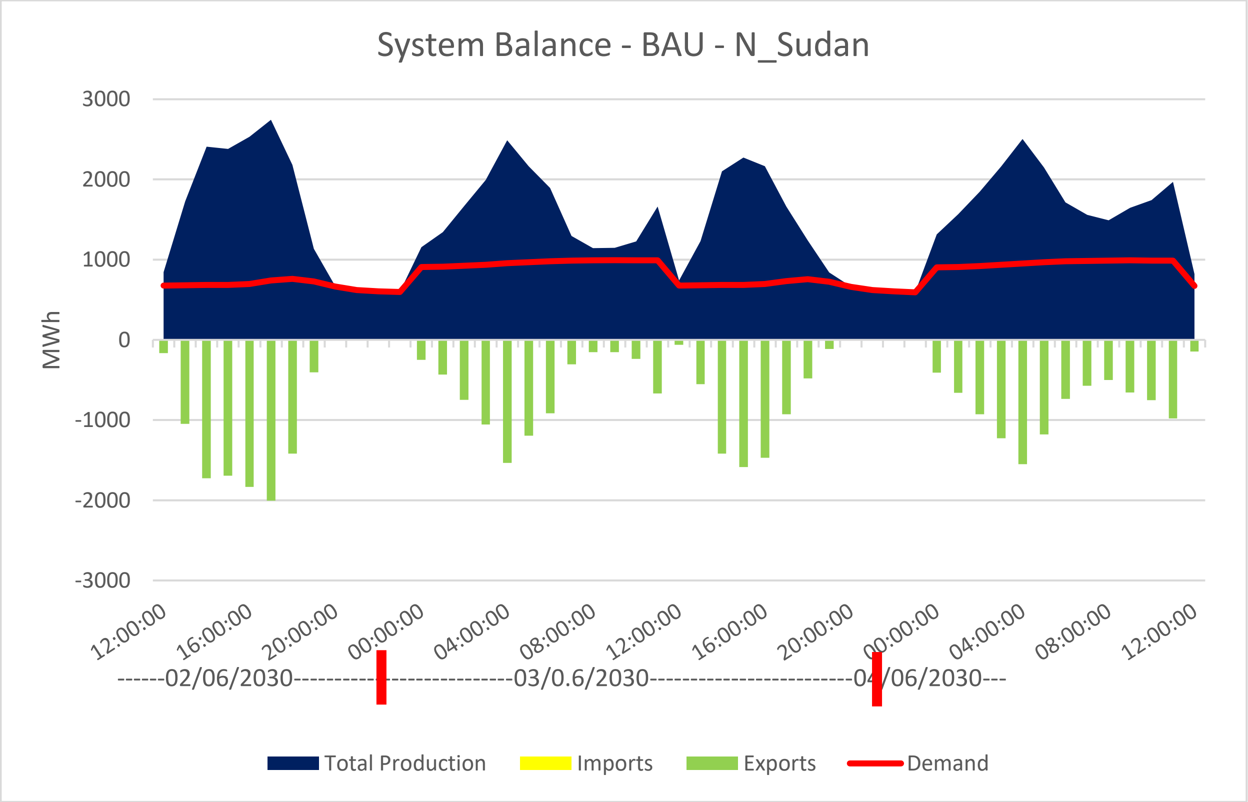


Figure 5.47 - Northern Sudan system balance, BAU, Calliope.

Khartoum

Figure 5.45 elaborates that Wind turbines totally dominate electricity production in Khartoum with a shy contribution of solar and NG-CCGT to fulfill the demand in case of wind energy insufficiency. The high wind potential and capacity factor allowed the wind turbines to exercise such dominance.

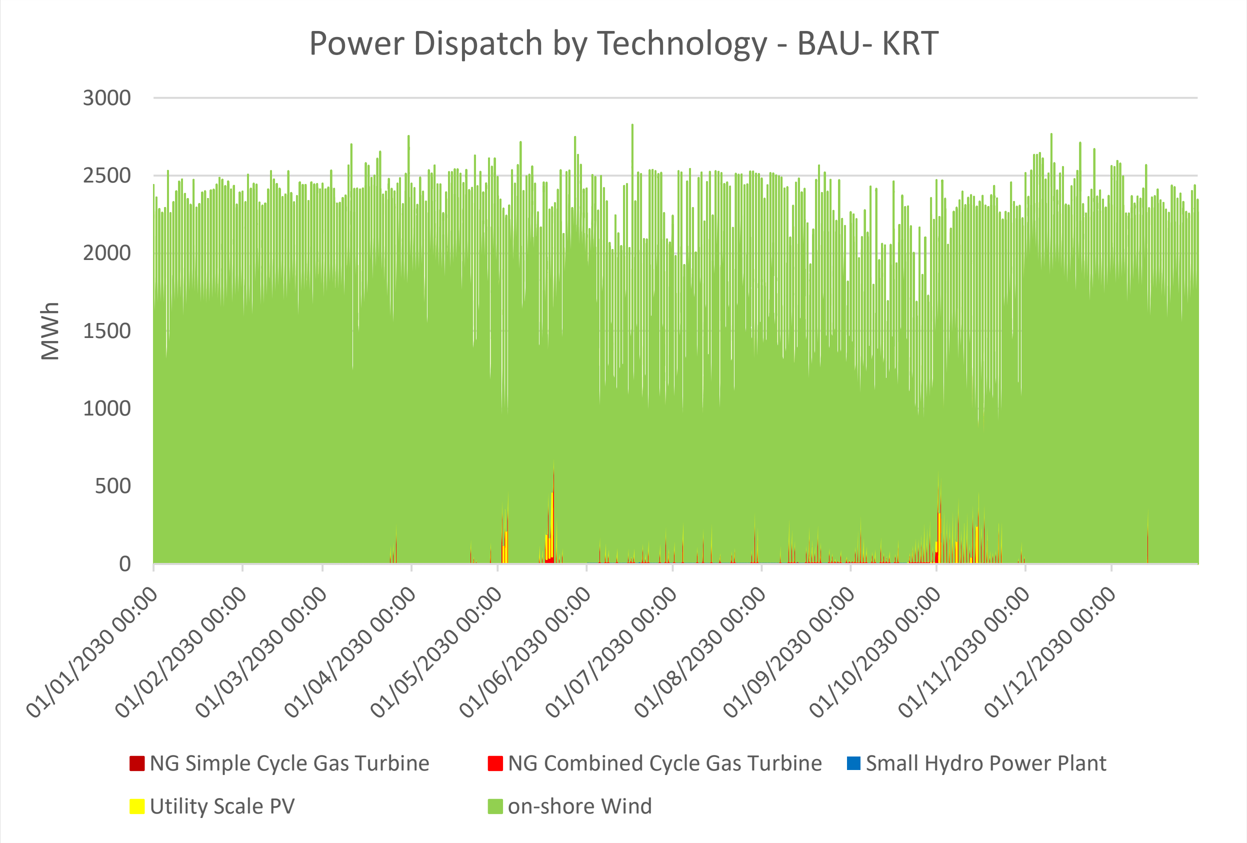


Figure 5.48 - Khartoum electricity production by technology, BAU, Calliope.

The system balance however is different from the other two models. Apparently, Calliope optimization resulted in Khartoum being a net importer throughout the year and even though the importation is as low as 140 GWh per year this interesting result can also be attributed to time slice representation. Where the coarse time resolution in OSeMOSYS and Hypatia resulted in an overestimate of wind turbines capacity in Khartoum where wind capacity factor is high that allowed Khartoum to export the cheap wind energy to the other regions. Simply Calliope is stating that even though production from wind turbines in Khartoum is the cheapest technology it is still not cheaper than producing locally in other regions avoiding the transmission lines cost.

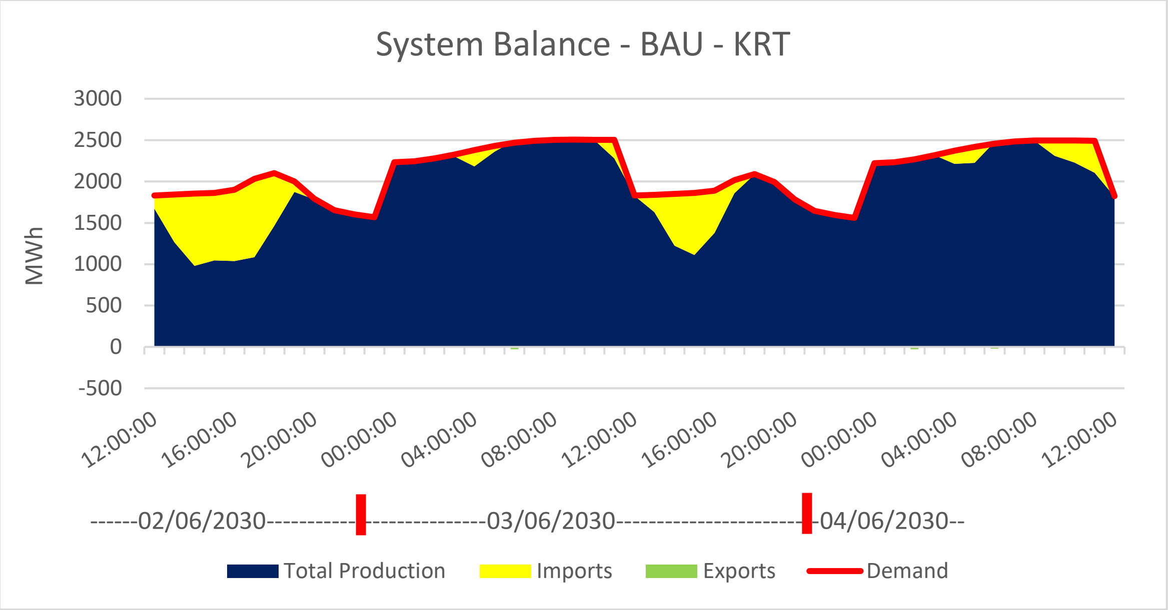


Figure 5.49 - Khartoum system balance, BAU, Calliope.

Eastern Sudan

Electricity production profile in Eastern Sudan shows a similar trend to the other regions where wind again has the highest share in the mix. Solar PV and NG-CCGT technologies also serve to compensate for the low wind generation specifically during the summer season.

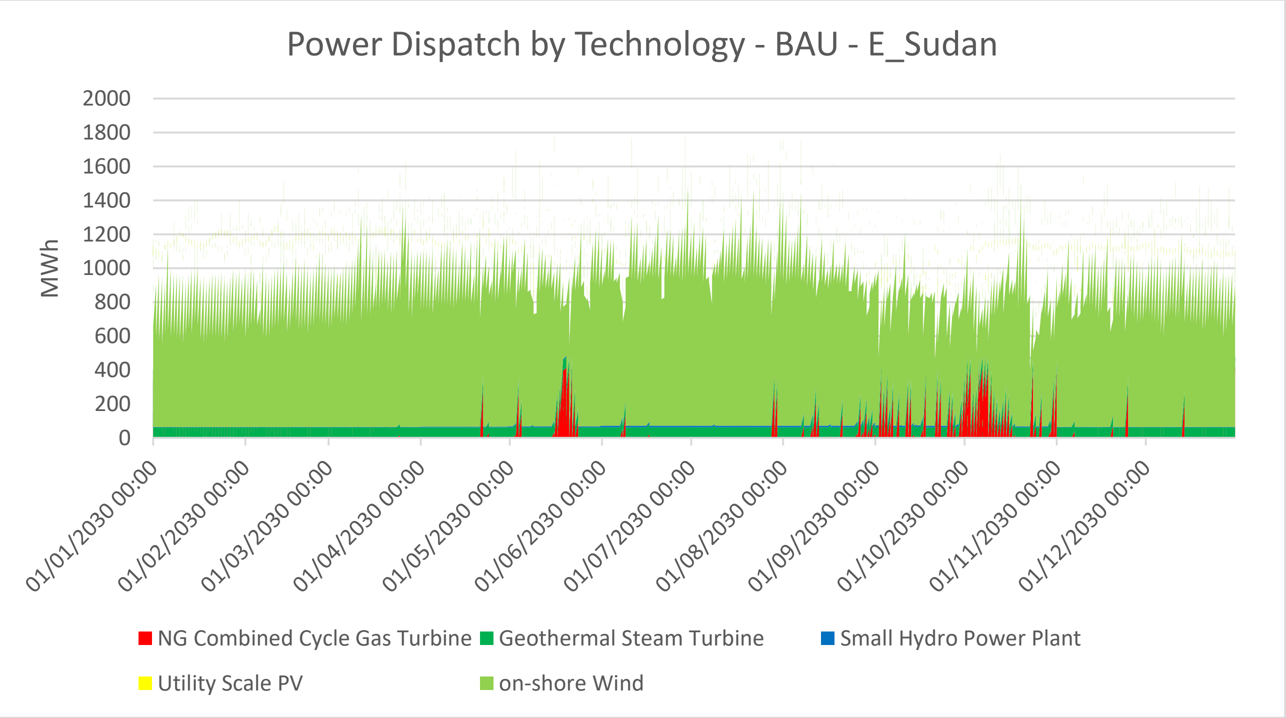


Figure 5.50 - Eastern Sudan electricity production by technology, BAU, Calliope.

The system balance shows that the region is a net exporter of electricity throughout the year except for the summer period (Figure 5.48) where both wind and solar energy production drop. The interaction of the region with other regions has a high frequency though due to the intermittent nature of wind turbines.

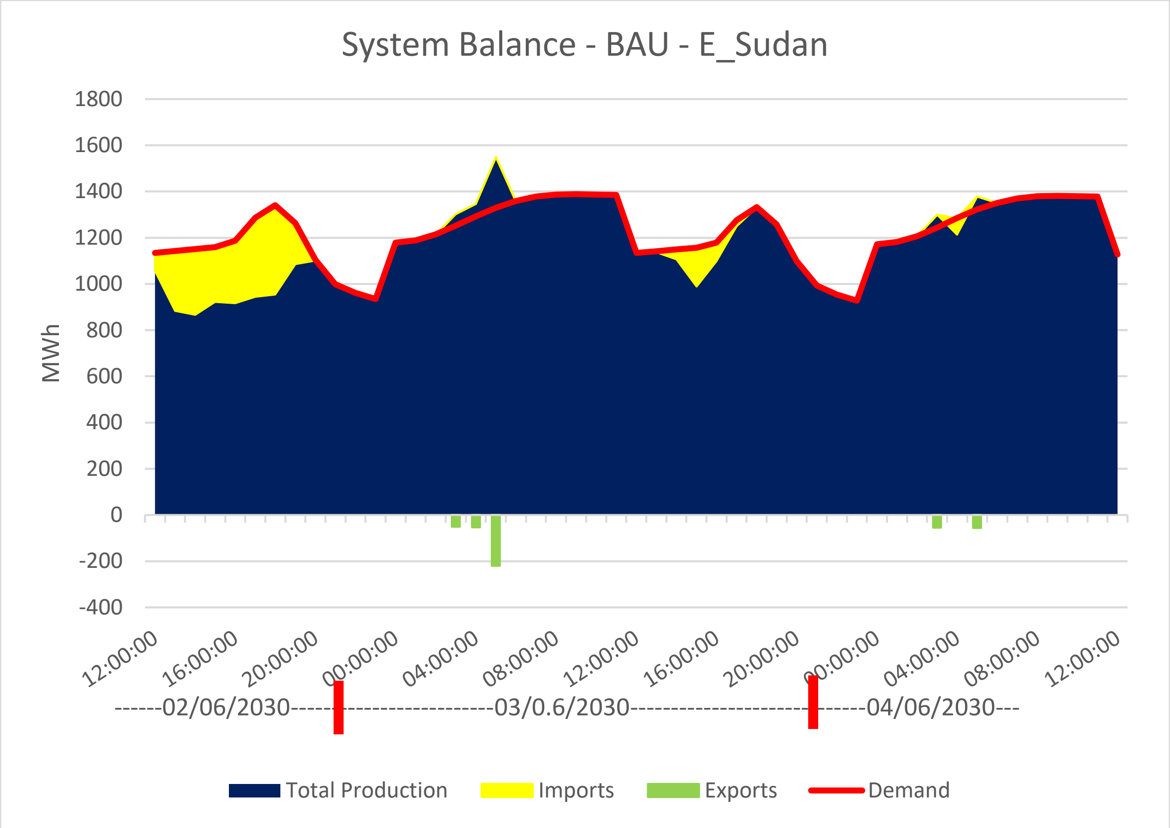


Figure 5.51 - Eastern Sudan system balance, BAU, Calliope.

Central Sudan

In the central region the existing and expanded large hydroelectric power plants provides the baseload. They are fully dispatched utilizing all the available capacity. In summer, the electricity production from hydro peaks as the capacity factor highly increases. Wind turbines in this region has the second largest contribution followed by NG-CCGT and solar PV that provides peak balancing.

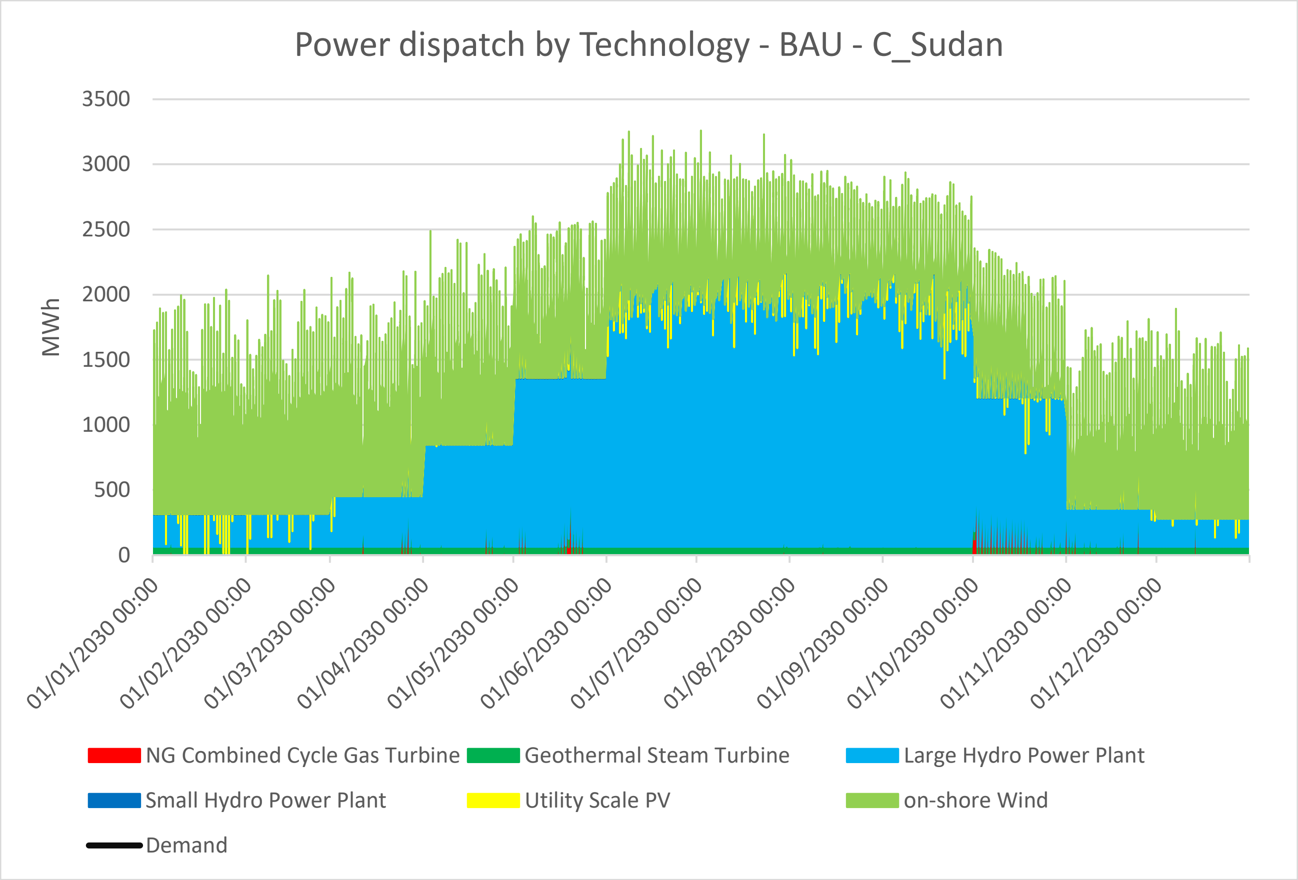


Figure 5.52 - Central Sudan electricity production by technology, BAU, Calliope.

The overall system balance of the region shows that it is a net importer of electricity. Except for the summer period (Figure 5.50) where hydroelectric production is peaking the region is forced to import electricity to meet the local demand.

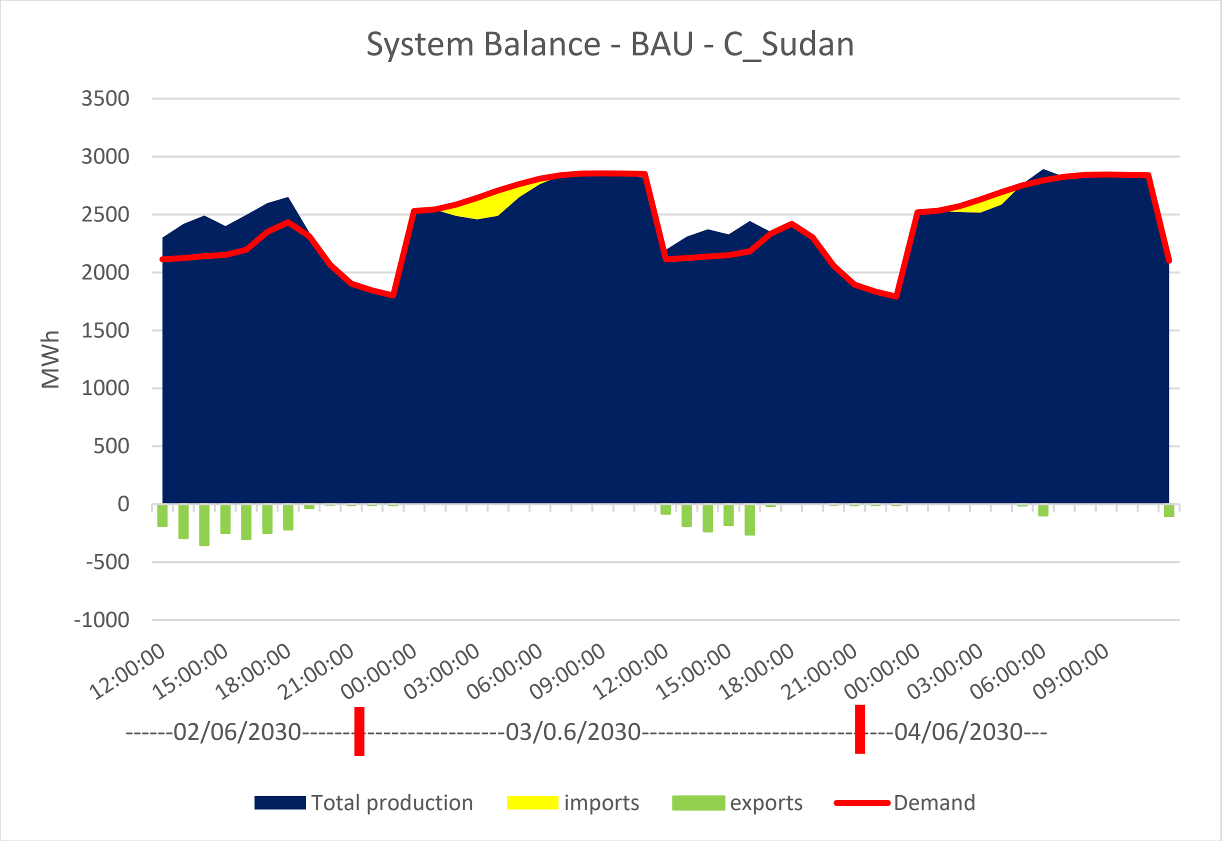


Figure 5.53 - Central Sudan system balance, BAU, Calliope.

In General, the main differences of Calliope and Hypatia are related to the time representation; this explains why Hypatia promotes wind rather than Solar PV. In addition, dispatchable technologies such as GEOST are utilized wherever they are available. One can say that Calliope deals better with the unreliability issue associated with renewables and implicitly defines this risk as a cost. It also further hinders the transmission of power between regions because seasonal representation of VRES results in an underestimate of their LCOE. Moreover, the snapshot logic of Calliope means that unlike the other two models the path toward the final year mix is unforeseeable. Losing this dynamic property might also affect the outcomes of the model especially when the demand is rapidly changing from year to year and the system parameters (i.e., capital costs, fuel costs, etc.…) are fluctuating. For example, in the Sudan described in this study the total demand of the country is enormously growing starting from 2022. Simultaneously in the first years 2020-2026 fossil fuel-based technologies have a lower LCOE. This means that in order to meet the growing demand installation of large fossil fuel-based power plants happens in the early times however as the system approaches the later years it would be unfeasible to decommission the installed plants. Alternatively, both OSeMOSYS and Hypatia show that they will continue being used toward the last modelled year.

Figures 5.51 and 5.52 show a breakdown of the investment costs and operational costs in 2030. Most of the investment is devoted to the building of wind power plants. Like Hypatia expanding the power network is not considered a smart investment and rather self-sufficient regions are promoted. The operating costs are mainly associated with NG-CCGT primarily for fuel extraction followed by the O&M costs of wind turbines.

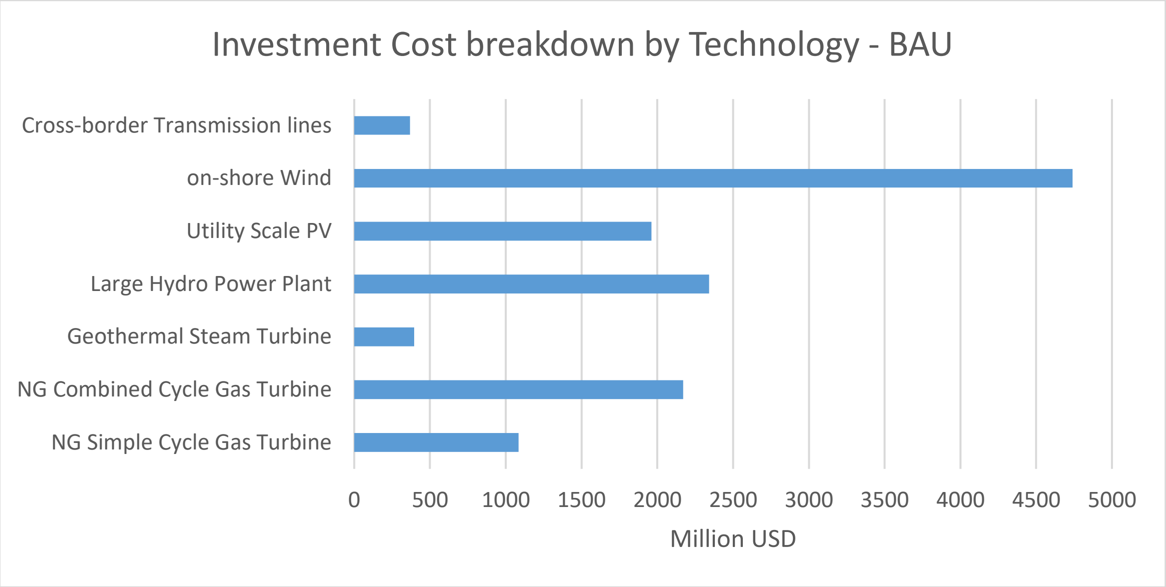


Figure 5.54 - Investment cost by technology, BAU, Calliope.

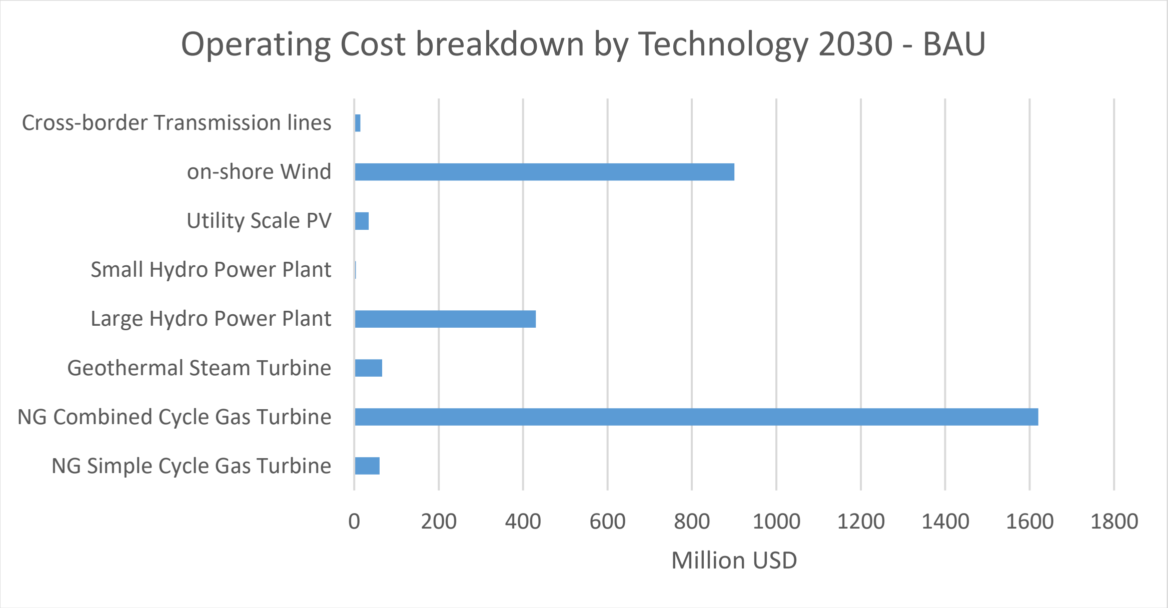


Figure 5.55 - Operating costs by technology, BAU, Calliope.

5.1.4 Models Comparison

The main objective of this study is to compare and contrast the different used energy models. While presenting the results obtained for the BAU scenario from the different models an active comparison between the results was conducted highlighting the differences and explaining their possible causes linked to model structure. In this section a formal comparison is performed using a unified approach by presenting the results listed in the introduction of chapter Five to solidify, examine and conclude the discrepancies between the different models observed and discussed in sections 5.1.1 to 5.1.3.

The most important outcome of planning mode for energy systems optimization models is the installed capacity. It is the desired end answering the question of how to practically apply a suggested energy policy. Comparing the total generation capacity in 2030 of the different models gives an insight of how different models present different results to apply the same policy (i.e., universal electricity access) for the same scenario (BAU) described in the same manner. Figure 5.53 shows the total installed capacity by technology in the five regions for the BAU scenario in 2030 for the different frameworks (only technologies with a capacity higher than 500 MW are taken into account).

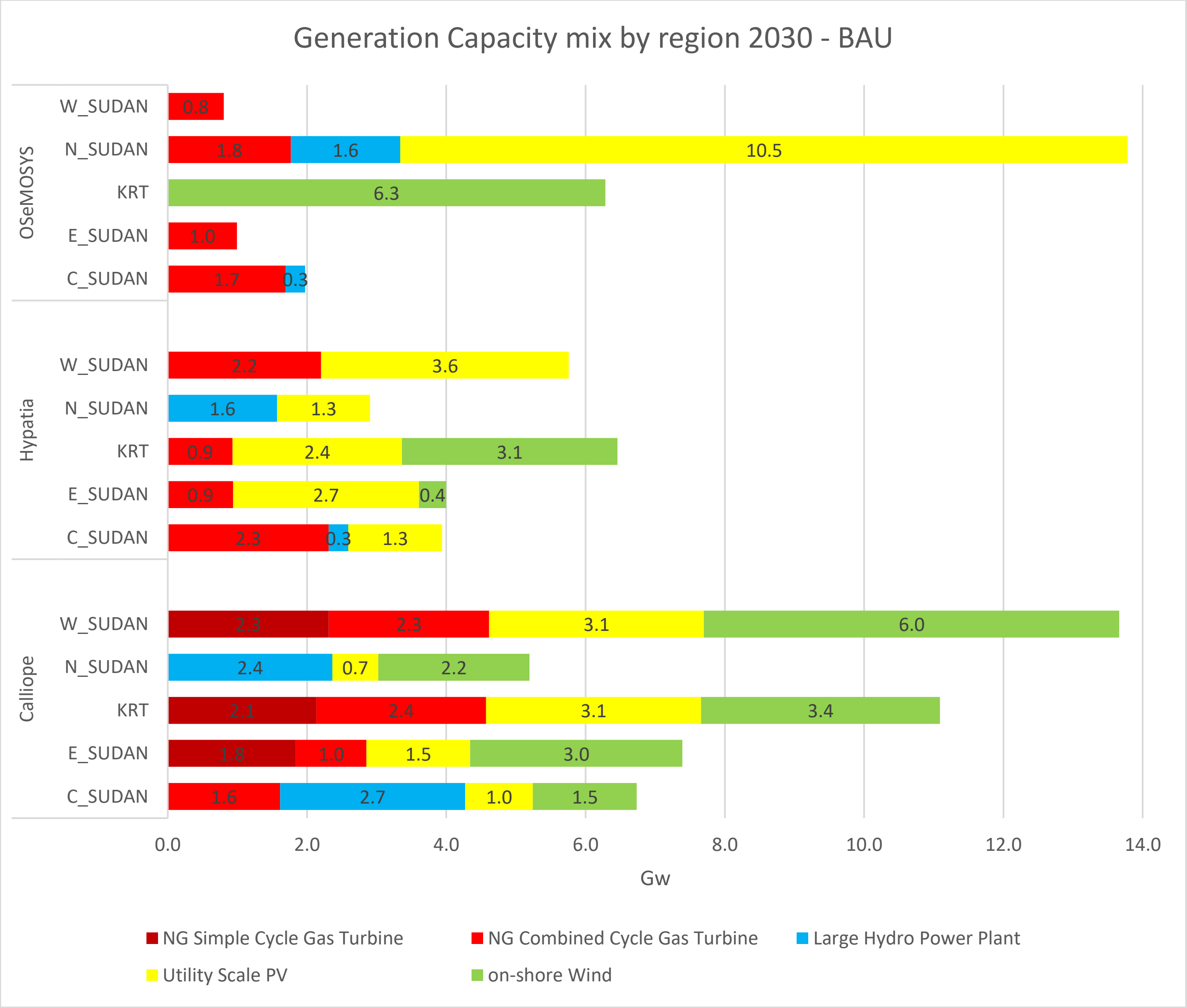


Figure 5.56 - Comparison of generation capacity (GW) by region in 2030 - BAU.

At the first glance the results appear as if different scenarios with different parameters were investigated because of the huge discrepancy between them. Nevertheless, a deeper look enables us to notice common patterns and in fact meets the expectations we had.

The first clear difference is how OSeMOSYS, unlike the two other models, promoted installation of capacity in certain regions rather than having a distributed production. Simply, the overlooking of transmission grid expansion costs promoted production where production costs are lower. Starting from 2026 the spatially variable solar PV and wind turbines becomes the most feasible technologies thanks to their falling capital cost and due to their enormous potential, all over the country; production occurs only where they have the highest capacity factor (i.e., solar PV in the north and wind turbines in Khartoum). In reality, considering transmission network expansion is of essential concern for a least cost plan hence, one might argue that the absence of a forward way to model transmission lines in OSeMOSYS not only affect the results but also decrease the value of multi-nodal approach toward modelling especially when electricity access is studied.

Secondly, Calliope appears to install much more capacity in total than the other two models. In fact, the installed capacity is roughly twice the total capacity of Hypatia and OSeMOSYS. In general, two explanations setting from different reasons might be argued. The obvious one is related to the technologies installed and their corresponding capacity factor. For instance, installation of VRES always involves higher installed capacity since a higher generation capacity is required to produce the same amount of electricity due to their significantly low-capacity factor compared to conventional power plants. Reflecting this to the obtained results shows a small relevance in fact Figure 5.54 shows that the combined share of solar PV and wind turbines (the two VRES) in the capacity mix is close ranging between 58% in Calliope to 70% in Hypatia therefore its less likely for the huge difference in total installed capacity to be related to this.

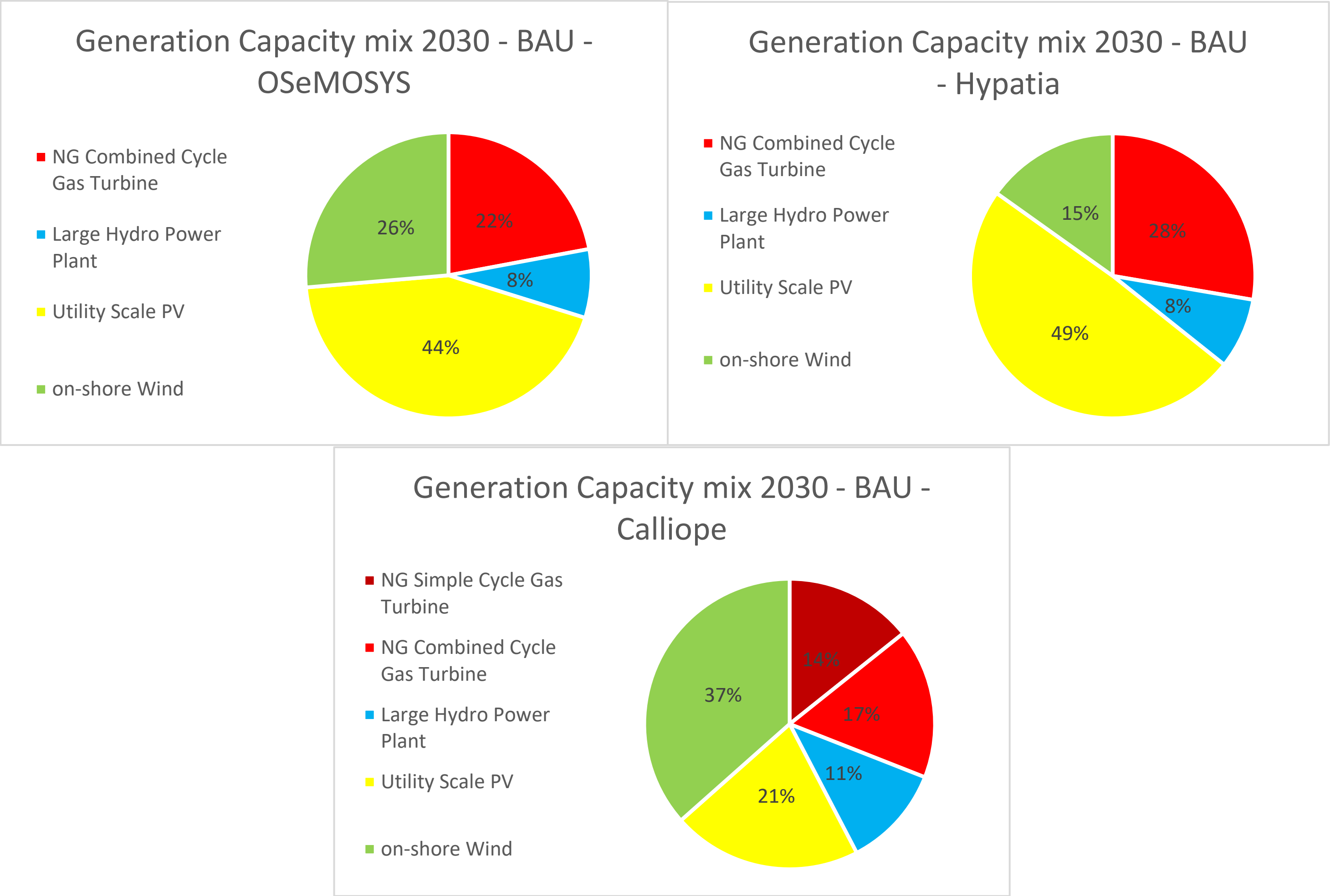


Figure 5.57 - Comparison of generation capacity mix in 2030 - BAU.

The second explanation of the discrepancy in total capacity is linked to two main features of Calliope: the hourly time representation and the snapshot logic it follows. Recalling the power dispatch by technology in Khartoum (section 5.1.3), NG-CCGT and NG-SCGT appeared as spikes to fulfill the demand when wind energy fills short of providing the total demand. This was common among the different regions. The dynamic behind this is related to the hourly detailed profile of wind and solar PV capacity factor. So even though they are the most feasible, at some hours their production is not enough to satisfy the demand, in those cases natural gas technologies have to compensate for the missing demand therefore a huge capacity of the fossil fuel-based technologies is deployed. Figure 5.55, however, shows that regardless of the huge installed capacity of NG-SCGT in Khartoum amounting to 2.1 GW it is rarely dispatched. This means that a huge capacity is added with very low penetration which curtails the capacity when Calliope is used. One might expect that since

NG-SCGT and NG-CCGT are dispatchable at desire, they must have been set as baseload technologies (i.e., to be dispatched always) while solar and wind covers the unmet demand to reduce the total installed capacity. However, since Calliope performs the optimization hourly (the snapchat logic) this is not possible because whenever the less-expensive VRES are available the demand will be met by them. In conclusion, the hourly time representation of Calliope forces new technologies to be installed while the snapchat logic does not allow them to be configured as baseloads. Resulting in a much higher capacity.

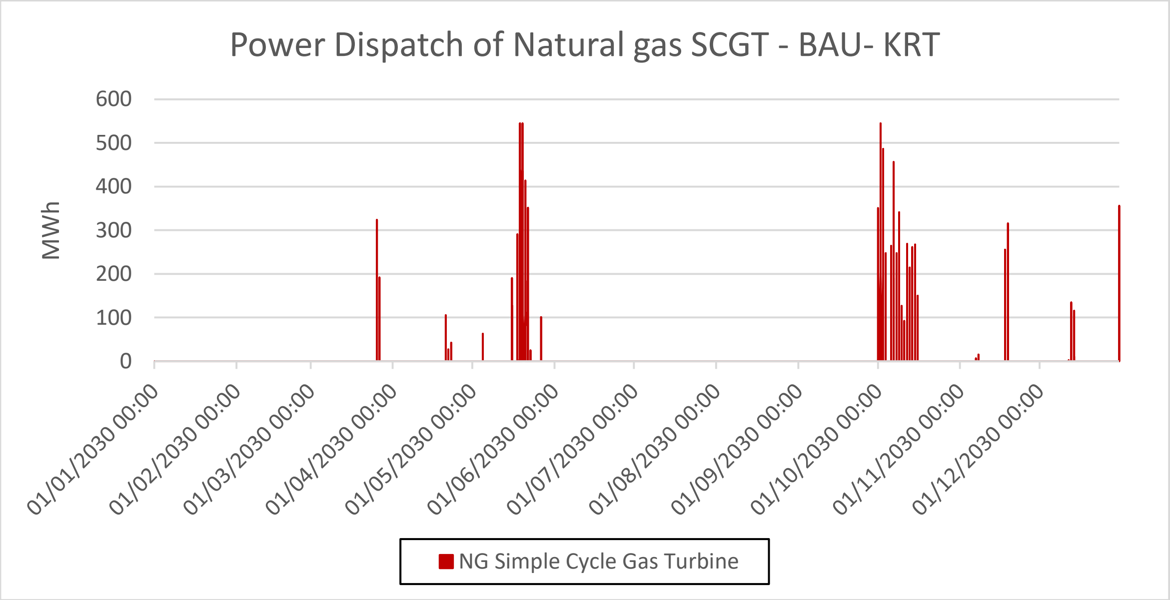


Figure 5.58 - Electricity production by Natural gas based simple cycle gas turbine in Khartoum, Calliope

Thirdly, a noticeable difference is the fact that wind energy is present in all of the regions in Calliope compared to Hypatia where solar PV is the technology available in all regions. Regardless of the fact that both models have the ability to model transmission lines and therefore production is regionally distributed, the role of PV and wind appear to be interchanged between the models. This is again regarded as the difference in time resolution. In Hypatia, the coarse representation of time and usage of average capacity factors over-estimated the availability of solar PV. Meanwhile, in Calliope, even though solar PV is still cheaper, at night and early morning its absence highly affects the results. Again, this explains why the small geothermal potential is fully exploited and hydro generation is expanded in Calliope results. Dealing with the reliability issue of VRES is of at most importance when modelling a system with high renewable energy penetration the time-resolution is therefore as suggested in most of literature is of particular interest in future energy projects.

Figure 5.56 shows the electricity production mix in 2030 which strengthens the conclusions reached. We can see that regardless of the high installed capacity of NG-SCGT in Calliope its total contribution is insignificant also, NG-CCGT technologies contribution is as low as 3%. On the other hand, in OSeMOSYS and Hypatia the contribution of NG-CCGT is high utilizing all of their installed capacity. Wind energy share in OSeMOSYS is higher than Hypatia thanks to the free of transmission charge wind production in the north.

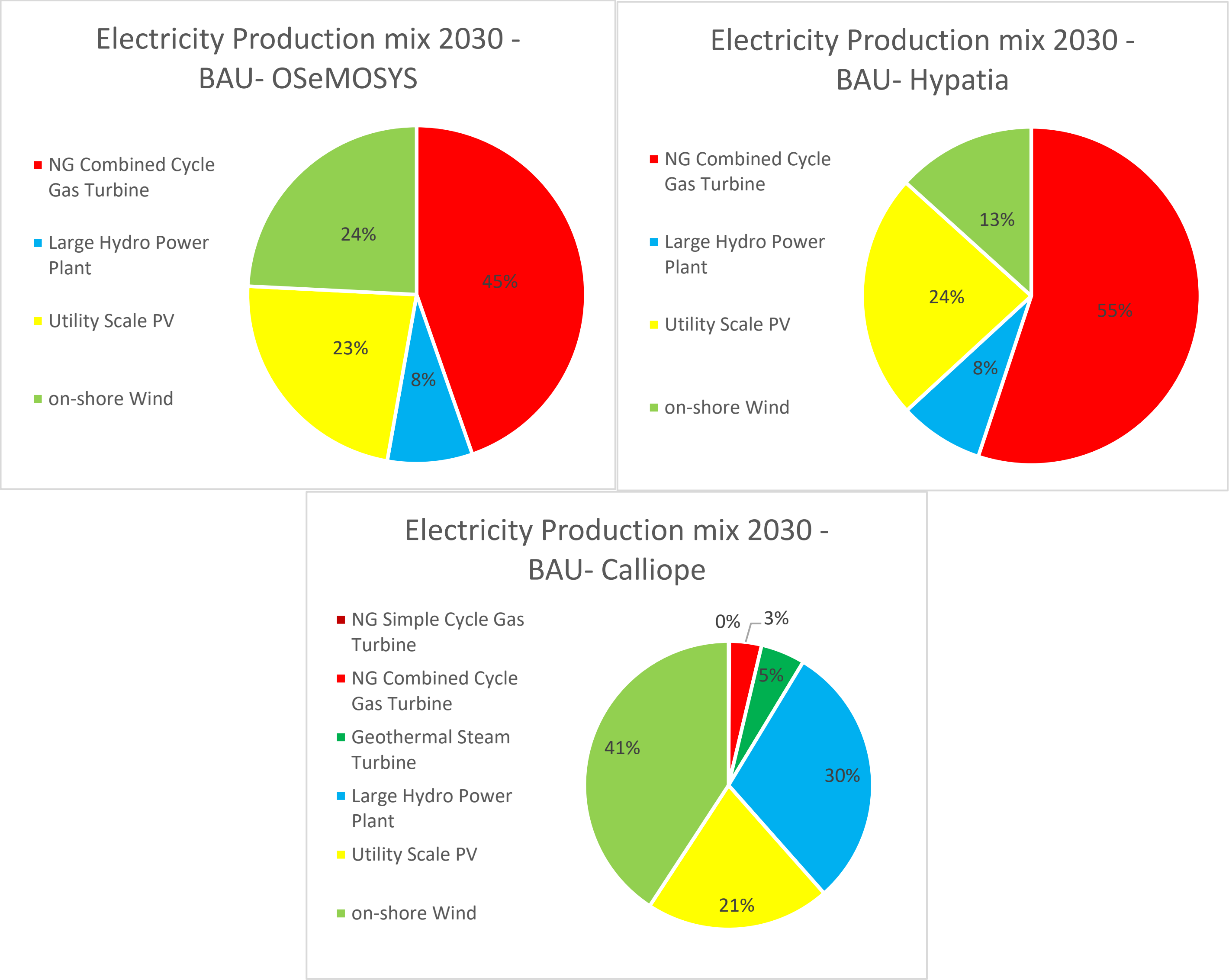


Figure 5.59 - Comparison of electricity production mix in 2030 - BAU.

5.2 Free Trade Scenario

As defined in section 4.7.2 this Scenario Explores the possibility of importing electricity from both Ethipoia and Egypt. The outcomes in this case differ significantly. In this section, instead of presenting the results for each region for the different modelling tools only the results of the entire country are presented. In the last section again the different results of the different models are compared to notice if the same conclusions reached can be duplicated.

5.2.1 OSeMOSYS Free Trade Results

Figure 5.57 shows how the capacity is not expanded at all throughout the years to meet the continuously growing demand. This implies that the total growing demand is being met by the unbounded imports from neighbors. In Fact, Figure 5.58 Shows that not only capacity was not expanded but also all of the fossil fuel-based technologies were not used to produce electricity and the total demand in all of the regions was being fed either by the existing Hydroelectric power plants or the Ethiopian imports in particular ruling out every other technology. This can be seen under the light of OSeMOSYS's characteristics as a very explainable solution because of the relatively cheap electricity price in Ethiopia and the neglect of the transmission lines modelling.

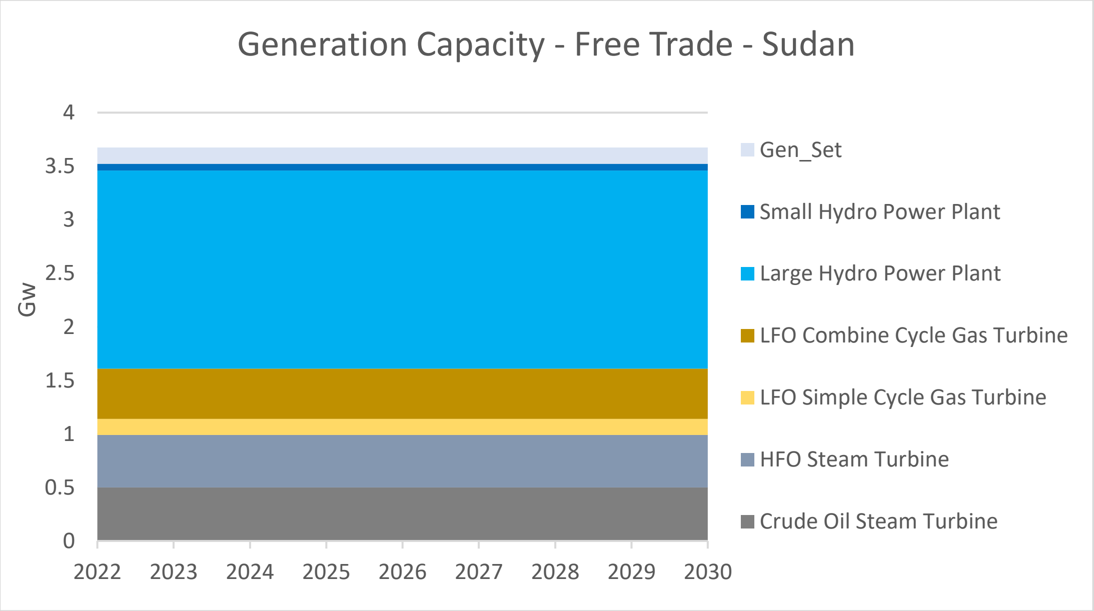


Figure 5.60 - Sudan generation capacity outlook, Free Trade, OSeMOSYS.

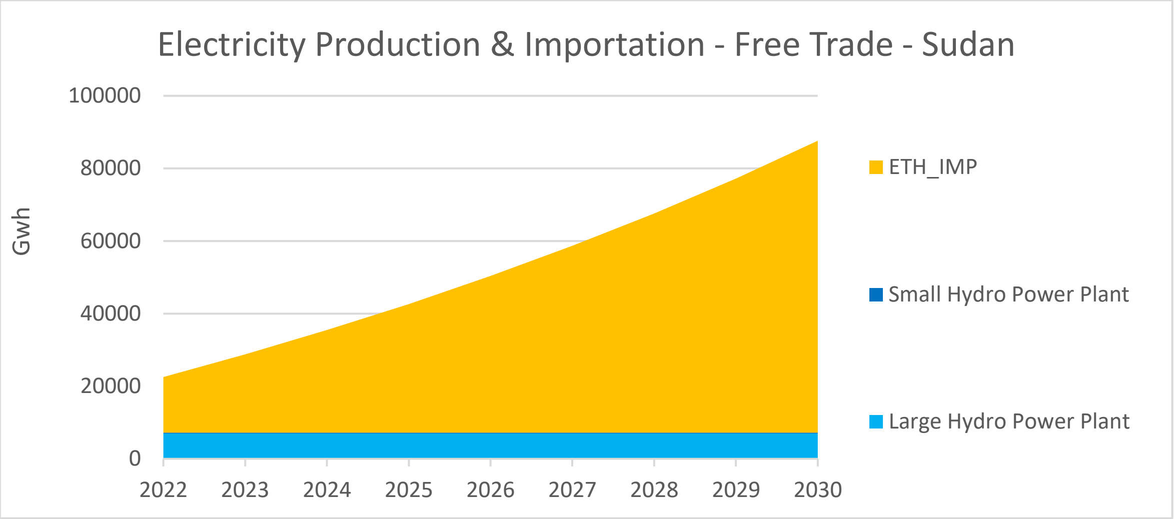


Figure 5.58 - Sudan Electricity supply outlook, Free Trade, OSeMOSYS.

Consequently, OSeMOSYS results show no consumption of fossil fuels whatsoever. Also, due to the absence of capacity expansion actions no investment costs were added. The annual operating costs as expected shows that most of the cost is devoted to buying electricity from Ethiopia amounting to a total of 7.7 billion USD throughout the nine years span. The other costs were divided between the generation plants mainly for the active hydroelectric plants and the fixed O&M costs for the thermal power plants.

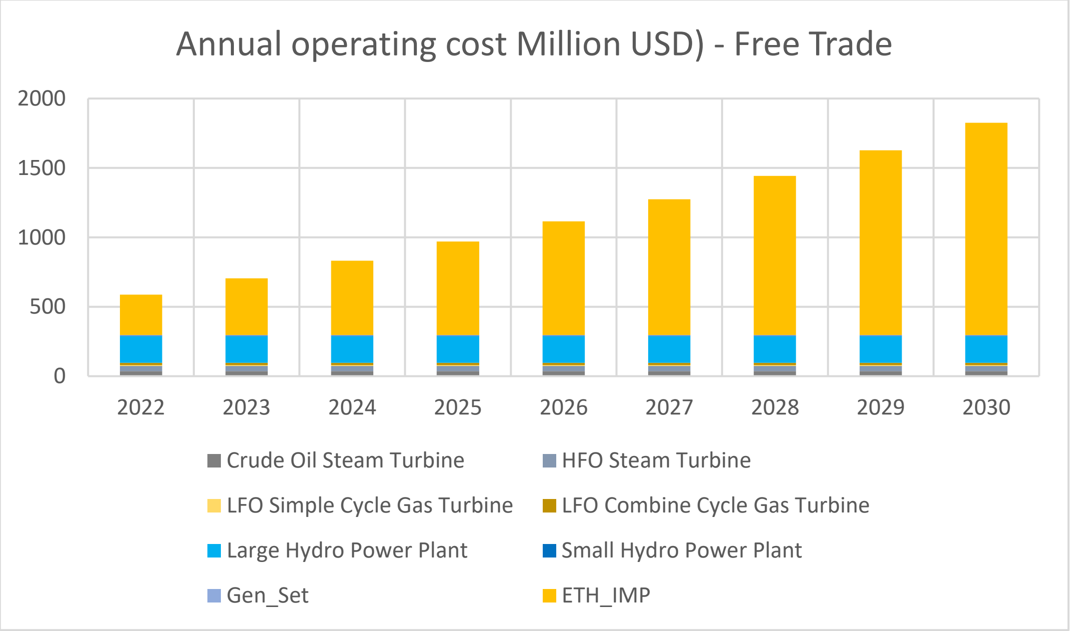


Figure 5.59 - Annual operating cost, Free Trade, OSeMOSYS.

5.2.2 Hypatia Free Trade Results

The capacity expansion across the country (Figure 5.60) unlike OSeMOSYS shows a growth in capacity starting from 2023 using NG-CCGT to supply for the demand specially in the western region. The capacity keeps growing although relatively slow merely by deploying NG_CCGT plants up to 2027. After which, utility scale PV and wind turbines are used. The growth in capacity is happening in all of the regions except the eastern region that is connected to Ethiopia.

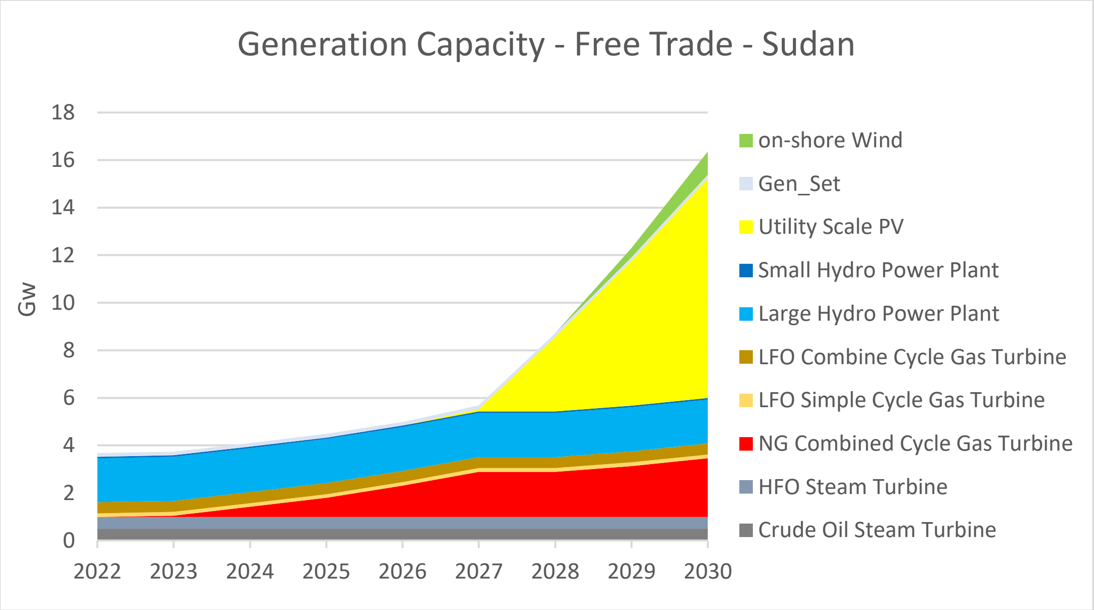


Figure 5.60 - Sudan generation capacity outlook, Free Trade, Hypatia.

The electricity supply again shows a high amount of electricity imports from Ethiopia however, we see the small contribution of the existing thermal power plants and the newly added technologies.

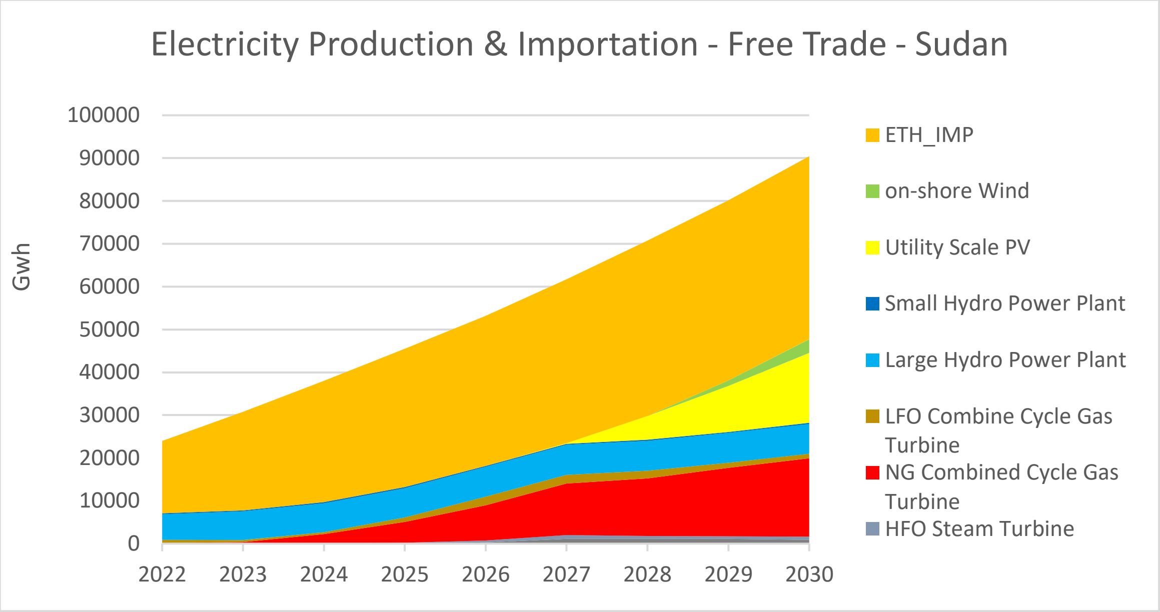


Figure 5.61 - Sudan electricity production outlook, Free Trade, OSeMOSYS.

Fossil fuels consumption (Figures 5.62 and 5.63) Shows that relatively low amounts of fossil fuels are consumed to fire the thermal power plants.

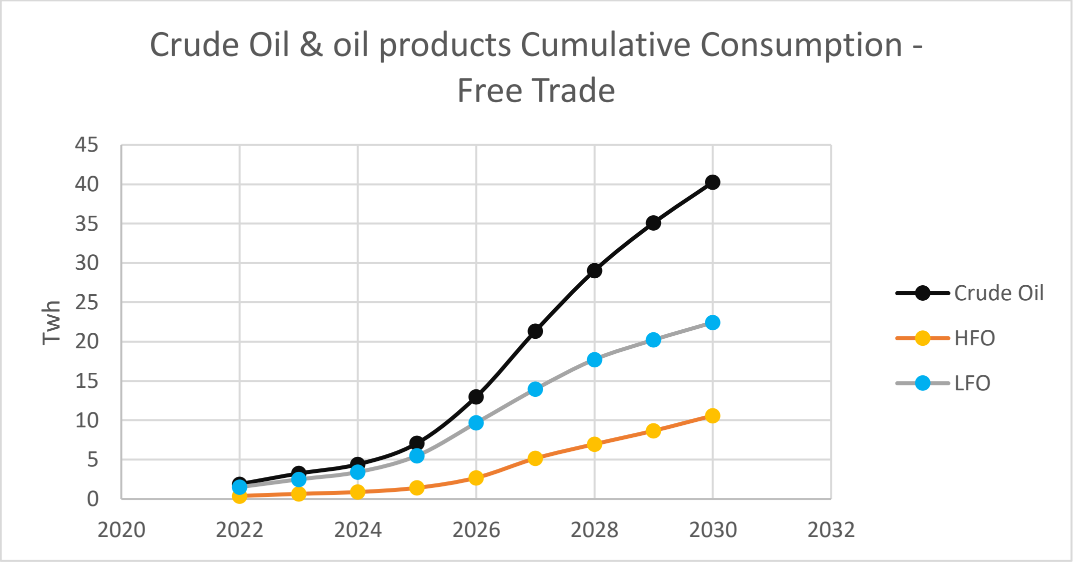


Figure 5.62 - Cumulative Crude oil and oil products consumption, Free Trade, Hypatia.

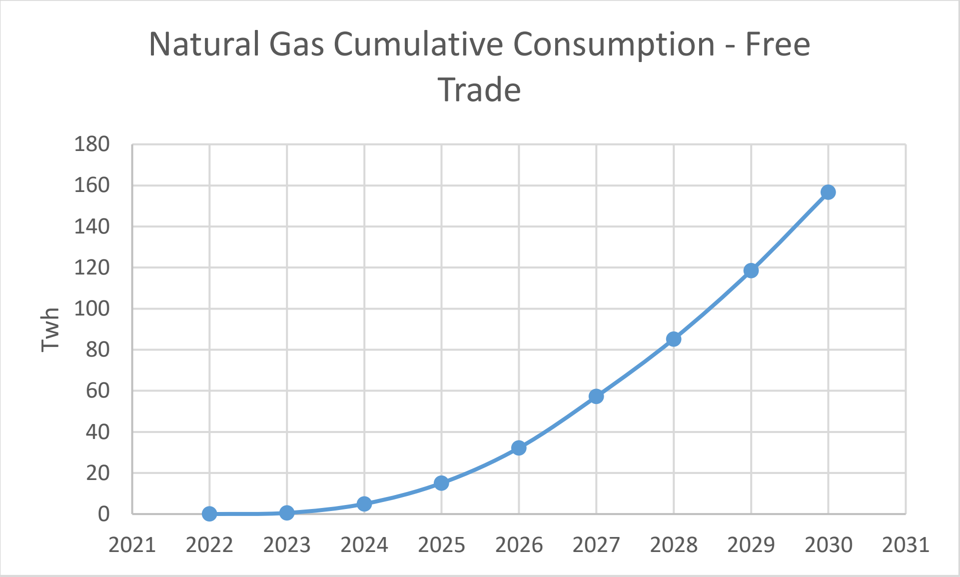


Figure 5.6362 - Cumulative Natural gas consumption, Free Trade, Hypatia.

The annual investment cost shows that in the early years of the modelled period most of the finance is allocated to expanding the cross-border transmission lines whether between E-Sudan and Ethiopia or between the different regions to exchange the imported electricity from ethiopia. Later on when the capital cost of PV falls they dominate the cost amounting to almost 50% of the total investment throughout the years.

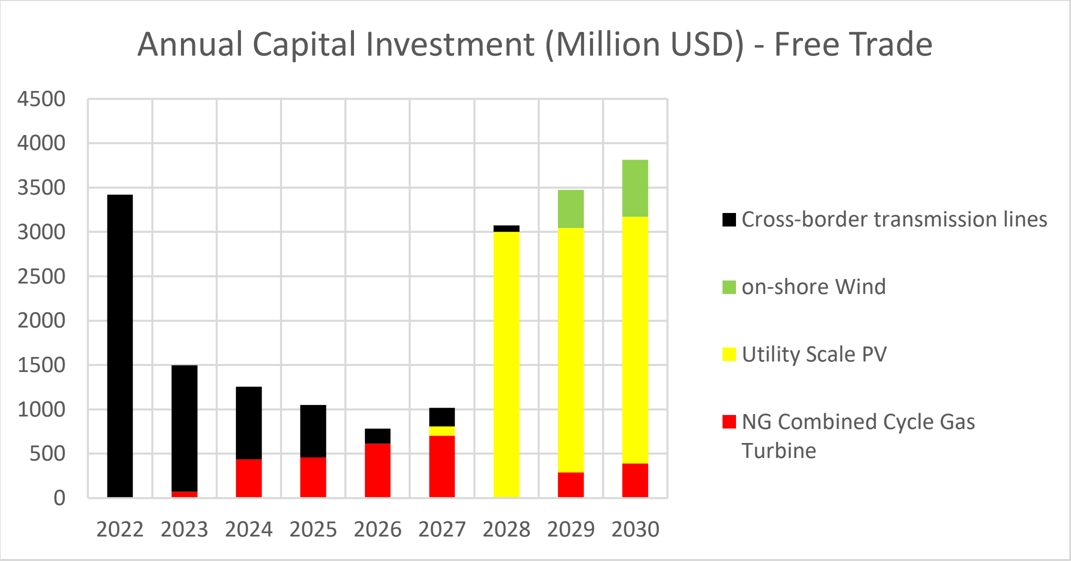


Figure 5.64 - Annual Investment cost, Free Trade, Hypatia.

The annual operating costs shows a considerable fall in the balance allocated for importing from Ethiopia by 50% compared to the case in OSeMOSYS. We can also see the costs associated with consumption of crude oil and gas.

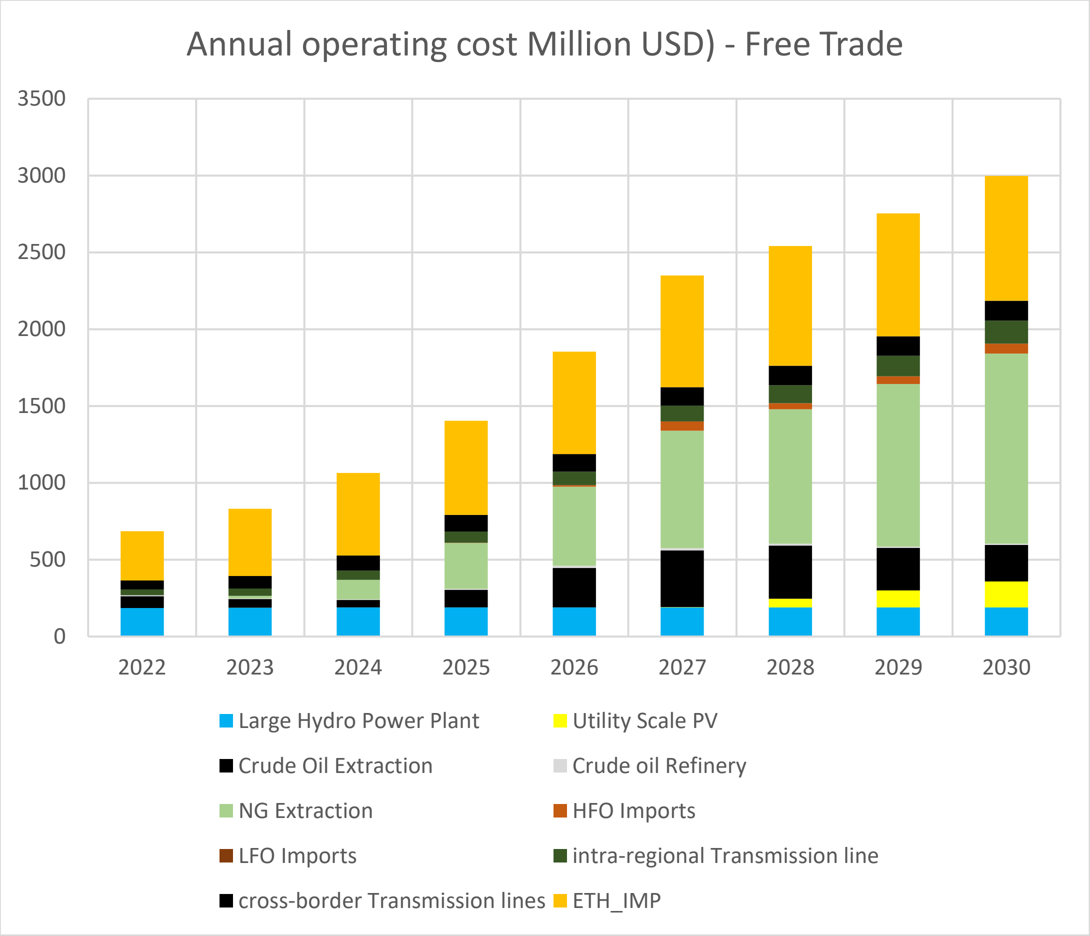


Figure 5.65 - Annual operating cost, Free Trade, Hypatia.

5.2.3 Calliope Free Trade Results

The hourly dispatch of power by technology shows the dominance of Ethiopian imports as the main source to meet the increasing demand followed by the seasonally fluctuating hydroelectric power plants.

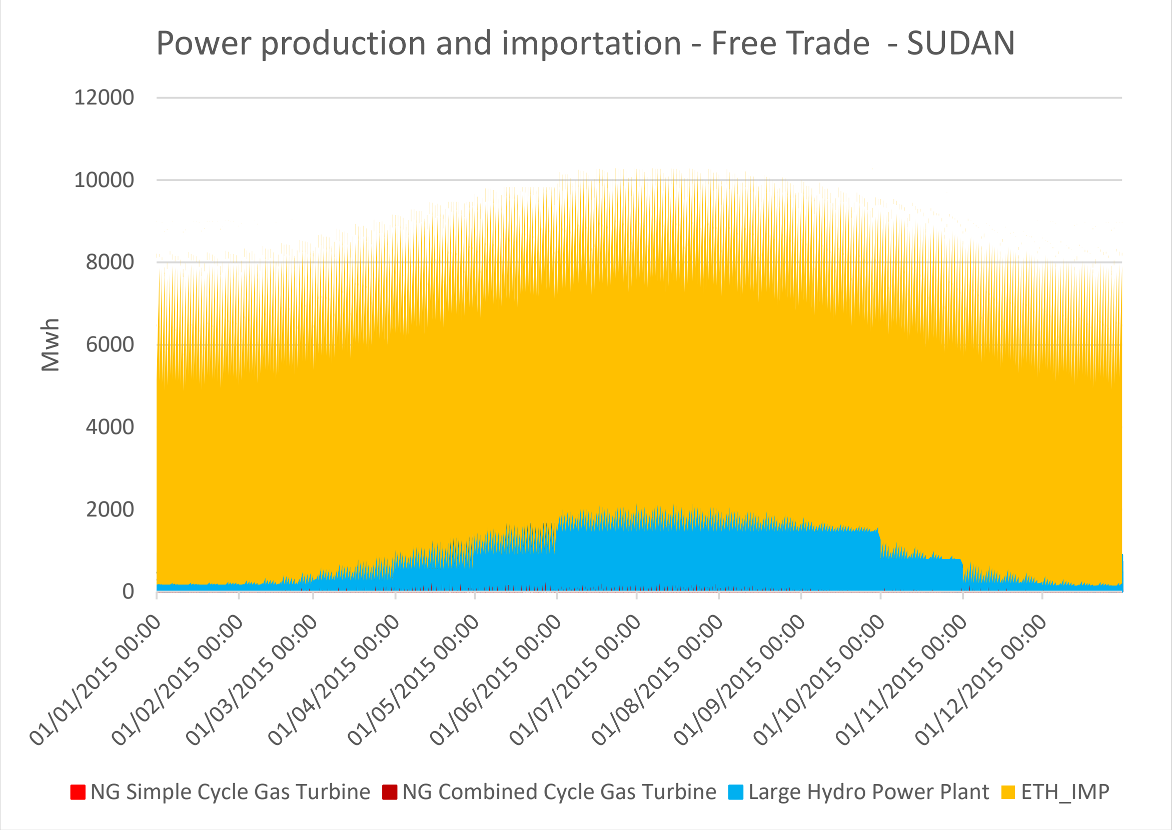


Figure 5.636 - Sudan electricity production by technology, Free Trade, Calliope.

Investment (Figure 5.67) is devoted primarily to expanding the transmission network rather than expanding the capacity of the system. Operating costs (Figure 5.68) are dominated by the costs associated with importing electricity from Ethiopia amounting to 1.2 billion USD in 2030 alone.

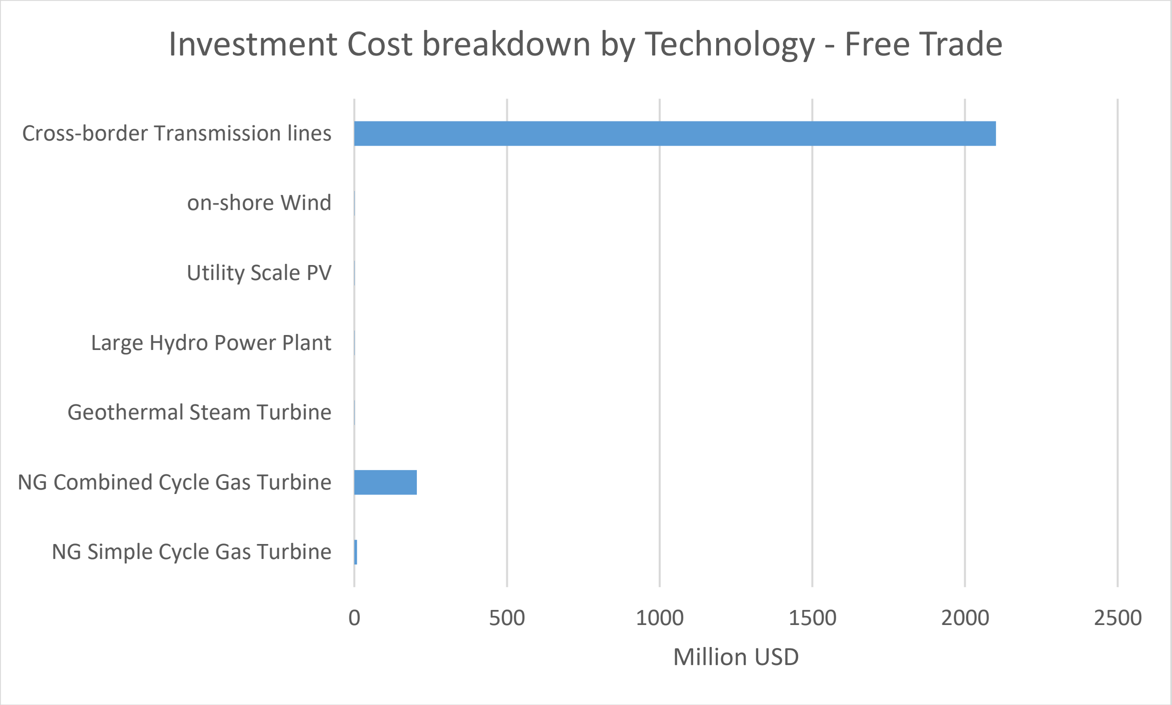


Figure 5.67 - Investment cost by technology, Free Trade, Calliope.

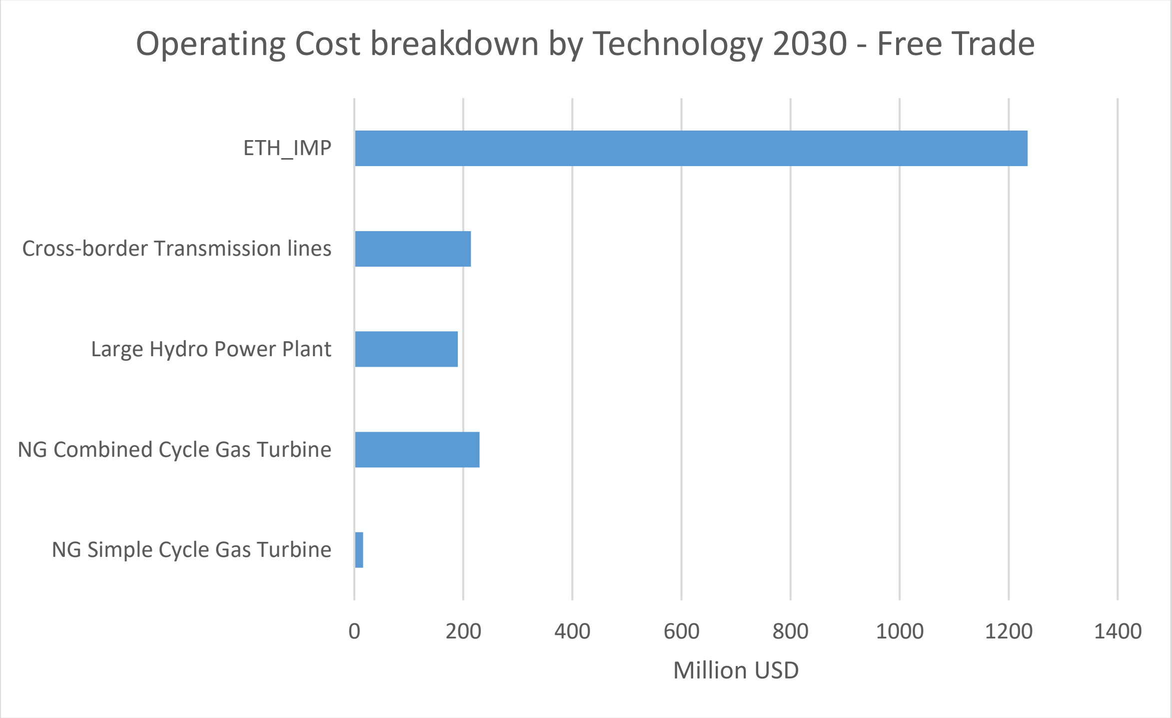


Figure 5.68 - operating cost by technology, Free Trade, Calliope.

5.2.4 Models Comparison

The comparison of the different models is performed in the same way as in BAU Scenario to investigate whether the same observations and accordingly conclusions can be reached. When we first look at the comparison of the regional installed capacity for the different regions, we notice that OSeMOSYS and Hypatia seems to have very similar results where no capacity expansion happens in the country except for a small addition of 0.69 kW from NG-CCGT in the western region in Calliope results. This is shockingly different than the benchmarking done on the BAU scenario. However, this similarity is caused by completely different reasons that in fact align with the explanations reported above. OSeMOSYS favored importing all of the electricity needs from Ethiopia because the transmission lines were not modelled therefore, the cheap electricity offered by the neighboring country proved to be the lowest LCOE regardless of the dropping VRES. Meanwhile, in Calliope even though the transmission lines costs were accounted for, the stable not fluctuating imports were favored against the fluctuating VRES due to the fine time resolution in Calliope as we explained earlier. On the other hand, Hypatia results showed expansion of the capacity in all of the regions with exception of the eastern region which met its demand from the Ethiopian imports. The western region experienced high increase in its capacity because geography prevents it from being directly connected with the importing eastern region which means that in order to meet the western demand from Ethiopia the electricity has to be transmitted from Ethiopia to the east and then from the east to one of the other regions and lastly finding its way to the west which makes domestic production favored. Also, in Hypatia utility scale PV is widely deployed in the last years when their cost falls. The installed capacity mix (Figure 5.70) shows the same information. Due to the increased production in Hypatia we can see (Figure 5.71) that the contribution of Imports from Ethiopia in the electricity production mix is almost 50% of the other two models however still feeding 50% of the demand. In all of the models we notice that the Egyptian imports amounted to almost zero such that the import price from Egypt is twice the price of the Ethiopian imports.

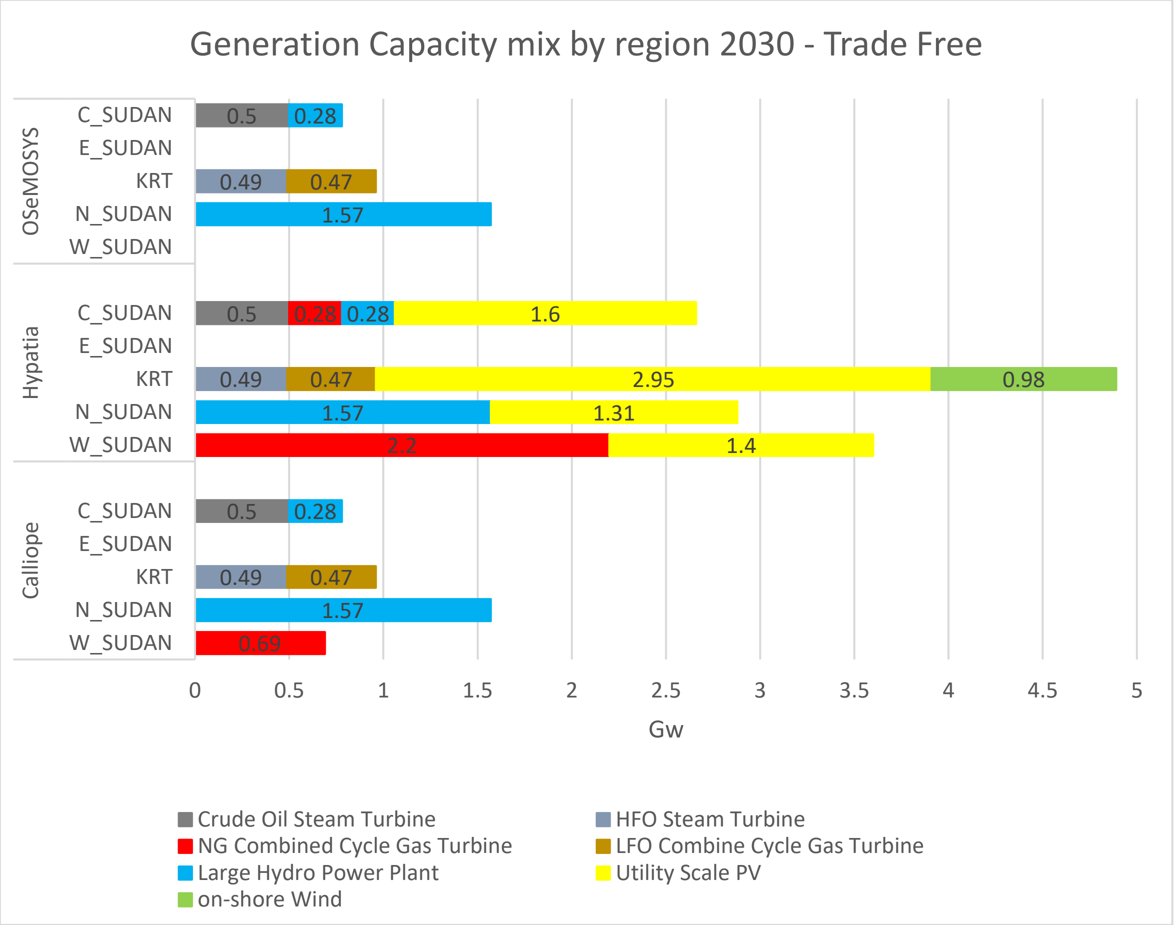


Figure 5.69 - Comparison of generation capacity (GW) by region in 2030 – Free Trade

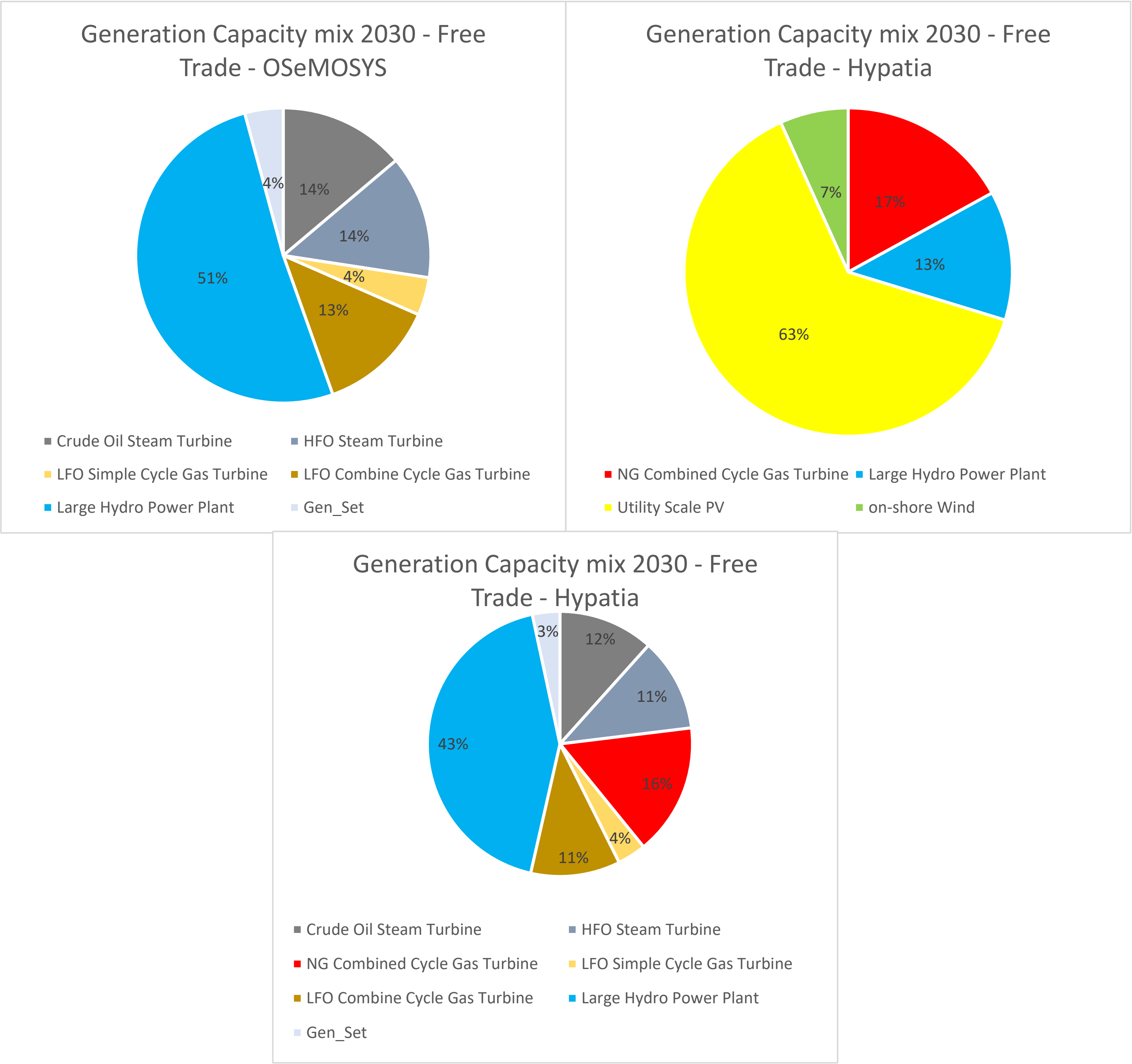


Figure 5.70 - Comparison of generation capacity mix by region in 2030 – Free Trade

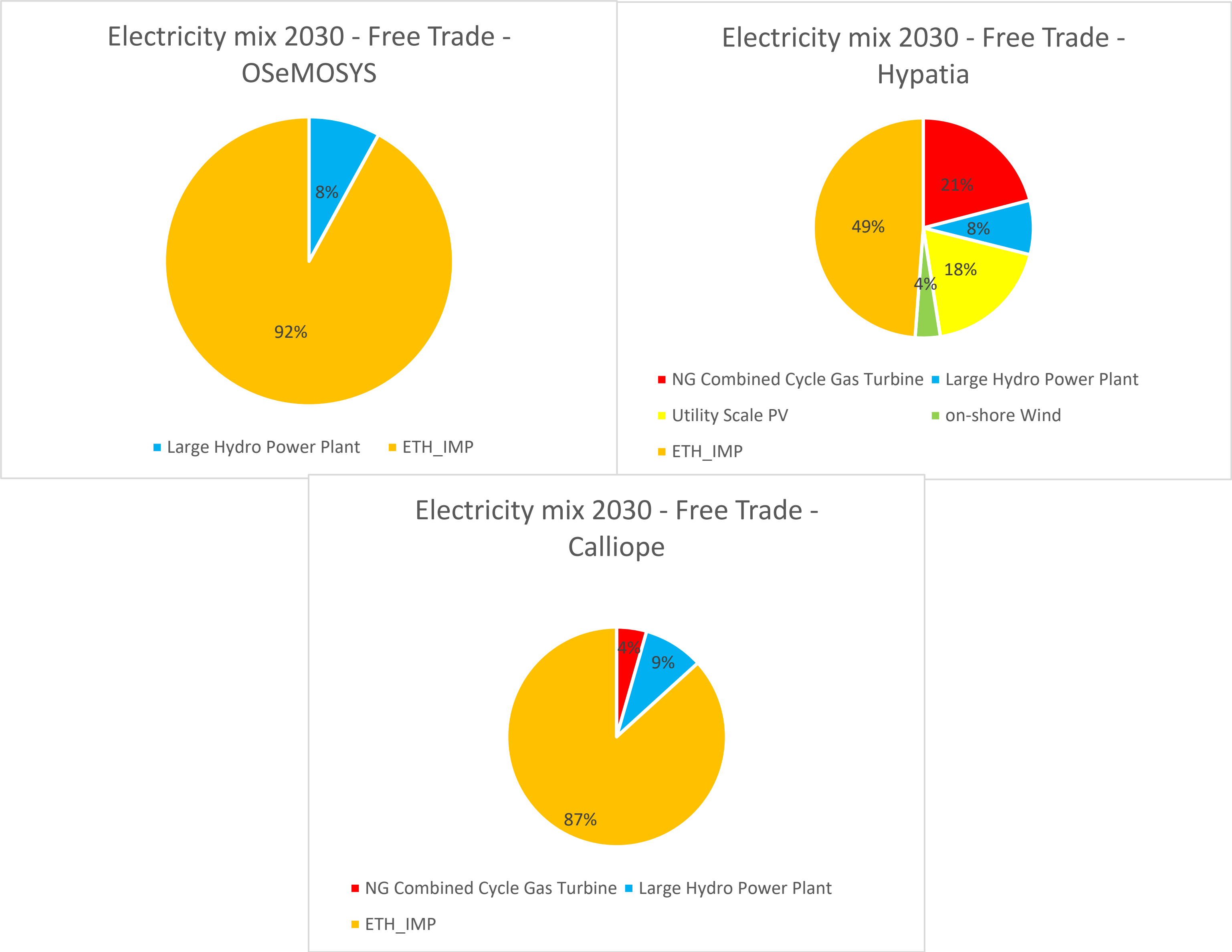


Figure 5.71 - Comparison of electricity production mix in 2030 – Free Trade

5.3 Limited Trade Scenario

As defined in section 4.7.2 this Scenario Explores the possibility of importing electricity from both Ethiopia and Egypt however a cap on the imported energy is accomplished by limiting the transmission line capacity. Nevertheless, because OSeMOSYS has no modelling of the transmission lines the capacity of the import technologies is restricted. This scenario is essential to be investigated given that the results of the free trade scenario showed a high dependence of the country on Ethiopian imports.

5.3.1 OSeMOSYS Limited Trade Results

Figure 5.72 shows that the capacity of production was expanded immediately starting from the first year mainly through PV and Wind systems. Where PV system are deployed in the northern region due to the high capacity factor and wind in the capital Khartoum. We also noticed a small addition of 0.5 GW of biomass power plant in Khartoum. The Electricity supply this time shows that existing thermal plants are activated in the first few years until the cost of VREs falls considerably. Also, the Ethiopian imports falls as they are restricted allowing the imports from Egypt to increase.

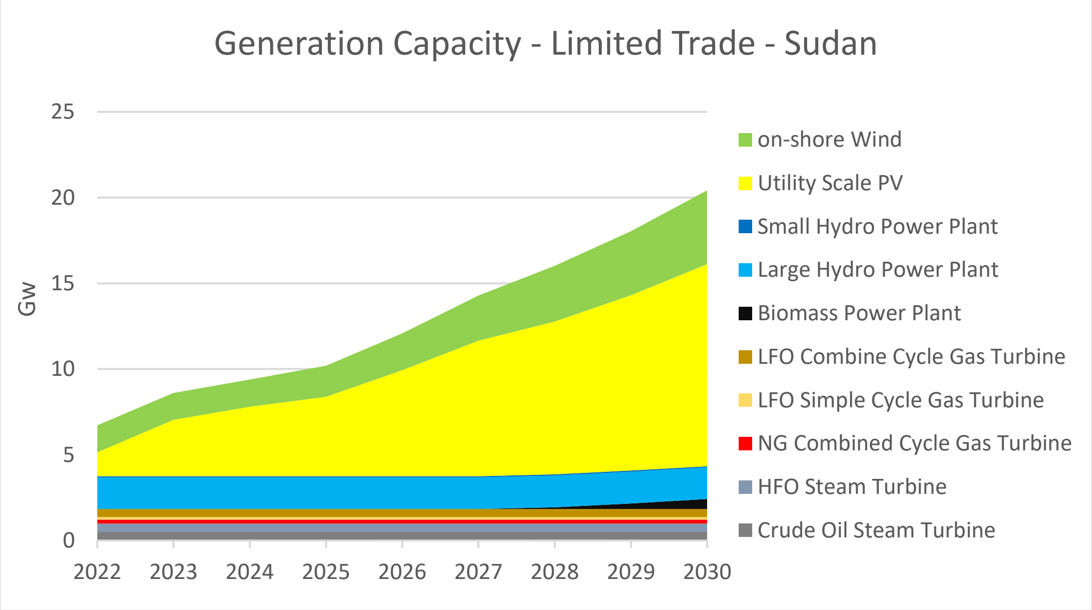


Figure 5.72 - Sudan generation capacity outlook, Limited Trade, OSeMOSYS.

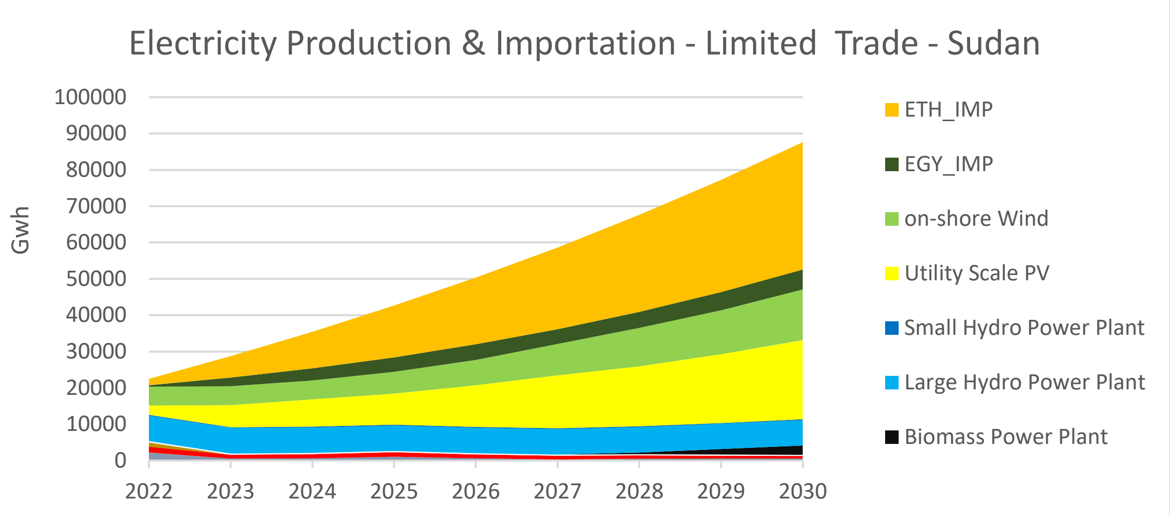


Figure 5.73 - Sudan electricity production outlook, Limited Trade, OSeMOSYS.

OSeMOSYS results show a small consumption of fossil fuels to run the existing thermal power plants for the first few years and the newly small, introduced capacity of NG-CCGT.

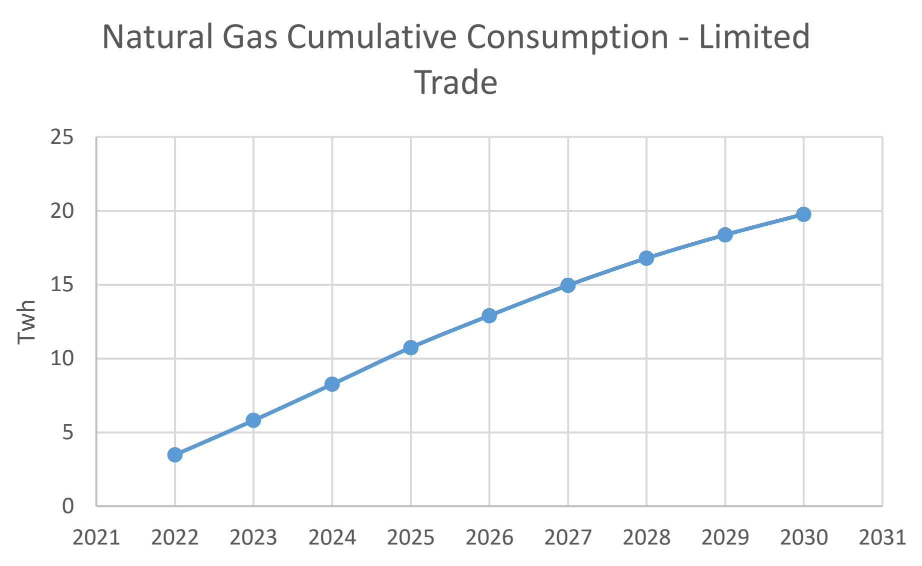
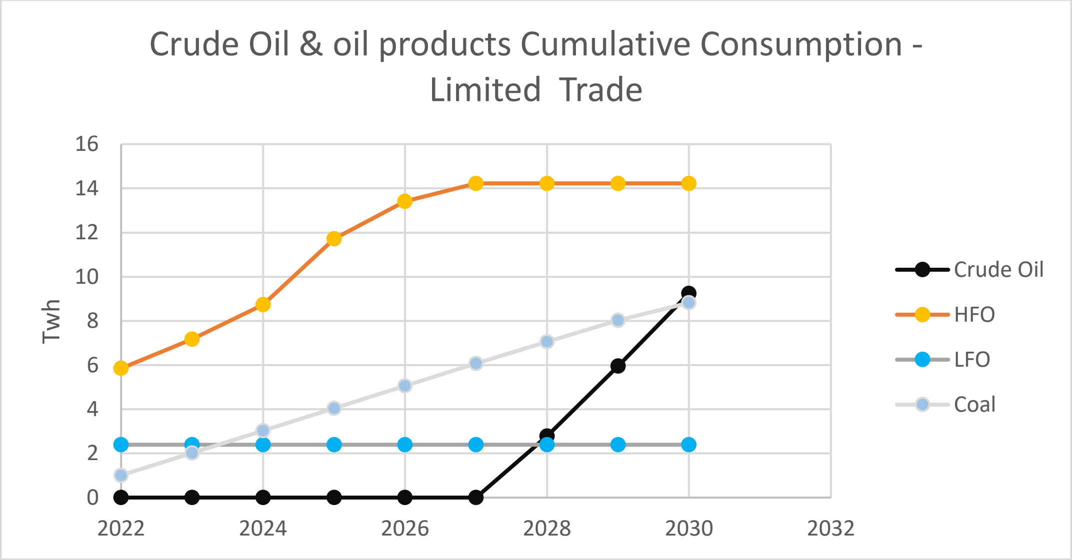


Figure 5.7464 - Cumulative Natural gas consumption, Limited Trade, OSeMOSYS.



‘ Figure 5.75 - Cumulative Crude oil and oil products consumption, Limited Trade, OSeMOSYS.

The annual investment costs are dominated by utility scale solar while the annual operating costs shows that the allocated finance for Ethiopian imports has dropped to 3.14 billion USD and the finance for Egyptian imports amount to 2 billion USD.

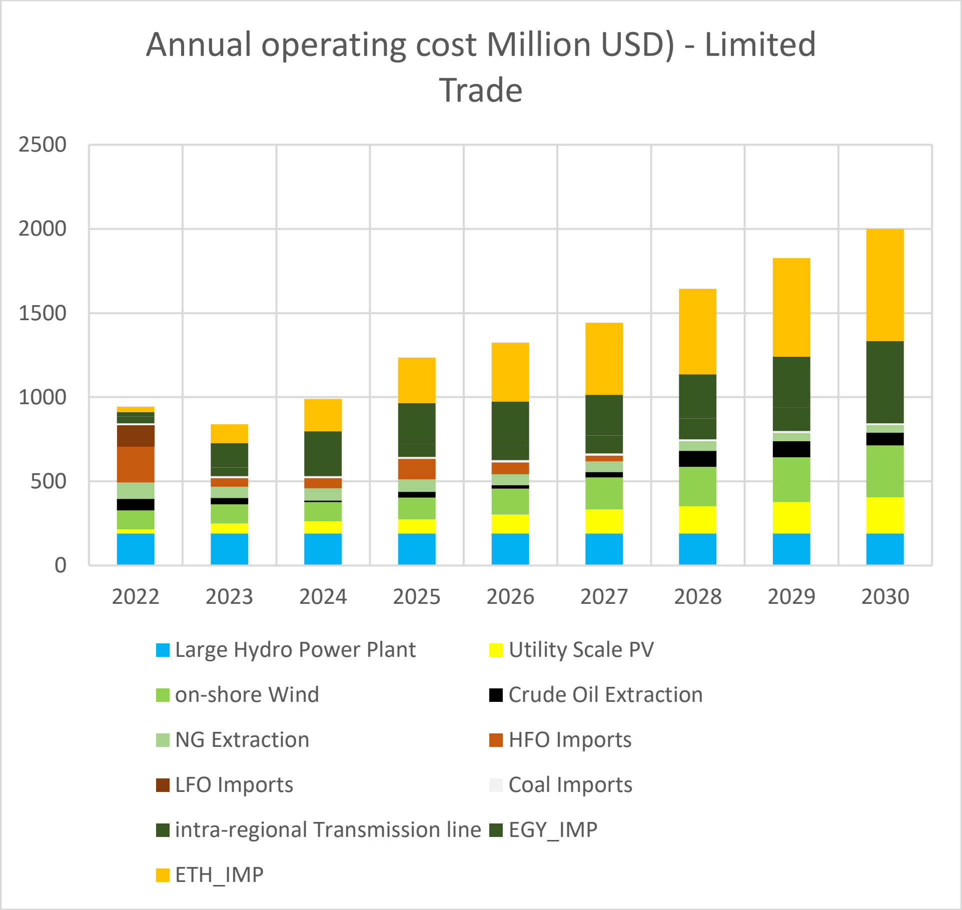


Figure 5.76 - Annual operating cost, Limited Trade, OSeMOSYS.

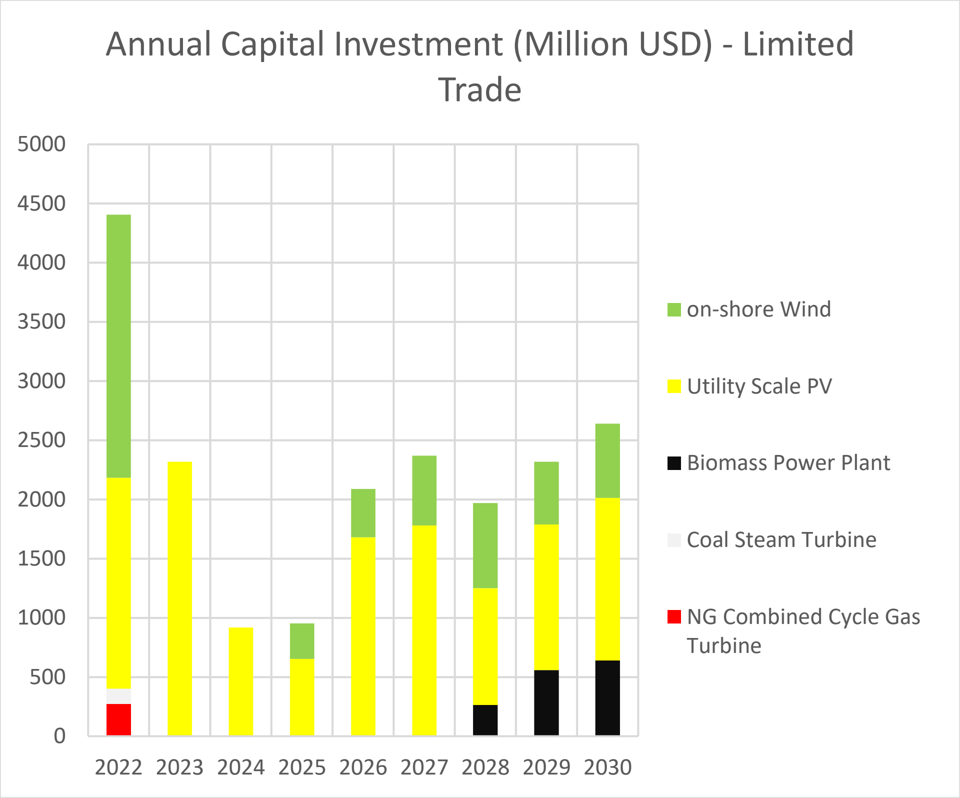


Figure 5.77 - Cumulative Crude oil and oil products consumption, Limited Trade, OSeMOSYS.

5.3.2 Hypatia Limited Trade Results

Figure 5.78 shows that the capacity of production was expanded across the country. In the years before 2026 the expansion happens by deploying NG-CCGT in almost all of the regions when the natural gas prices are lower and further expansion through PV and wind systems is noticed after that.

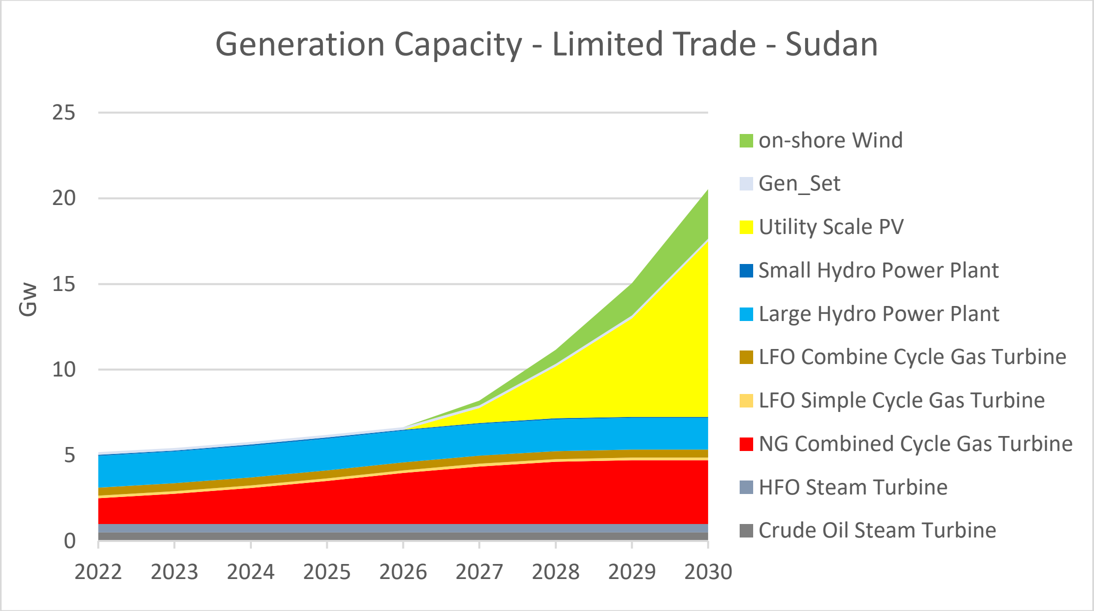


Figure 5.78 - Sudan generation capacity outlook, Limited Trade, Hypatia.

The electricity supply now shows a high amount of electricity production from NG-CCGT. And a very small amount of imports from Egypt.

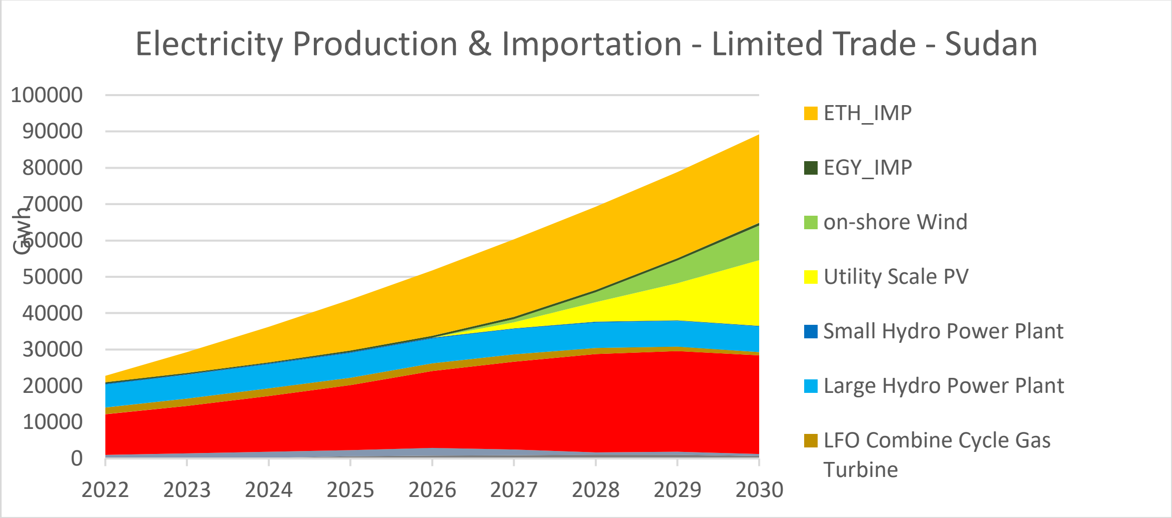


Figure 5.79 - Sudan electricity production outlook, Limited Trade, Hypatia.

Fossil fuels consumption in this case increases by magnitude of orders specially for the natural gas because of the high deployed NG-CCGT and also for the crude oil and its products since they are contributing more in the electricity supply.

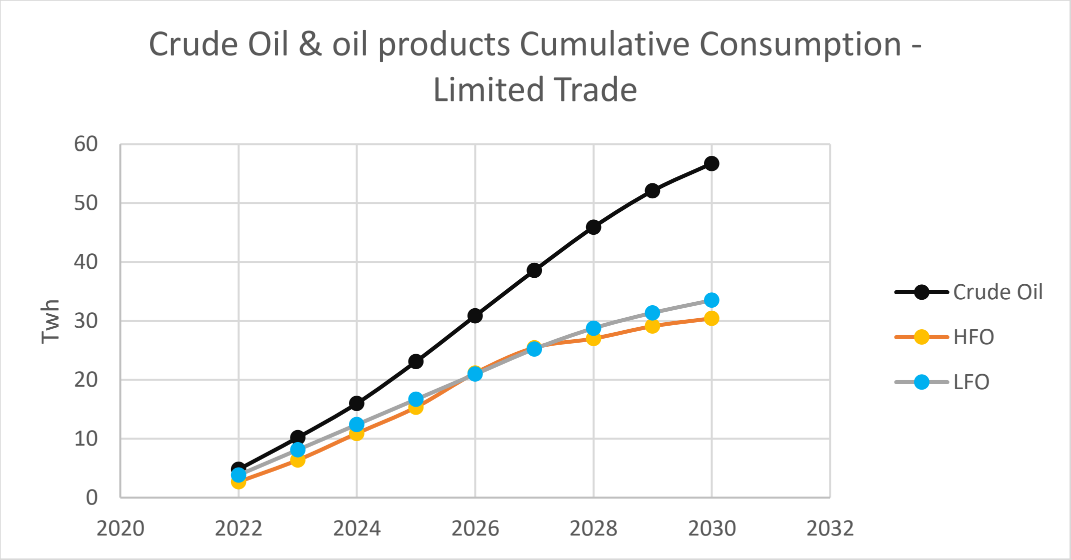


Figure 5.80 - Cumulative Crude oil and oil products consumption, Limited Trade, Hypatia.

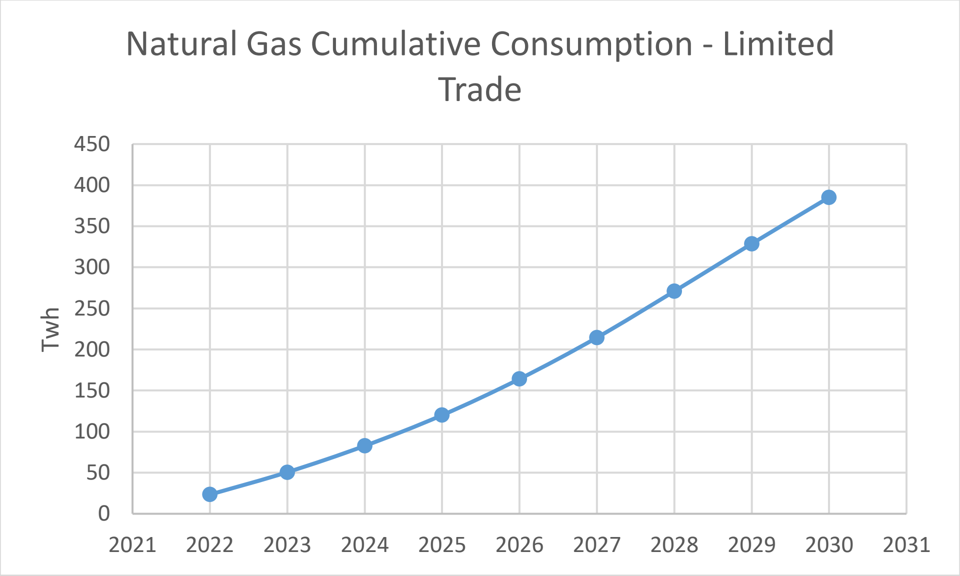


Figure 5.8165 - Cumulative Natural gas consumption, Limited Trade, Hypatia.

The annual investment cost shows that in the early years of the modelled period most of the finance is allocated to expanding the cross-border transmission lines and deploying NG-CCGT. Later on when the capital cost of PV and wind falls they dominate the cost.

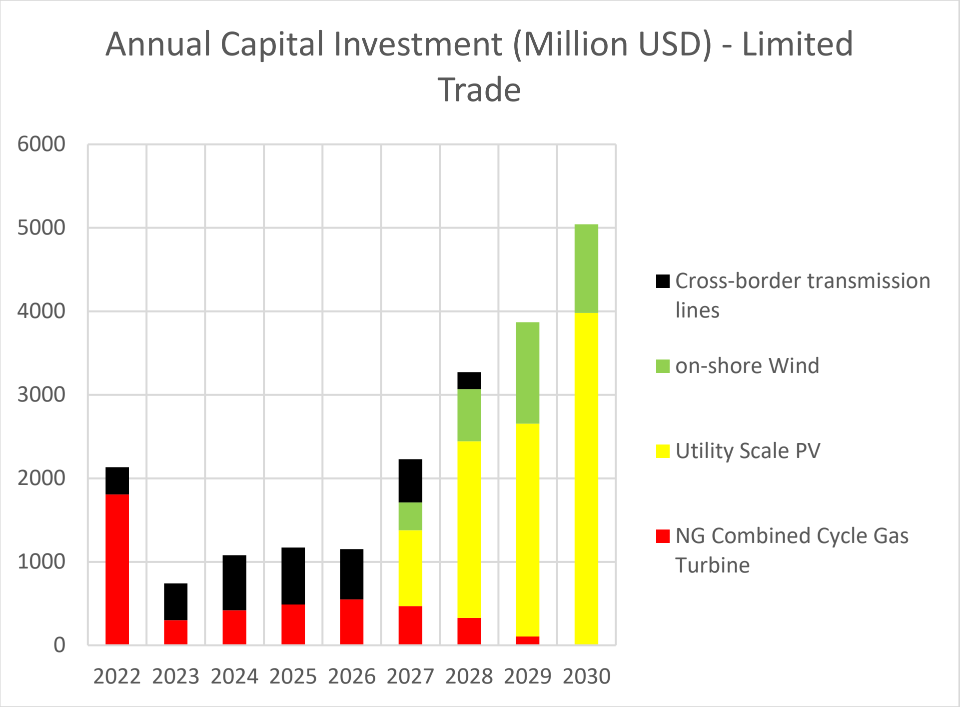


Figure 5.82 - Annual Investment cost, Limited Trade, Hypatia.

The annual operating costs shows a considerable fall in the balance allocated for importing from Ethiopia, and increased spending on the natural gas.

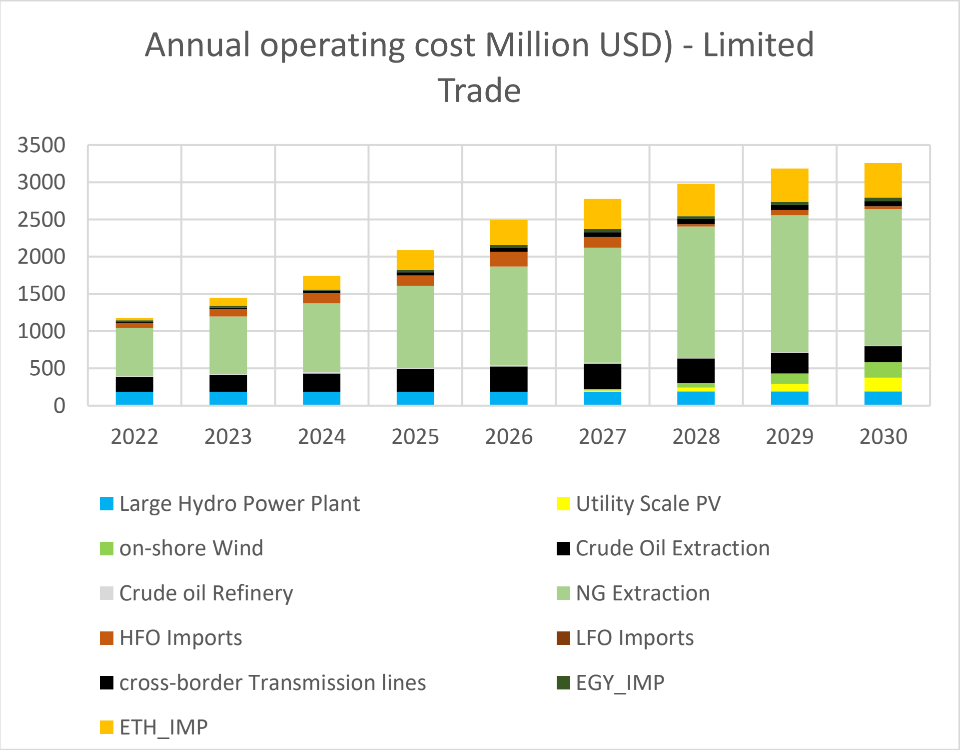


Figure 5.83 - Annual operating cost, Limited Trade, Hypatia.

5.3.3 Calliope Limited Trade Results

The hourly dispatch of power by technology shows that Ethiopian imports still are the main source to meet the increasing demand in calliope regardless of the limits. However, a growing relevance of the Egyptian imports and the NG-CCGT production is noticeable.

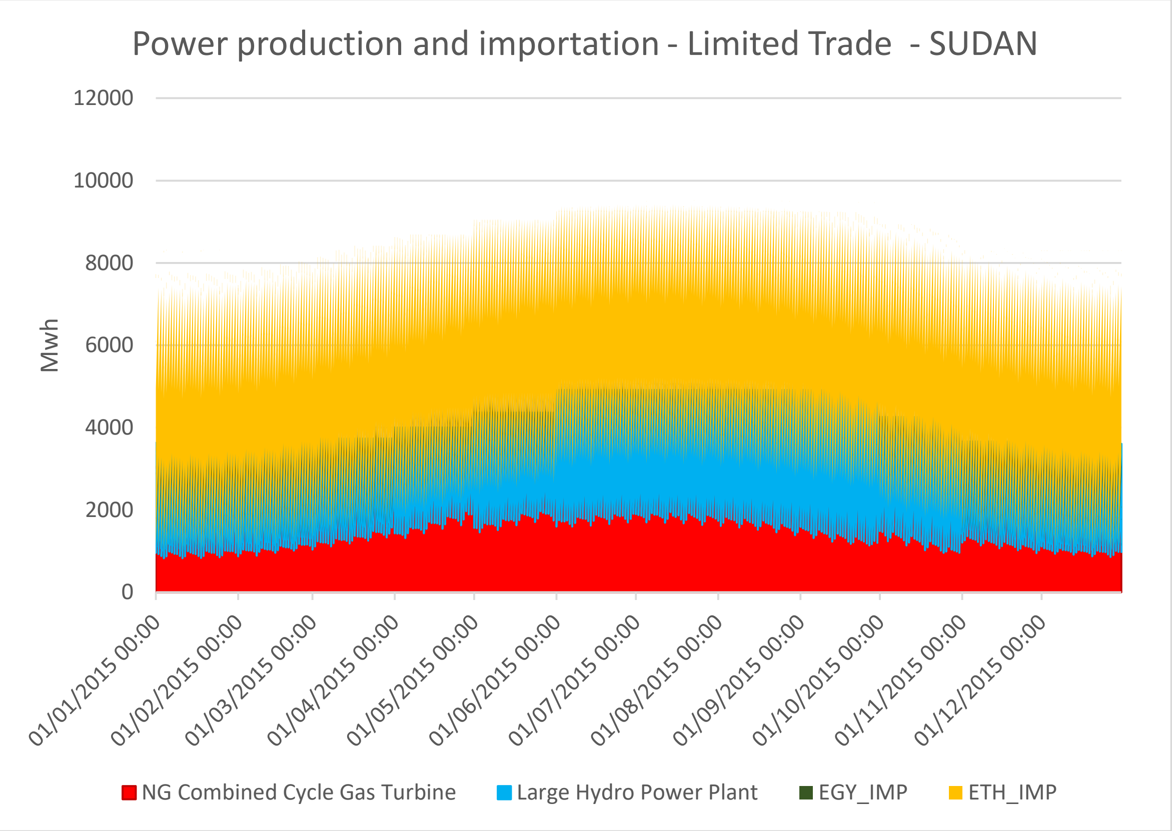


Figure 5.84 - Sudan electricity production by technology, Limited Trade, Calliope.

Investment (Figure 5.85) is almost divided in its entirety between expanding the cross-border transmissions lines and the installation of natural gas plants. Operating costs (Figure 5.86) are however mostly devoted to operate the natural gas power plants and mainly to for purpose of fuel buying.

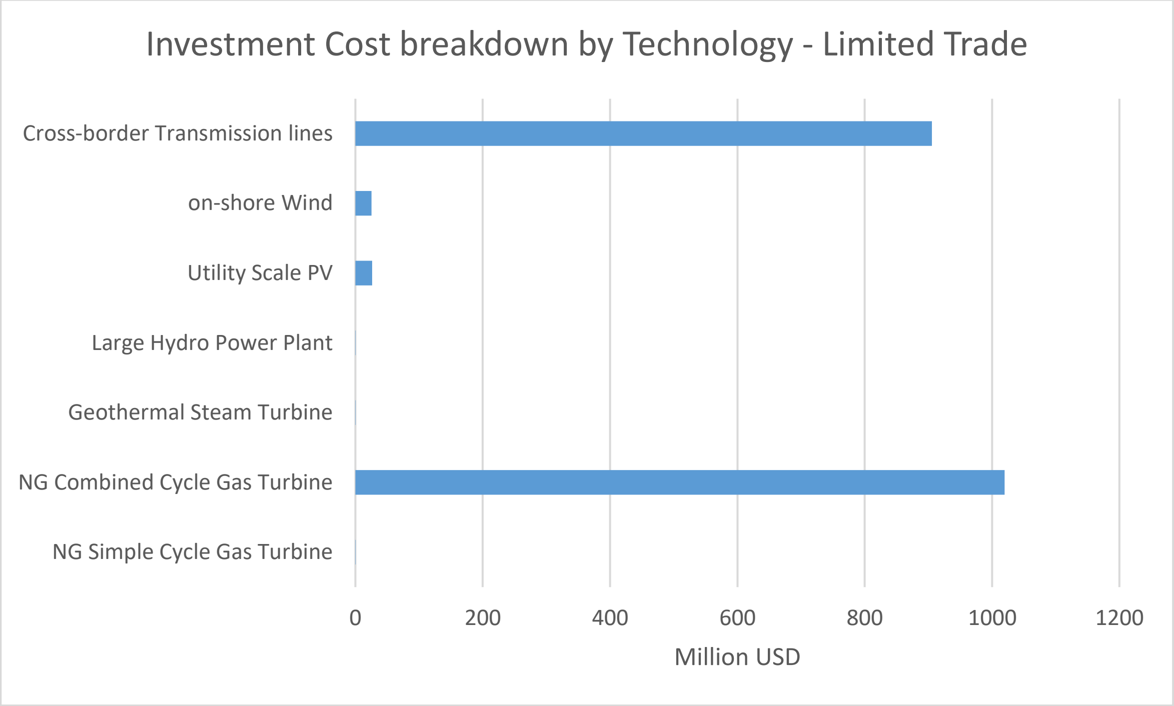


Figure 5.85 - Investment cost by technology, Limited Trade, Calliope.

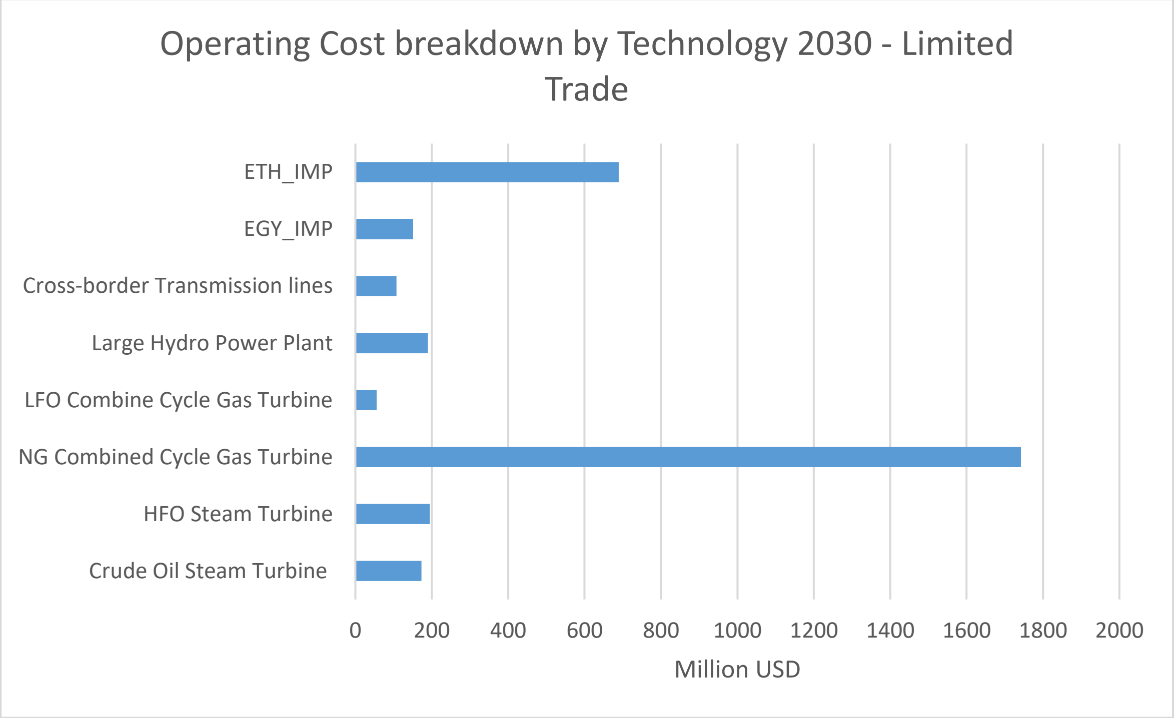


Figure 5.86 - operating cost by technology, Limited Trade, Calliope.

5.3.4 Models Comparison

The Generation capacity mix by region shows a trend that is very similar to the BAU case influenced by the same reasons where we see that both OSeMOSYS and Hypatia shows a high contribution of VREs compared to calliope because of the way they represent time seasonally. Moreover, we notice how OSeMOSYS leaned toward production by PV in the region where the capacity factor is higher neglecting the transmission costs. In the electricity supply mix comparison Figure(5.89) we can see that the amount of imports from Ethiopia and is lower in Hypatia compared to OSeMOSYS because Hypatia again models the transmission grid cost. The imports contribution is also lower than calliope again because of time representation and the logic Hypatia follows of capacity expansion (i.e. the installed capacity to meet the demand in the years where imports were not available is not going to be discarded).

Eventually one can notice that the main discrepancies between the different models are:

1- Time resolution: Both Hypatia and OSeMOSYS offers a seasonal representation of time aggregating the data according to the user definition while Calliope has a hourly time resolution. This affects the contribution of Variable peak demand technologies such as VREs that it results in overestimation of their deployed capacity in Hypatia and OSeMOSYS.

2- Logic: Hypatia and OSeMOSYS are capacity expansion models that follows the growth of the electricity demand year by year while calliope follows a snapshot logic. This makes Calliope vulnerable to produce a pathway toward an end and makes it more suitable to be used in operational mode. For universal supply achievement a detailed pathway is required.

3- Transmission lines modelling: Calliope and Hypatia has the ability to directly model transmission lines unlike OSeMOSYS. The ability to include transmission lines techno-economic details as a factor in reaching the optimized solution is important when dealing with a multi-nodal system and specially when considering power trade between countries.

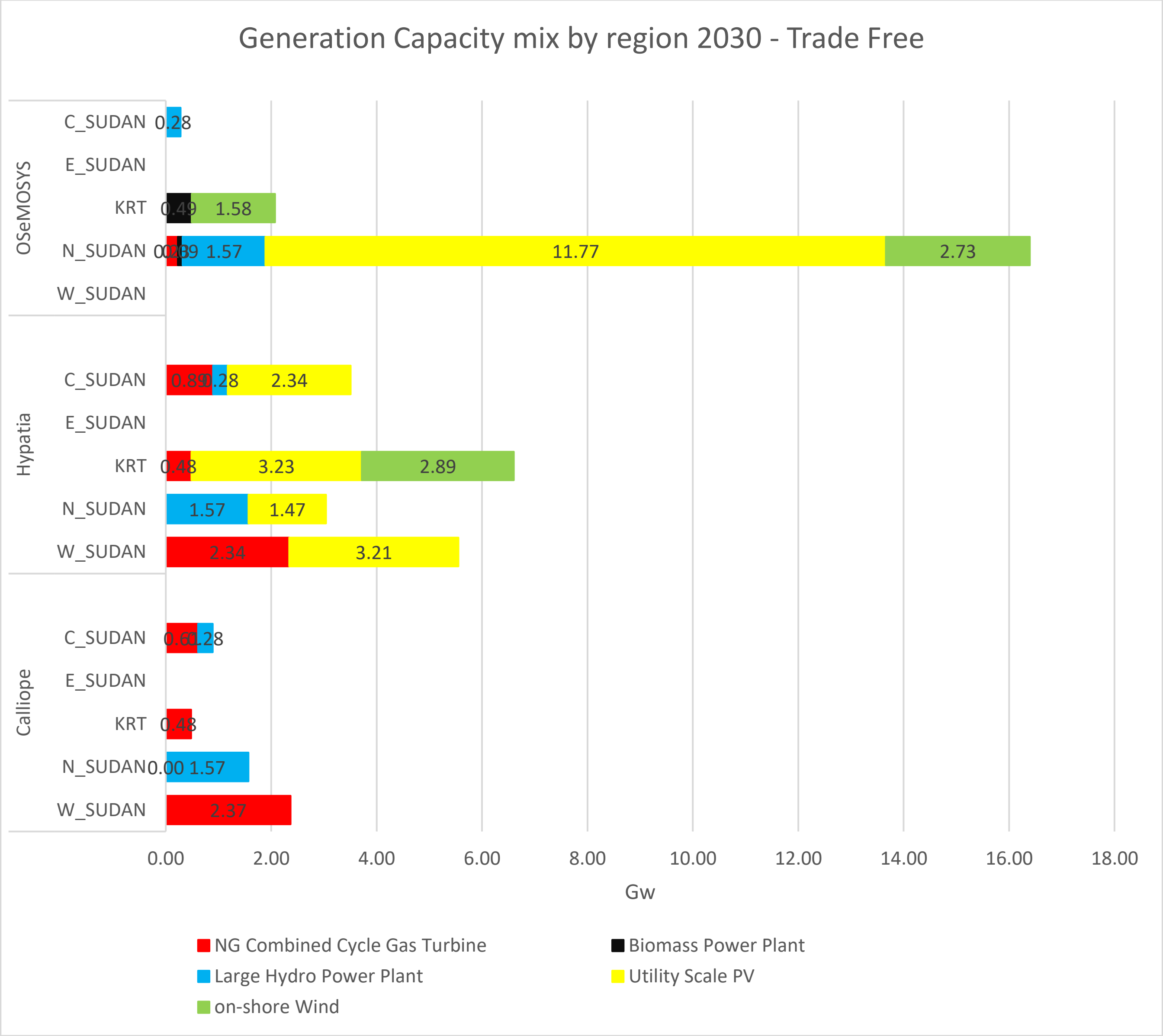


Figure 5.87 - Comparison of generation capacity (GW) by region in 2030 – Limited Trade

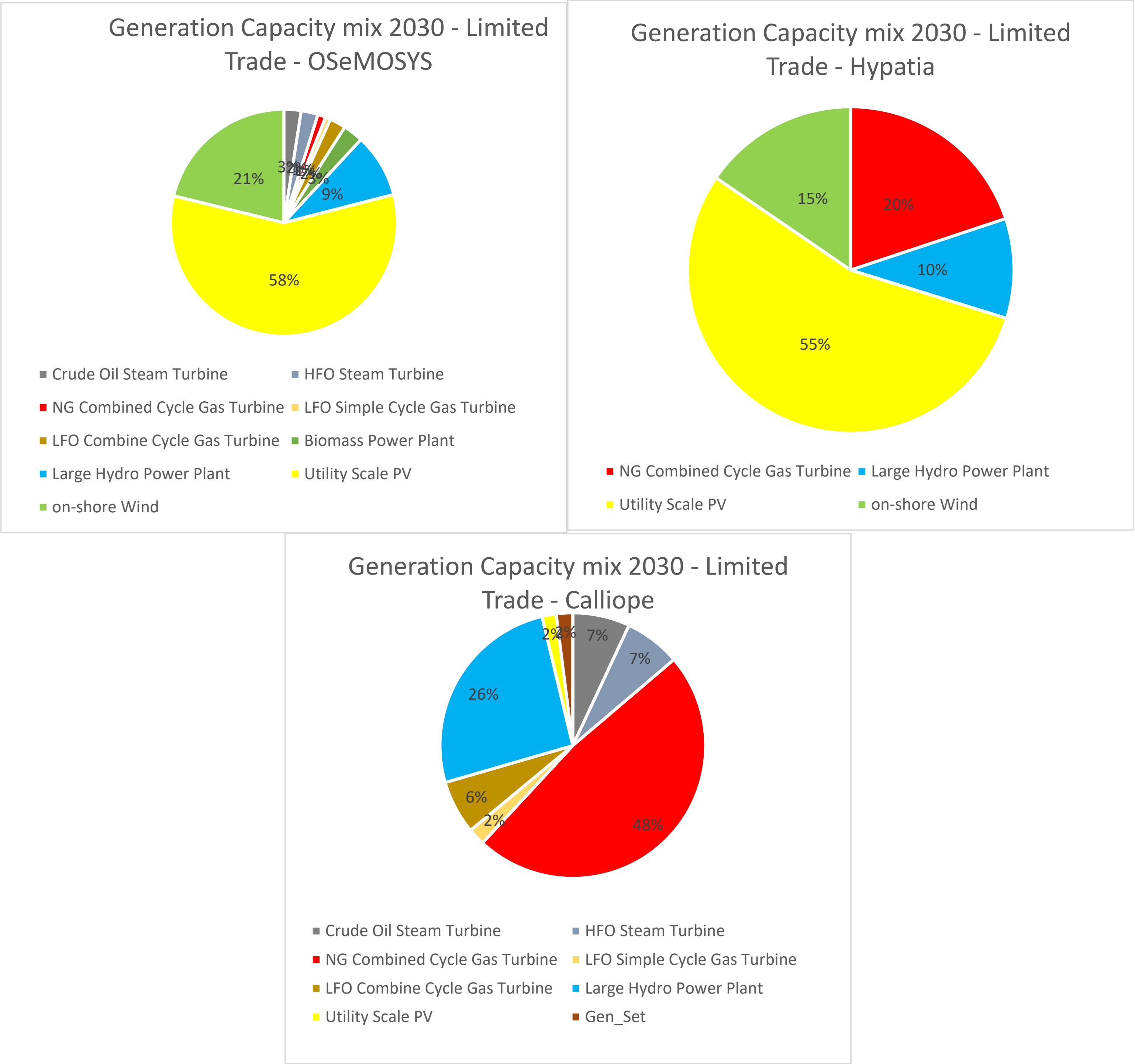


Figure 5.88 - Comparison of generation capacity mix by region in 2030 – Limited Trade

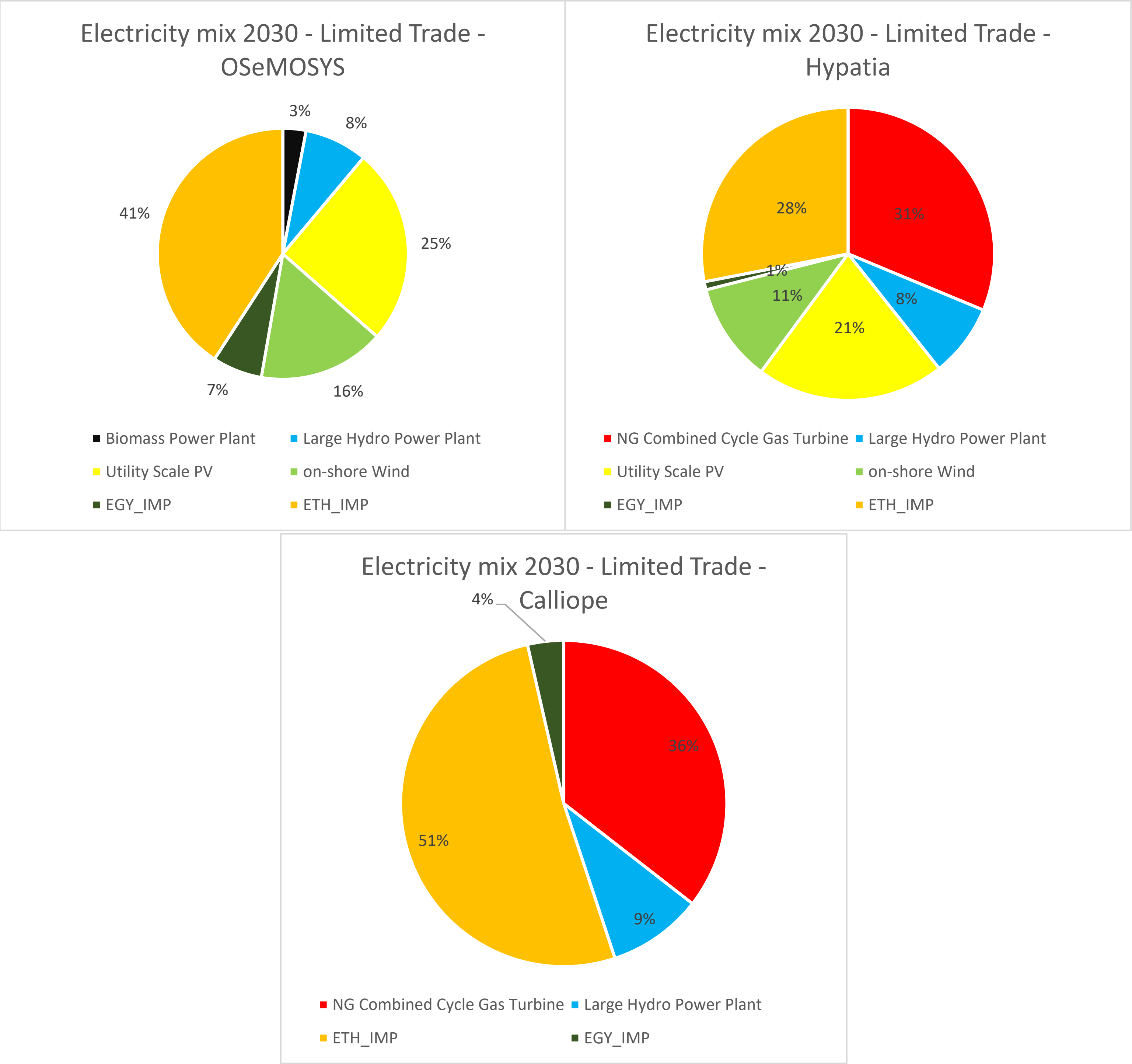


Figure 5.89 - Comparison of electricity production mix in 2030 – Limited Trade

5.4 Insights on scenario comparison

In this section a comparison between the different scenarios for the different models is performed.

5.4.1 OSeMOSYS

The most obvious discrepancy between the BAU scenario and the two scenarios considering trade with the neighboring countries is that the total installed capacity is significantly lower in the trade cases. This is a direct consequence of the fact that electricity imports from Ethiopia and Egypt are much cheaper when compared to producing electricity However the two countries in reality subsidize the electricity sector for both industrial and residential applications therefore the price of electricity is expected to be low, in addition to that in OSeMOSYS the capital cost of expanding the grid either inside the country or at the borders is neglected which means that importing from Ethiopia would always prevail as the best alternative. In fact, the free trade scenario shows that the capacity is not expanded at all. The comparison between the free and limited trade scenarios in OSeMOSYS shows that if the border grid is to be expanded as planned the demand must be met through a mixed approach of: operating the currently existing thermal plants and hydroelectric plants, introducing a high penetration of VREs where the capacity factor are high (North Sudan and Khartoum) reaching 41% share in 2030 and lastly importing the maximum possible imports from Ethiopia and Egypt. Figure 5.90 Shows that the high penetration of NG-CCGT in the BAU Scenario is replaced by electricity imports in the limited trade scenario while the PV and wind share remains close in the two scenarios. Meanwhile in the free trade scenarios we see the almost total dependance on the imports from Ethiopia. In terms of the total cost, the free trade as expected curtails the minimum cost which is one-fifth the cost compared to the BAU scenario the costliest choice while the limited trade falls in between.

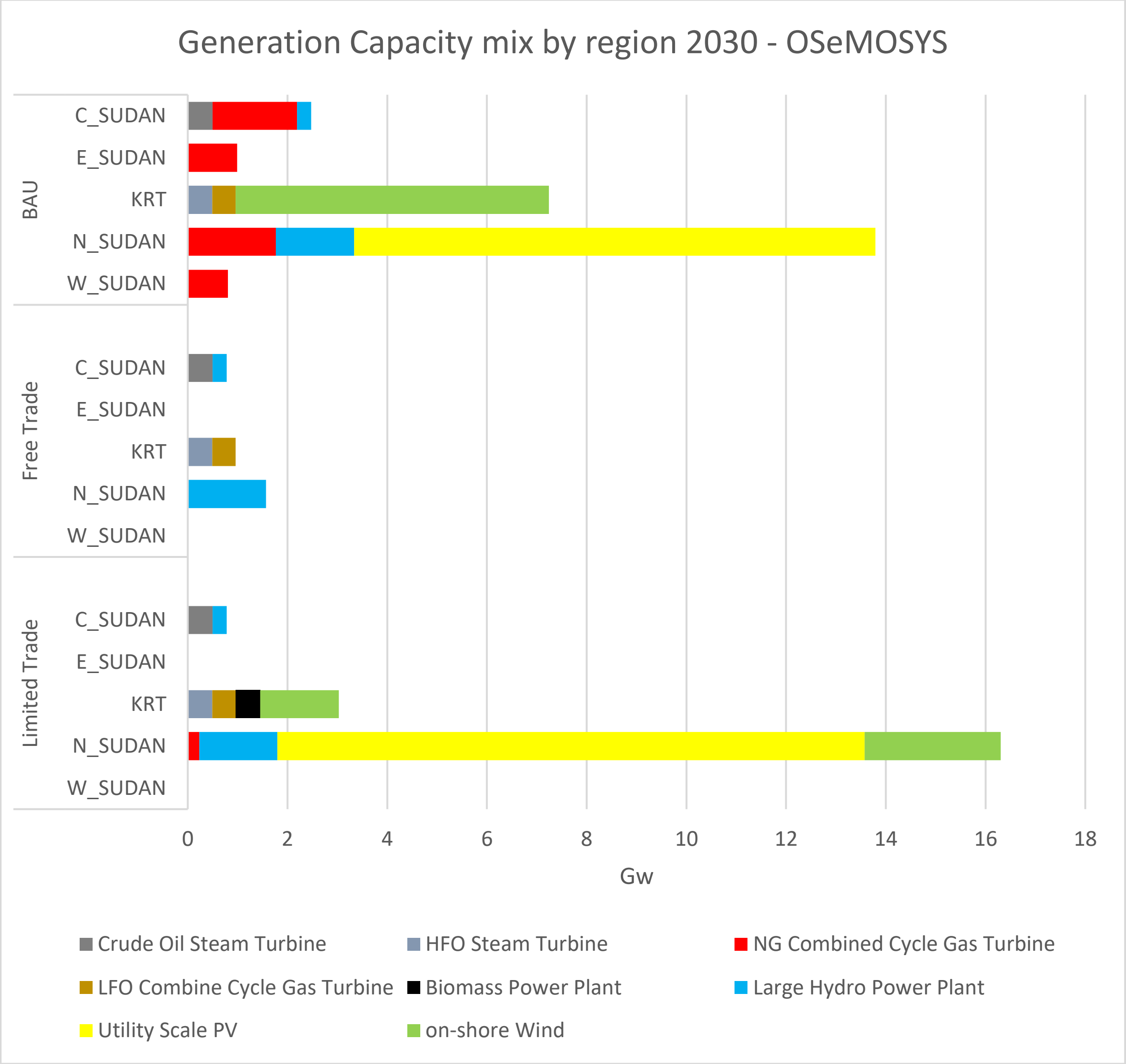


Figure 5.90 - Comparison of generation capacity (GW) by region in 2030 – OSeMOSYS

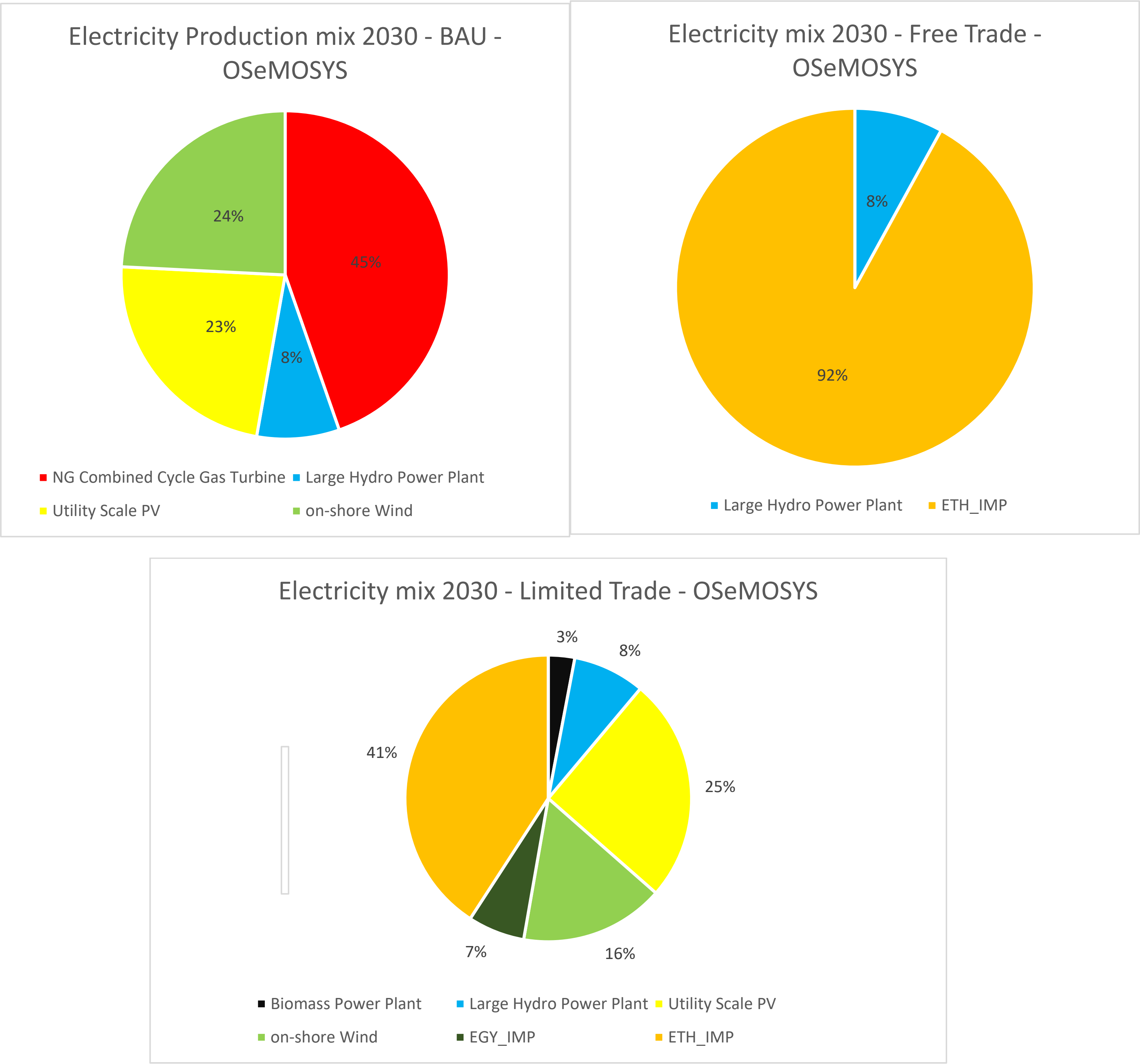


Figure 5.91 - Comparison of electricity production mix in 2030 – OSeMOSYS

5.4.2 Hypatia

Consistent with OSeMOSYS the comparison across the different scenarios showed a similar trend due to the same reasons where the electricity production decreases with allowing the imports from Ethiopia and more drastically in the case of the scenario of free trade. Again, we see a high penetration of VREs. However, this time in all of the cases even the free trade case and the main changes happen to the NG-CCGT contribution as it decreases with increasing the amount of electricity imported.

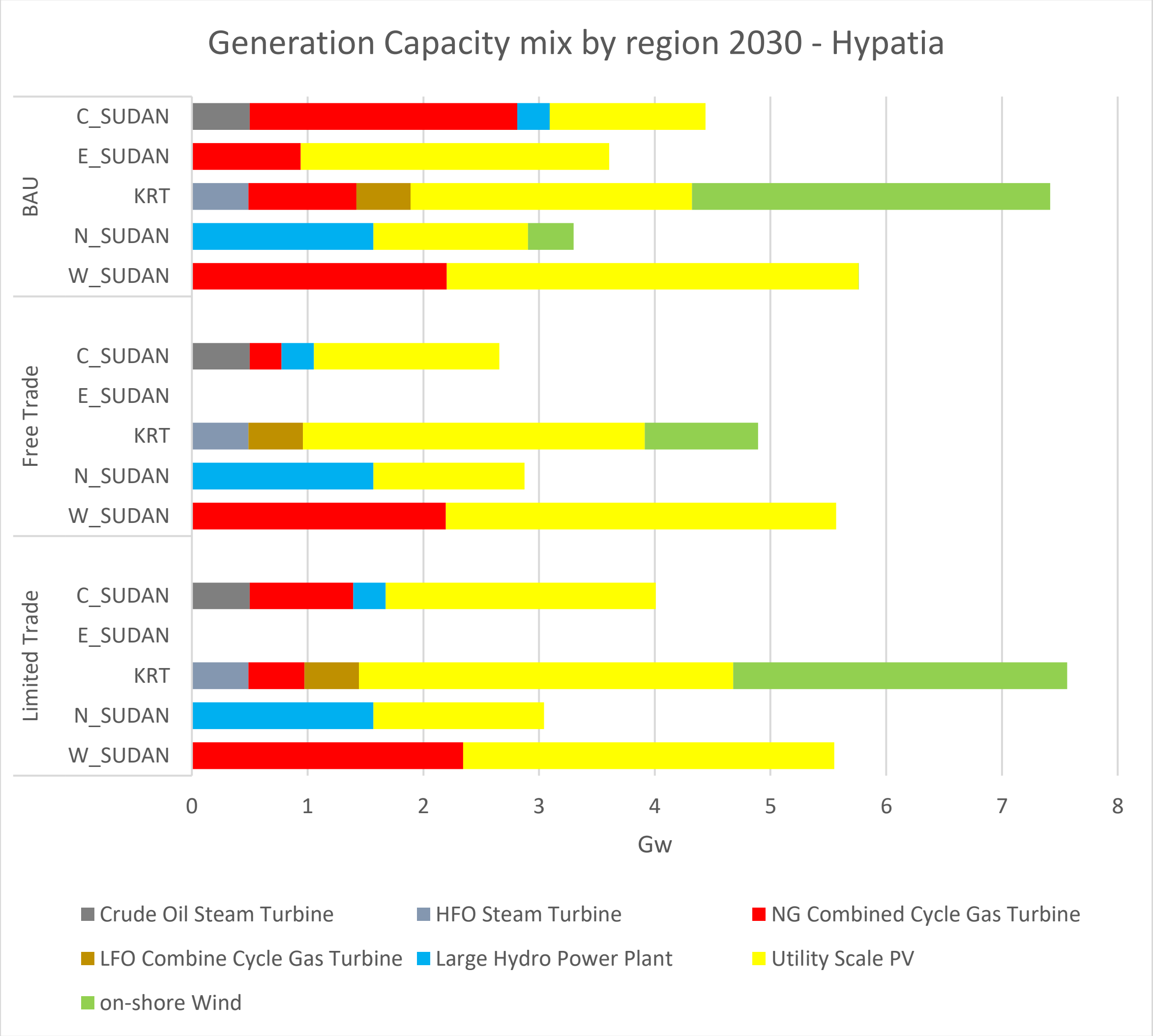


Figure 5.92 - Comparison of generation capacity (GW) by region in 2030 – Hypatia

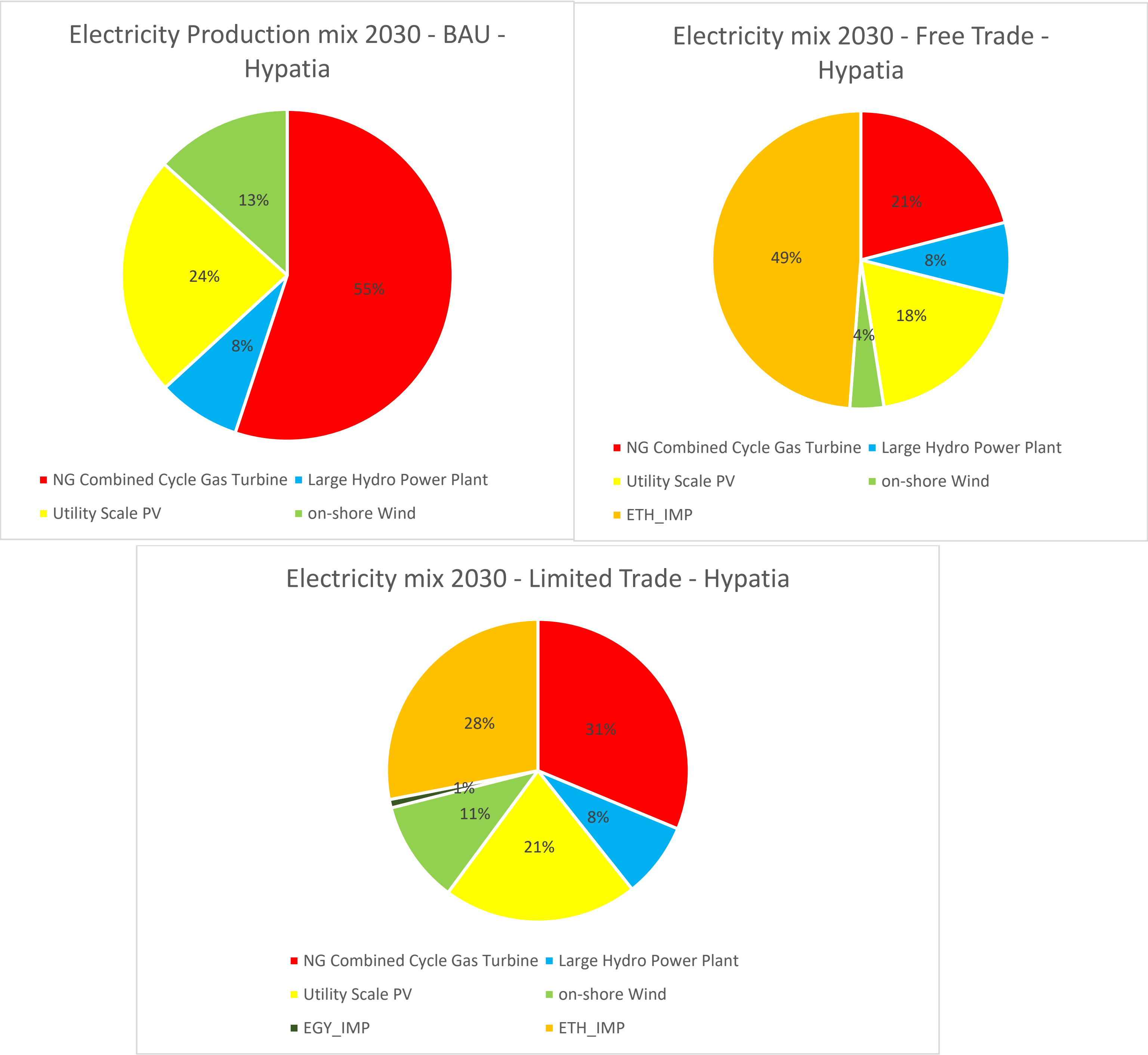


Figure 5.93 - Comparison of electricity production mix in 2030 – Hypatia.

5.4.3 Calliope

Calliope results again coincided with the same conclusions which are:

1- The Free trade scenario curtails the lowest capacity.

2- The demand satisfied by imports is compensated for by local production that is dominated by NG-CCGT unlike OSeMOSYS and calliope which penetrates higher VRES.

3- The eastern part of the country experiences no capacity expansion and act as electricity importer from Ethiopia.

Chapter 6 CONCLUSION AND FUTURE DEVELOPMENT

6.1 Conclusion

This thesis covered a broad range of subjects and enabled the removal of various barriers. This paper demonstrates the possibilities for modeling-related research. Today, tools like OSeMOSYS, Calliope, and Hypatia can address important issues in an energy optimization problem, not just in terms of the capacity across the country but also considering distances, the country's disparities, the resource potential of particular areas, transmission, and distribution structure challenges, import and export from other regions and countries.

The country was divided into five regions for the purpose of this study, and each of those regions had its own distinct resources, sectoral demand forecasts for the present and the future, potential for different types of energy sources, and access to the transmission and distribution network. Due to the lack of present data regarding the current electricity sector situation in Sudan, this thesis was highly dependent on the international resources such as the International Energy Agency and International Renewable Energy Agency. Currently, hydropower plants that take advantage of dams and the Nile basin and thermal power generation from conventional power plants, which primarily use oil products as energy resources, make up Sudan's electricity production. Other renewable energy sources, like solar PV and wind, are not used, despite the nation's vast, untapped potential. Compared to developed and nearby nations, the rate of access to electricity in both urban and rural regions is quite low.

In order to achieve the universal electricity access in Sudan by the year 2030, Three distinct scenarios: Business as Usual (BAU), Free Trade and Limited Trade were implemented in the three energy models investigated in this research. The transitional transmission scenarios allowed exploring alternative pathways for Sudan to achieve its goals by importing electricity from neighbor countries. The results showed that this approach might lower the total costs for Sudan to reach its optimistic goals.

Calliope, unlike OSeMOSYS and Hypatia, relies on snapshot logic rather than capacity deployment. The time resolution in OSeMOSYS and Hypatia used in this study is the seasonal division throughout the year. The Four seasons are further subdivided by day and night operation to account for the variable renewable energy production specially from Solar PV systems. Calliope model is one of the modern energy models that performs effectively with variable renewable energy sources due to its high resolution (hourly resolution).

Key findings in this thesis:

I. The issue of renewable energy's unreliability is handled better by Calliope, which also quantifies this risk as a cost. Furthermore, because seasonal representation of variable renewable sources results in an underestimation of their levelized cost of electricity, it further impedes the transmission of power between regions. Furthermore, Calliope's snapshot logic makes the path to the final year mix unpredictable, in contrast to the other two models.

II. In addition to having an impact on the results, OSeMOSYS's lack of a forward method for modeling transmission lines makes the multi-nodal approach to modeling less valuable, especially when studying access to electricity. OSeMOSYS unlike the two other models (Calliope and Hypatia) allows the electricity to be freely traded and encourages installation of capacity in certain regions rather than having a distributed production in both planning scenarios. Simply, the overlooking of transmission grid expansion costs promoted production where production costs are lower.

III. The modeling of the transmission grid in Calliope and Hypatia, which encourages the regions to achieve self-sufficiency while restricting electricity trade to remain within the existing network capacity, is obviously the biggest difference between OSeMOSYS and the other models investigated in the study, this is noticeable looking at Hypatia and Calliope results in different scenarios:
    - Supply capacity was expanded in all regions in Hypatia and Calliope.
    - Existing power plants were utilized more.
    - Electricity trade magnitudes reduced by orders of magnitudes.

IV. In both planning scenarios, Calliope looks to build significantly more capacity than the other two models. In fact, the installed capacity is roughly twice the total capacity in Hypatia and OSeMOSYS to meet the same demand values in 2030, this is related to the combined effect of hourly time resolution and snapshot logic

V. Calliope leaning toward the dispatchable technologies, geothermal powerplant, hydropower and wind turbines instead of solar PV because of the time resolution effect.

VI. To achieve universal access of electricity Sudan can enter agreements with its neighboring countries and particularly Ethiopia to import electricity dramatically decreasing the overall costs.

VII. The relevance of importation is high regardless of the used model but this relevance also relies on the price of imported electricity in fact doubling the price of electricity imports from Ethiopia reduces the limited trade scenario to the BAU scenario and the imports are completely neglected.

VIII. As renewable energy sources mature and experience a drop in their capital price they tend to become economically more feasible than thermal plants,

IX. Sudan Electricity sector needs a quick and major actions by the government to meet the growing demand and facilitate human development. This action requires a strong political will.

The following Git-hub repository contains the configuration and input data for all the models across the different scenarios:

https://github.com/AhmedAhmed101/Sudan-Electricity-sector-modelling.git

6.2 Future development

Possible improvements to the work are here listed:

1. To more accurately estimate the country's resources and potential, the division of the country can be done while taking into account a higher number of nodes.
2. Environmental aspects such as CO2 emissions and climate change could be explored as decision making parameters for Sudan case study.
3. More precise data from local sources that reflect the nation's current electricity sector situation can fine tune the outputs and present a more realistic outcome.
4. Demand forecasting could be carried out taking into consideration the elasticity of demand with the population and the GDP growth.
5. Conducting a sensitivity analysis on some of the elements that can influence the outcomes, including demand, transmission line capacity, cost, and CO2 emissions penalty.
6. Expanding the scope of the study that exporting electricity from Sudan to its neighbors is an option.

Appendix I

The following appendix represents the C++ program code used to find the average capacity factor for PV and Wind in the previously defined time slices (Seasonal division).

e.g. (Central Sudan average wind capacity factor)

```
#include<iostream>
#include<fstream>
#include<iomanip>
#include<cmath>
#include <stdio.h>
#include <math.h>
using namespace std;
int main()
{
    int i, j, k = 0;

    float SCF [8784][9];
    float wdsum = 0;
    float wnsum = 0;
    float spdsum = 0;
    float spnsum = 0;
    float sdsum = 0;
    float snsum = 0;
    float fdsum = 0;
    float fnsum = 0;
    float wdCF, wnCF, spdCF, spnCF, sdCF, snCF, fdCF, fnCF;

    ifstream infile;

    infile.open ("WCF_center.txt");

    if (infile.is_open())
    {

        for (i = 0 ; i < 8784 ; i++)
        {
            for (j = 0 ; j < 9 ; j++)
            {
              infile>> SCF[i][j];
```

```
    }

}

for (i = 0 ; i < 8784 ; i++ )
{
    for (j= 0 ; j < 9 ; j++)
    {
        if (i >= 0 && i <= 2181)
           {
            if (k >= 4 && k < 16)
            wdsum = wdsum + SCF[i][j];
            if (k < 4 || k >= 16)
            wnsum = wnsum + SCF[i][j];
           }
        if (i >= 2182 && i <= 3645)
           {
            if (k >=4 && k < 16)
            spdsum = spdsum + SCF[i][j];
            if (k < 4 || k >= 16)
            spnsum = spnsum + SCF[i][j];
           }
        if (i >= 3646 && i <= 6573)
           {
            if (k >=4 && k < 16)
            sdsum = sdsum + SCF[i][j];
            if (k < 4 || k >= 16)
            snsum = snsum + SCF[i][j];
           }
        if (i >= 6574 && i <= 8037)
           {
            if (k >=4 && k < 16)
            fdsum = fdsum + SCF[i][j];
            if (k < 4 || k >= 16)
            fnsum = fnsum + SCF[i][j];
           }
        if ( i >= 8038 && i <= 8783)
           {
            if (k >=4 && k < 16)
            wdsum = wdsum + SCF[i][j];
            if (k < 4 || k >= 16)
            wnsum = wnsum + SCF[i][j];
           }

    }
    k++;
     if (k == 24 || i == 2181 || i == 3645 || i == 6573 || i == 8037 )
```

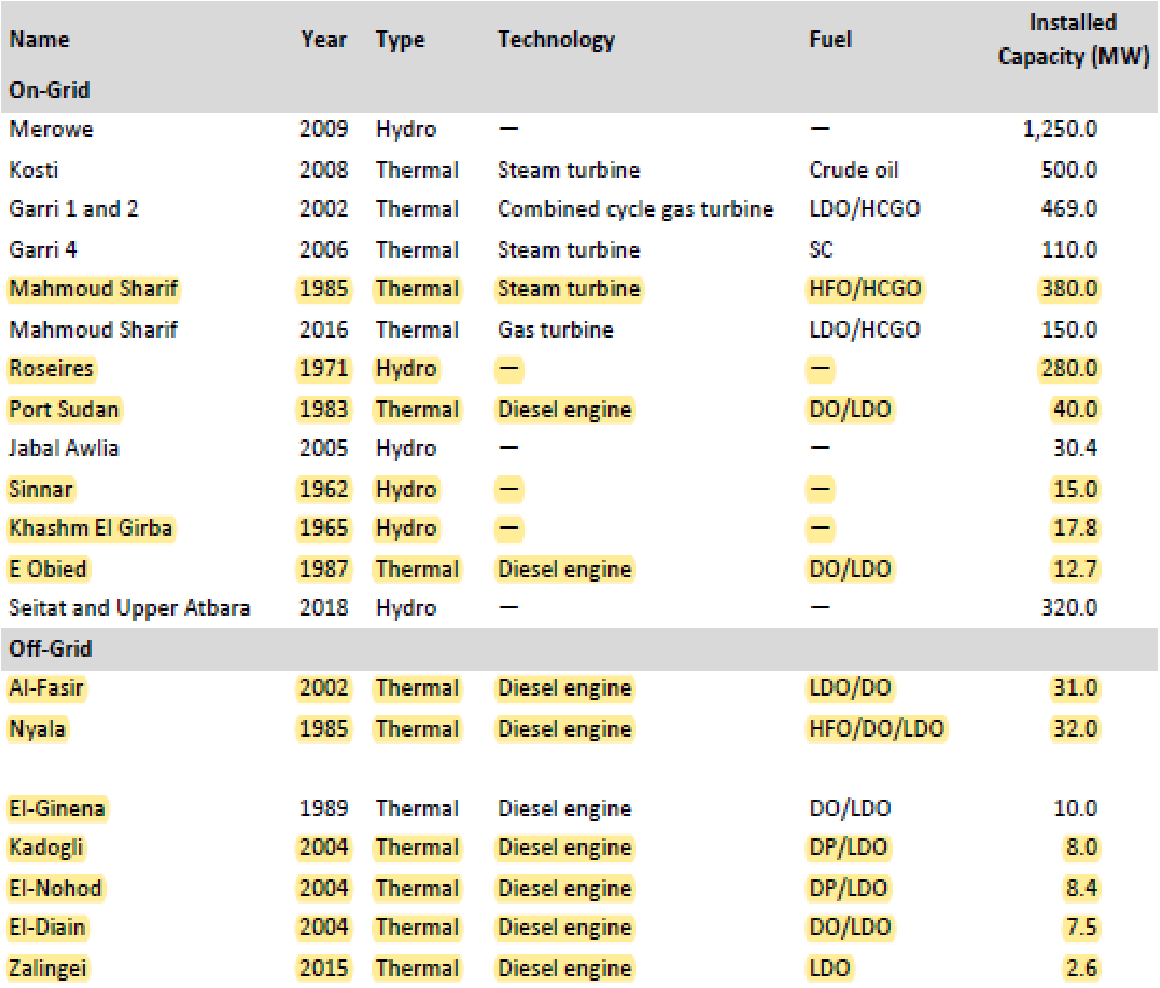
```
              k = 0;
    }

    wdCF= wdsum/13176.0;
    wnCF= wnsum/13176.0;
    spdCF= spdsum/6588.0;
    spnCF= spnsum/6588.0;
    sdCF= sdsum/13176.0;
    snCF= snsum/13176.0;
    fdCF= fdsum/6588.0;
    fnCF= fnsum/6588.0;
    cout<<"wdCF"<<"  "<<wdCF<<"\n";
    cout<<"wnCF"<<"  "<<wnCF<<"\n";
    cout<<"spdCF"<<" "<<spdCF<<"\n";
    cout<<"spnCF"<<" "<<spnCF<<"\n";
    cout<<"sdCF"<<"  "<<sdCF<<"\n";
    cout<<"snCF"<<"  "<<snCF<<"\n";
    cout<<"fdCF"<<"  "<<fdCF<<"\n";
    cout<<"fnCF"<<"  "<<fnCF<<"\n";
    infile.close();
    return 0;

}
```

Appendix II

The following table shows the different existing power plants in Sudan and their respective commissioning year. It also shows the powerplants the surpassed their technological lifetime and considered in the phase-out scenario (yellow marked powerplants).



Name	Year	Type	Technology	Fuel	Installed Capacity (MW)
On-Grid					
Merowe	2009	Hydro	—	—	1,250.0
Kosti	2008	Thermal	Steam turbine	Crude oil	500.0
Garri 1 and 2	2002	Thermal	Combined cycle gas turbine	LDO/HCGO	469.0
Garri 4	2006	Thermal	Steam turbine	SC	110.0
Mahmoud Sharif	1985	Thermal	Steam turbine	HFO/HCGO	380.0
Mahmoud Sharif	2016	Thermal	Gas turbine	LDO/HCGO	150.0
Roseires	1971	Hydro	—	—	280.0
Port Sudan	1983	Thermal	Diesel engine	DO/LDO	40.0
Jabal Awlia	2005	Hydro	—	—	30.4
Sinnar	1962	Hydro	—	—	15.0
Khashm El Girba	1965	Hydro	—	—	17.8
E Obied	1987	Thermal	Diesel engine	DO/LDO	12.7
Seitat and Upper Atbara	2018	Hydro	—	—	320.0
Off-Grid					
Al-Fasir	2002	Thermal	Diesel engine	LDO/DO	31.0
Nyala	1985	Thermal	Diesel engine	HFO/DO/LDO	32.0
El-Ginena	1989	Thermal	Diesel engine	DO/LDO	10.0
Kadogli	2004	Thermal	Diesel engine	DP/LDO	8.0
El-Nohod	2004	Thermal	Diesel engine	DP/LDO	8.4
El-Diain	2004	Thermal	Diesel engine	DO/LDO	7.5
Zalingei	2015	Thermal	Diesel engine	LDO	2.6

Chapter 7 Bibliography

[1] International Energy Agency (IEA), "Defining energy access: 2020 methodology," 13 October 2020. [Online]. Available: https://www.iea.org/articles/defining-energy-access-2020-methodology. [Accessed January 2022].

[2] International Energy Agency (IEA), "World Energy Outlook 2016," IEA, 2016.

[3] International Energy Agency (IEA) , "Africa Energy Outlook 2019," IEA, 2019.

[4] International Energy Agency (IEA), "Africa Energy Outlook 2021," IEA, 2021.

[5] World Bank, "Access to electricity (% of population) - 2020 - Sub-Saharan Africa," 2020. [Online]. Available: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG. [Accessed January 20222].

[6] International Energy Agency (IEA), "Africa energy outlook 2000," IEA, 2000.

[7] World Bank, "The world bank data- GDP per capita (current US$) - Sudan - 1960-2021," 2021. [Online]. Available: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=SD. [Accessed January 2022].

[8] World Bank, "From Subsidy to Sustainability: diagnostic review of Sudan's electricity sector," WB, 2019.

[9] Macrotrends, "Sudan inflation rate 1960-2022," www.macrotrends.com, 2022. [Online]. Available: https://www.macrotrends.net/countries/SDN/sudan/inflation-rate-cpi#:~:text=Sudan%20inflation%20rate%20for%202021,a%2099.33%25%20increase%20from%202019. [Accessed January 2022].

[10] P. S, H. A and K. J, "Energy system modelling for twenty-first century energy challanges," *Renwable and Sustainable Energy Reviews,* vol. 33, pp. 74-86, 2014.

[11] B. Van and N. M. J. P. , "Classification of Energy Models," *FEW Research Memorandum,* vol. 777, 1999.

[12] G. Manzolini, M. Prina, D. Moser , B. Nastasi and W. Sparber, "classifications and challanges of bottom-up energy systems models," *Renewable and Sustainable Energy Reviews,* vol. 29, 2020.

[13] H. Ringkjob, P. Haugan and I. solbrekke, "A review of modelling tools for energy and electricity systems with large shares of variable renewables," *Renweable and Sustainable Energy Reviews,* vol. 96, pp. 440-459, 2018.

[14] J. Depres, N. Hadjsaid, P. Criqui and I. Noirot, "Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools," *Energy,* pp. 486-495, 1 February 2015.

[15] C. Budischak, D. Sewell, H. Thomson , L. Mach, D. Veron and W. Kempton, "Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time," *Journal of Power Sources,* vol. 225, pp. 60-74, 2013.

[16] G. Haydt, V. Leal, A. Pina and C. Silva, "The relevance of the energy resource dynamics in the mid/long-term energy planning models," *Renewable Energy,* pp. 3068-3074, November 2011.

[17] S. Jebraj and S. Inyian , "A review of energy models," *Renewable and Sustainable Energy Reviews,* vol. 10, no. 4, pp. 281-311, August 2006.

[18] International Renewable Energy Agency (IRENA), "Planning and Prospects for Renewable Power: Eastern and Southern Africa," IRENA, Abudhabi, 2021.

[19] International Energy Agency (IEA), "Sudan Sankey Diagram," 2020. [Online]. Available: https://www.iea.org/sankey/#?c=Sudan&s=Balance. [Accessed January 2022].

[20] International Energy Agency (IEA), "Sudan Total Final Consumption by Sector 1990-2019," 2019. [Online]. Available: https://www.iea.org/countries/sudan. [Accessed January 2022].

[21] International Energy Agency (IEA), "World Energy Outlook Special Report: Africa Energy Outlook 2022," IEA, 2022.

[22] M. Brinkkerink and D. Paul, "PLEXOS-Wrold 2015," *Harvard Dataverse,* vol. 6, 2020.

[23] S. Ibrahim and O. Khayal, "Solar Energy Potential and Assessment of CSP Plant Accounting for sustainability in Sudan," *International Journal of Engineering Applied Sciences and Technology ,* vol. 5, no. 7, pp. 13-19, 2020.

[24] Solargis, "Solar resource maps of World," © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis., 2020. [Online]. Available: https://solargis.com/maps-and-gis-data/download/world. [Accessed January 2022].

[25] J. Tran , N. Grue and S. Cox, "Renewable Energy Data," National Renewable Energy Laboratory (NREL), USA, 2018.

[26] Global Modelling and Assimilation Office (GMAO), "inst3_3d_asm_Cp: MERRA-2 3D IAU State, Meteorology Instantaneous 3-hourly (p-coord, 0.625x0.5L42), version 5.12.4," Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC), Greenbelt, 2022.

[27] Philadelphia Solar, "PS-M60-(305-330w) Mono PERC Crystalline Module," 2018. [Online]. Available: https://philadelphia-solar.com/wp-content/uploads/2022/10/PS-M60325-330W.pdf.

[28] G. Richard, "How Much Land Is Needed for Wind Turbines?," 10 May 2018. [Online]. Available: https://sciencing.com/much-land-needed-wind-turbines-12304634.html. [Accessed 15 January 2022].

[29] State Information Service, "Egypt, Sudan to execute projects on seismic stations, geothermal energy," 17 August 2021. [Online]. Available: https://www.sis.gov.eg/Story/158726/Egypt%2C-Sudan-to-execute-projects-on-seismic-stations%2C-geothermal-energy?lang=en-us. [Accessed 25 Ocotber 2022].

[30] ACRES International Limited, "Interim Report. Long Term Power System Planning Study. Heat Flow Data in the Central Red Sea Region. Unpublished report.," 1992.

[31] Worldometer, "Sudan Oil," Worldometer, 2022. [Online]. Available: https://www.worldometers.info/oil/sudan-oil/. [Accessed January 2022].

[32] Sudanese Ministry of Oil and Petrolum, "Oil Reserve Map," 2022. [Online]. Available: https://www.mop.gov.sd/eng/page/map. [Accessed January 2022].

[33] United Nations Environment Programme, "Energy Profile Sudan," UN, 2017.

[34] B. Sawe, "What Are The Biggest Industries In Sudan?," *Economics,* 3 June 2019.

[35] Agricultre Bank of Sudan, "Agriculture points and centres," 2022. [Online]. Available: https://cbos.gov.sd/en/content/agricultural-bank-sudan. [Accessed January 2022].

[36] United Nations Statistical Division, "Population and Vital Statistics Report," UN, 2019.

[37] International Renewable Energy Agency (IRENA), "Planning and Prospects for Renewable Power: West Africa," IRENA, AbuDhabi, 2018.

[38] Energy Information Adminstration (EIA), "Assumptions to the Annual Energy Outlook 2022: International Energy Module," EIA, U.S.A., 2022.

[39] I. H. M. S. V. U. W. S. A. G. F. a. R. E. Pappis, "Energy projections for African countries," Luxembourg, 2019.

[40] S. Pfenninger, "Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability," *Applied Energy,* pp. 1-13, 1 July 2017.

[41] Egypt Today Staff, "Egypt-Sudan electricity interconnection to become corridor for energy transmission to Africa, Europe," Egypt Today, 23 February 2022. [Online]. Available: https://www.egypttoday.com/Article/3/113156/Egypt-Sudan-electricity-interconnection-to-become-corridor-for-energy-transmission. [Accessed 25 October 2022].

[42] Global Petrol Prices, "Egypt Electricity Prices," 2022. [Online]. Available: https://www.globalpetrolprices.com/Egypt/electricity_prices/. [Accessed 25 October 2022].

[43] Global Petrolum Prices, "Ethiopia Electricity Prices," 2022. [Online]. Available: https://www.globalpetrolprices.com/Ethiopia/electricity_prices/. [Accessed 25 October 2022].

[44] African Union - Program for infrastructure Development in Africa , "Ethiopia - Sudan Transmission Interconnector (Ethiopia section)," PIDA, 2022. [Online]. Available: https://www.au-pida.org/view-project/312/#:~:text=The%20project%20comprises%20a%20power,Ethiopia%20Renaissance%20Dam%20(GERD).. [Accessed 25 October 2022].