Modelling the Development of East Africa's Interconnected Electricity Network

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***Abstract*—The East African region is planning to move to increase its energy supply and increase access to electricity by 2030 to 100%. The East African Power Pool (EAPP) proposed building power plants and interconnected transmission infrastructures between the countries. In this study, we develop a multi-region economic dispatch model to assess if the proposed EAPP increased generation capacity and interconnections Master Plan will meet demand by 2050. Our results show that under the EAPP Master Plan, most countries will be able to meet demand either from national supply or imported electricity by 2030; however, after 2030 demand outpaces supply and the electricity supply-demand gap widens. Our study shows that East African countries will need an additional 124 TWh of supply by 2050 to meet demand. This is a significant gap and countries should increase their current plans for electricity generation beyond 2030.**

Keywords—East Africa, economic dispatch model, energy access, interconnected network, multi-region energy model.

I. INTRODUCTION

To fulfill the projected growing demand for electricity in Eastern Africa by 2050, particularly in a scenario of high economic growth [1], requires an increase of electricity generation as well. This indicates a significant disparity between the regional electricity supply and demand, highlighting the pressing need for increased capacity. To address the shortage in electricity supply and bridge the regional gap, countries in East Africa, particularly Ethiopia, Kenya, Tanzania, Sudan, Democratic Republic of Congo (DRC) and Rwanda have developed national policies aimed at achieving 100% electricity access and enhancing electricity supply capacity. These policies encompass various strategies and initiatives, which are tailored to the specific needs and resources of each country. In an effort to address the regional electricity access issues, the Eastern African Power Pool (EAPP) was formed under the Inter-Governmental Memorandum of Understanding (IGMOU) in 2005 by seven member countries; Sudan, Kenya, Rwanda, Ethiopia, DRC, Burundi and Egypt with the aim of delivering reliable, affordable and secure electricity across East Africa from regional interconnections and proposed power plants [2]. As of 2022, the EAPP has incorporated 13 countries that are: Djibouti, DRC, Burundi, Egypt, Ethiopia, Libya, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania and Uganda [2]. In addition, national policies are implemented in these countries including the National Electrification Program (NEP) in Ethiopia, the Kenya National Electrification Strategy (KNES), the National Electricity Grid Code in Sudan to regulate and manage the country's electricity sector, Rwanda National Electrification Plan (NEP) to achieve universal access to electricity by 2024 and beyond [3][4][5][6]. Countries in the region are consistently short on electricity supply and hence experience significant power outages. Further, countries that meet national electrification rates like Egypt and Libya still experience significant power cuts as an outcome of increased consumption needs in hotter seasons in the year, and with increased population density in urban areas over the past decade [2]. Power supply is particularly unavailable in rural areas, which dominates the population demographic in most EAPP countries; electricity supplied is centralized, therefore rural areas in EAPP countries either do not receive grid connected electricity, or limited to small scale or intermittent supply as national demand exceeds the overall generation. EAPP interconnections can potentially tap into a larger demand in the region, and help alleviate pressures of national grids through the export of surplus electricity to neighbouring countries, and facilitate systems flexibility.

The concept of regional multi-interconnections and the integration of power plant projects in East Africa have received considerable attention in the literature. Various studies have examined the potential benefits, challenges and implications of such initiatives. Kuyioni and Ong'anda (2018) provides an analysis of the existing power interconnections in East Africa and discusses the challenges and prospects for regional multi-interconnections, highlighting the potential benefits of enhanced electricity trading and cooperation among countries in the region [7]. Mutale and Moriarty (2017) reviewed the potential for integrating large-scale renewable energy projects in East Africa and discusses the technical challenges of integration, policy frameworks, and the potential socio-economic and environmental benefits [8]. Lesaoana and Kenyon (2016) focuses on the EAPP and its strategic framework for regional power system development, examining the potential for large-scale renewable energy projects such as hydropower and geothermal energy [9]. Further research and analysis in this field can contribute to the development of robust strategies for regional energy cooperation and sustainable energy transitions in East Africa.

This study focuses on modelling the EAPP regional interconnected electricity system to assess the feasibility of the proposed plans for both interconnections and large scale renewable energy in delivering reliable andsustainable electricity. The application of high temporal and spatial resolution on an hourly simulation is applied to covey the variable output of renewable energy in various areas in the EAPP region. A Business as Usual (BaU) model that reflects the EAPP existing, committed and proposed interconnection lines and power plants is modelled from 2020 to 2050. The model presents the impact of large scale power plants and interconnections in meeting electricity demand, addressing

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the question on whether the proposed plans can close the electricity supply-demand gap and deliver secure electricity.

II. Literature Review

Limited research has been conducted on modelling electricity networks in East Africa; specifically examining the EAPP. Several studies have contributed to understanding the interconnections and capacity requirements within the EAPP. Musau et al. (2017) modelled various types of interconnection including High Voltage Direct Current (HVDC) and Direct Current (DC) to assess the technology capacity in the EAPP [10]. Their research aimed to determine the optimal interconnection types and capacity to support efficient electricity transmission and exchange within the region [10]. In a related study, Musau (2018) examined the emissions associated with HVDC and DC (MTCD) interconnections in the EAPP [11]. By evaluating the environmental impact, the research aimed to provide insights into the sustainability of interconnection projects and their potential contribution to reducing greenhouse gas emissions [11]. Wright (2014) conducted a modelling analysis to assess the wholesale cost of existing and planned interconnections within the EAPP and explored the optimization of power plant maintenance performance in Kenya and Tanzania alone [12]. The study focused on cost-efficiency and maintenance strategies to ensure the reliable operation of interconnected power systems [12]. Additionally, the EAPP (2014) developed a model to project the region's generation capacity for 2020 and 2025 [2]. Through a least cost- optimization approach, the study aimed to identify the marginal costs associated with electricity generation in the region. The modelling exercise provided insights into the economic feasibility and cost-effectiveness of various generation sources within the EAPP [2].

Overall, the current literature highlights the cost-optimization generation supply within the EAPP, which largely has unreliable and low electricity access that is highly dependent on hydro, coal and gas power plants with little progress in other energy technologies to increase capacity. The EAPP supply mix as of 2020 is mainly hydro and fossil fuels (specifically coal and gas) [2]. Current national plans in the EAPP continue to prioritize hydro, gas and coal supply by 2030. Hence, further research is needed to address the temporal-spatial modelling of East Africa's supply and interconnections plans by 2050 in a high spatial and temporal resolution model. Further research in this domain is essential to support evidence-based decision-making for regional energy planning and the integration of large-scale energy sources.

This study focuses on assessing the planned supply power plants by 2050 in the EAPP in a multi-region economic dispatch model to evaluate if the planned generation capacity increase and interconnections will meet demand and fulfill national electrification rate in 2030 and beyond.

III. Methodology

A. Electricity Modelling Tool

To model the planned power plants and interconnections under the EAPP proposed, the PLEXOS Integrated Energy Model was utilized to simulate the electricity networks and power plants. Specifically, the Long Term (LT) Plan was employed to optimize the expansion of generation and transmission capacities between the years 2020 to 2050 [13]. The electricity networks were modelled with single nodes per country and respective power plants linked to single nodes representing countries. The power plants were simulated based on national planned capacity expansion [2]. The simulation aims to provide insights into the potential outcomes of the proposed plans, considering factors such as electricity demand, generation capacity, and transmission infrastructure. The LT Plan optimization process allowed for the identification of the most efficient and cost-effective expansion strategies to meet the projected electricity access targets within the specified timeframe [11].

B. Electricity Demand Forecasting

To determine the necessary supply to meet total electricity access, the electricity demand is forecasted until 2050 with consideration to growth projections. As data was limited on the hourly electricity demand for each country, available hourly demand over a year was sourced from IRENA [1]. Countries without available hourly demand had the same hourly demand profile as countries with hourly demand profiles and similar annual electricity demand. Peak electricity demand and projected annual electricity consumption were obtained from the EAPP [2] datasets. The Advanced Growth Algorithm in PLEXOS was applied to forecast hourly load profiles towards 2050 built from the hourly demand profile, consumption, and peak demand with the energy growing rate from EAPP [12] and the projected demand growth vary between 40-60% among the EAPP countries. Figure 1 presents the demand profile for EAPP for 2020.

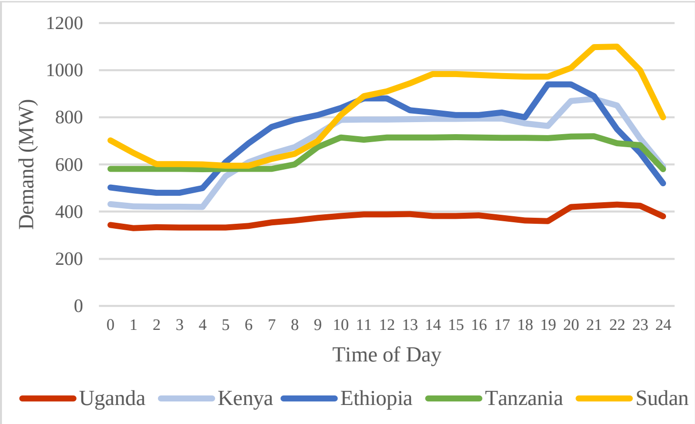

Fig. 1. Demand Profiles for EAPP countries.

C. Generation and Power Plants

In order to model the development of supply in East Africa, the capacity aims are extracted from national master plans and the EAPP, as presented in Table 1. The power plant capacites, technology charateristics, fuel and cost were inputed to establish the generation capacity as planned in the EAPP Master Plan, including existing, committed and planned power plants until 2050 [2]. The capital costs, transport costs and operating and maintence costs of power plants were inputed based on the EAPP reports and IRENA [1]. The fuel costs for coal and gas, and technical life and retirement age of each power plants were considered based on IRENA (2017) [1].

TABLE I. SUPPLY CAPACITY AIMS (DATA SOURCE: EAPP, 2014).

Country	Capacity Aims
DRC	Hydro: gradual increase to 42 GW by 2050.
Egypt	Natural gas, coal, Nuclear: 24.2 GW, 7 GW, 1.65 GW by 2020 respectively; 9.6 GW, 6 GW, 3.3 GW by 2030 respectively.
Ethiopia	Hydro power: 9 GW by 2030. Wind: 900 MW by 2016. solar: 300 MW by 2030. Geothermal: 5 GW by 2037.
Kenya	Nuclear: 5 GW by 2030. Geothermal: 5 GW by 2037. Coal: 2 GW by 2020. LNG: 1 GW by 2020.
Libya	Natural gas and oil: 23.6 GW.
South Sudan	Hydro: 40 MW, 300 MW by 2020 and 2025 respectively. Diesel: 336 MW by 2020. Additional 11 MW by 2025.
Sudan	3.3 GW by 2030.
Tanzania	Hydro, gas, coal: 3.3 GW, 1 GW; 3.8 GW by 2035 respectively.
Uganda	Hydro power: 2.4 GW by 2030.

D. *Regional Interconnection Lines*

All existing, committed and proposed interconnection lines between countries were simulated based on the EAPP Master Plan [2], which extends towards 2040 only. PLEXOS LT Planning simulates the last cost expansion planning while considering the electricity constraints of tranmission lines' capacities [11]. The existing and planned interconnections are presented in table 1. Although delays in the installation and opertation of the interconnection lines are expected, this model assumes lines planned before 2020 would be in operation by 2020, and all interconnections after 2020 are installed within the specified year.

TABLE II. INTERCONNECTIONS IN EAPP (DATA SOURCE: EAPP, 2014).

Countries	Existing and Planned Lines					
	Existing	2020	2025	2030	2035	2040
DRC – Rwanda	100		318	1198	1830	1861
DRC – Uganda	5		488	950	1266	2270
Egypt - Libya		176	176	176	176	176
Egypt – Sudan		500	1000	1000	1000	1000
Ethiopia – S. Sudan						446
Ethiopia - Sudan	200	1596	1596	1596	1596	1683
Kenya - Uganda	145	277	624	989	989	989
Rwanda - Tanzania		196	954	1724	2274	2274
Sudan – S. Sudan	300		330	330	330	330
S. Sudan - Uganda		623	623	623	623	724

IV. RESULTS AND DISCUSSIONS

A. *Electricity Generation and Demand*

To explore development of generation in the EAPP, the electricity demand and supply are demonstrated in figure 3. From 2020 to 2030, several countries are able to meet demand under the planned power plant projects, except Egypt, Kenya and Tanzania which have substantial supply-demand gaps exceeding almost 20TWh in 2020 and 2030, highlighting the growing population, consumption and consequent electricity demand. However, in 2030, the regional aggregate demand and supply are met, and countries Libya, Sudan, South Sudan, Ethiopia, Djibouti, Uganda, DRC and Burundi meet national electrification, while countries Rwanda, Kenya, Tanzania and Libya still have higher demand than national supply. From the overall region, and interconnections facilitate electricity flow from countries with surplus electricity to countries in electricity shortage.

Coal and gas make most of the supply mix, however, the presence of Egypt, a coal and gas reliant country, as the country with the largest supply skews the supply mix towards coal and gas. The region transitions from a gas-heavy mix to a coal-heavy mix predominately in countries Kenya, Tanzania, Sudan and Egypt, and in 2040, coal is the largest supply technology. Although coal continues to be the largest supply technology in 2050, geothermal energy grows substantially, making almost 150 TWh in 2050, from just 60 TWh in 2020. Traditional sources of energy like peat and waste make a marginal contribution to the mix as the application is small in scale, whereas hydro power is still a significant energy source, maintaining 5% of the energy source from 2020 to 2050, and the primary source of energy in all countries except Libya, Egypt, Tanzania and Kenya. Although supply grows significantly by approximately 20%, 30% and 40% consecutively from 2020 to 2050 each decade, the demand grows much more, with an almost 116 TWh gap in demand-supply across the timescale, and considerably in 2050 where the supply-demand gap is almost 60 TWh alone.

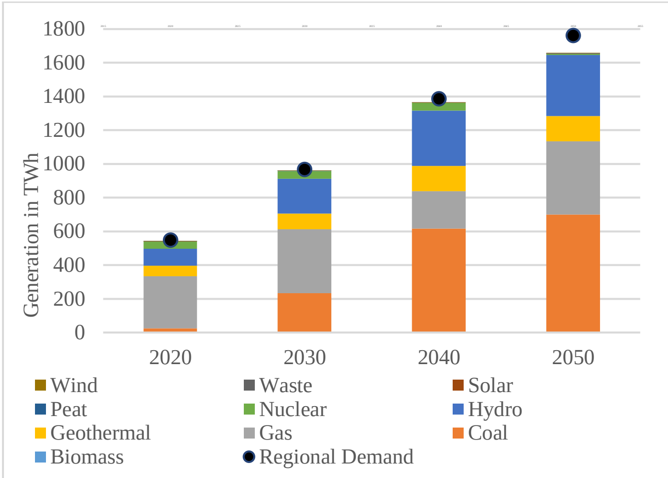

Fig. 2. Regional Generation and Demand in EAPP.

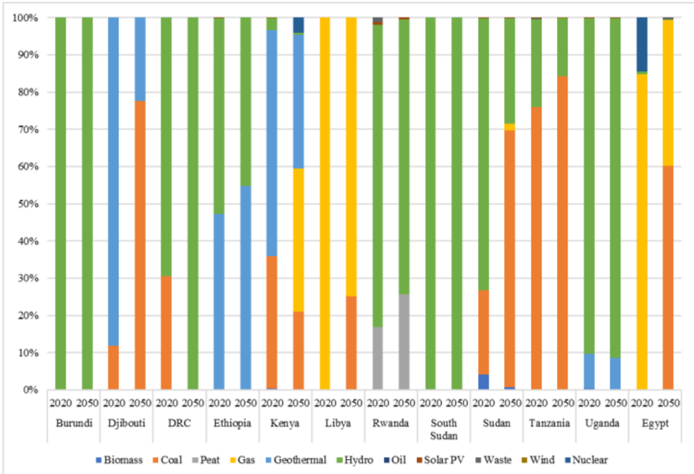

Fig. 3. Supply Mix in 2020 and 2050.

B. *Interconnection Flows*

To counter the shortage of supply in countries, interconnection lines facilitate the flow of surplus electricity to countries experiencing electricity shortages in the EAPP. As national electricity demand is forecasted to grow, it is evident that more supply is required but unavailable. Interconnections continue towards the north starting from Uganda towards South Sudan, Sudan, Egypt and Libya. Countries that meet national electricity demand like DRC, Ethiopia and Uganda continue to export electricity to neighboring countries specifically Rwanda and Burundi, Sudan and Kenya and South Sudan respectively. Overall, an increased regional demand places significant pressure on the electricity systems to perform and meet export demand. As countries like Ethiopia prioritize exporting electricity, neighboring countries like Sudan benefit significantly in meeting demand. In 2020, countries Egypt, Tanzania, Kenya and DRC experience supply shortage, and hence neighboring countries supply electricity via cross-border lines. This trend continues; as seen in Figures 4 to 7 that countries Egypt, Kenya and Tanzania suffer electricity shortages across the projected period, and electricity flow from interconnections still does not offset the imbalance of national supply-demand gaps.

Figure 4: Interconnection Flows in EAPP from 2020 to 2050.

The year of 2030 is when most countries meet demand, but following 2030, there is a steep growth in demand and countries struggle to compete in electricity export and import. Further, countries like Ethiopia, Uganda and Sudan continue to export electricity at the risk of reduced national electricity access after 2030. Similarly, relatively smaller countries Djibouti and Burundi manage to maintain some national electricity access, but after 2030, the demand exceeds supply. Towards 2050, almost all countries cannot meet electricity demand apart from DRC and Djibouti under the planned power plants and interconnection projects. Although the interconnections relieve some pressures from the overall power systems, the projected electricity demand and economic growth, as well as population will likely require significantly more electricity demand. By 2050, almost 60 TWh more of electricity is needed to meet national electricity demand in the EAPP.

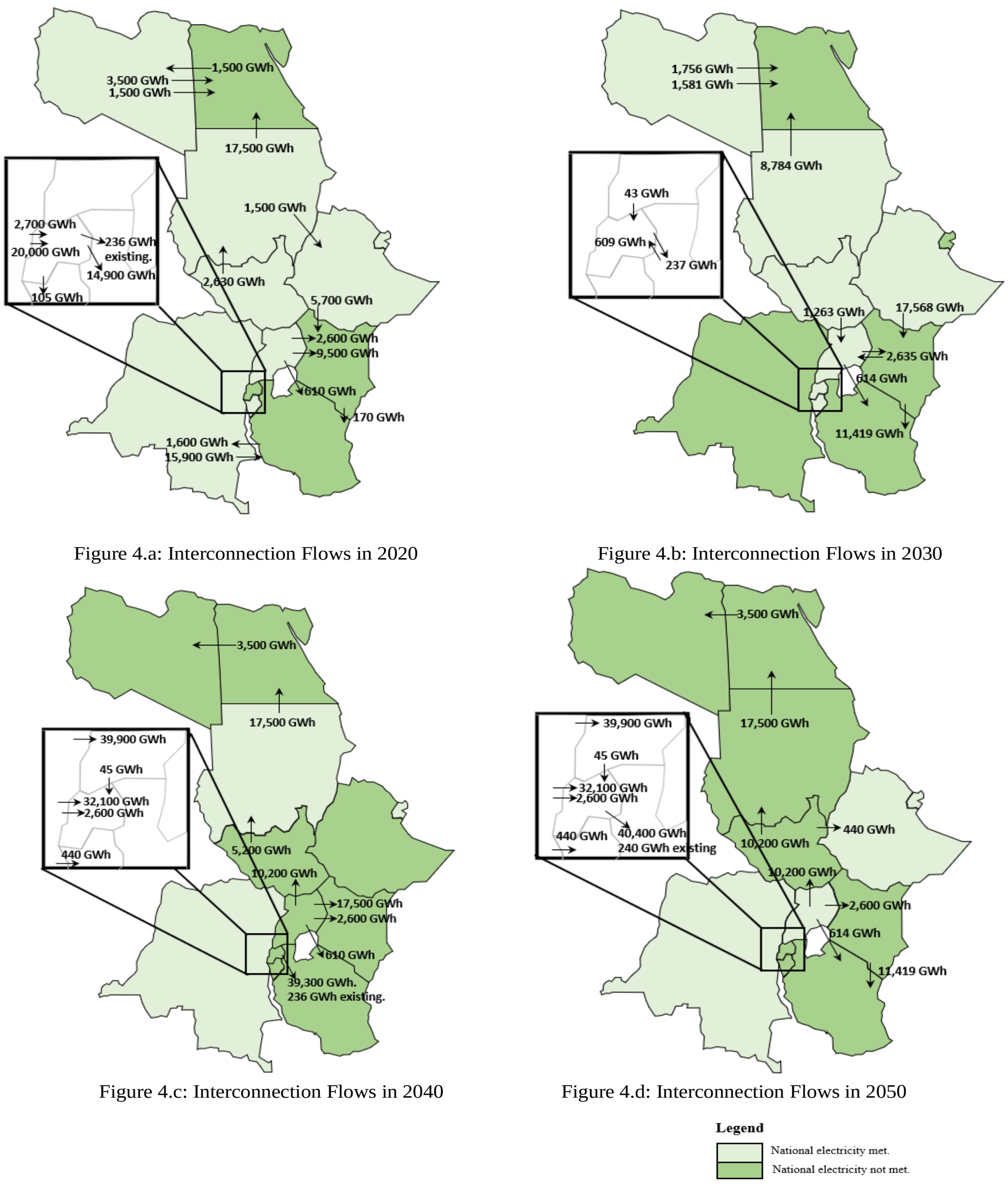

Figure 4.a: Interconnection Flows in 2020

Figure 4.b: Interconnection Flows in 2030

Figure 4.c: Interconnection Flows in 2040

Figure 4.d: Interconnection Flows in 2050

C. Emissions

A regional increase in emissions production is anticipated with the growth in coal and gas. Countries Tanzania, Egypt, Kenya and Sudan are particularly expected to have high emissions output as a result of new coal power plant projects planned to avoid supply shortages and potential blackouts. Although gas contributes substantially in the region, the carbon content of coal is significantly higher, and Libya and Egypt alone are predominately engaged on building new gas power plants. Furthermore, the total emissions from 2020 to 2050 of peat and waste power plants of 25 and 3 million tonnes of carbon emissions respectively waste highlight a marginal scale of emissions in comparison to coal and gas in the region, and likely continue to insignificantly with low expected large scale projects in waste and peat regionally.

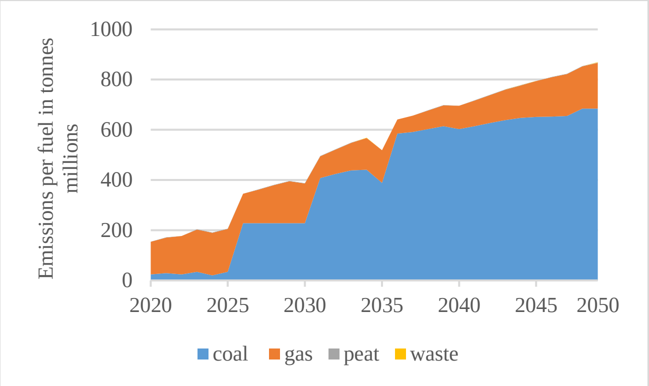

Figure 5: Total Emissions per fuel in tonnes millions in East Africa.

D. Model Validation

A validation has been performed between the PLEXOS model, which is formed from the EAPP dataset on supply capacities, and compared with the IRENA dataset on annual generation of countries in 2020. Table 3 outlines the generation varies in countries, where overall PLEXOS anticipated much more generation than IRENA recorded, and hence outlines potentially greater demand-supply gap and significantly more supply needed to attain national electricity access in East Africa. An F-test resulted in a statistically insignificant difference between the modelled scenario with PLEXOS and the IRENA data.

Countries	Model (GWh)	Data (GWh)
Libya	39,754	44,719
Rwanda	1,362	915
Sudan	23,816	16,548
Tanzania	8,042	7,975
Uganda	5,909	4,442

TABLE III: RESULTS FROM PLEXOS VS DATA FROM IRENA.

V. CONCLUSIONS

In this study, the impact of interconnections and large scale supply projects were modelled to address the supply-demand gap and consequent national access of electricity in East Africa. EAPP supply capacities and interconnections were modelled from 2020 to 2050. Results present a series of supply increase is necessary to follow the growing pace of demand across all countries, with a regional supply deficit of 116 TWh in the modelled period, and although some countries in the model meet national electricity access in 2030, the access declines substantially after 2030 onwards. Furthermore, by 2050 very few countries can meet electricity needs, which highlights the importance of assessing long-term supply plans alongside interconnection agreements. Furthermore, some countries risk the national supply over exporting electricity; this trend may highlight the contractual obligations of bilateral agreements to supply cross-border electricity irrespective of whether national electricity access is met. In terms of supply technology, countries with higher hydro mix like DRC, Sudan, South Sudan, Uganda, and Ethiopia have greater export capacity than coal and gas-heavy countries Egypt, Libya, Tanzania and Kenya. Countries that are predominately reliant on coal in the future will need substantially much more supply, which may risk projected net zero targets as part of global efforts to combat climate change. Potential for shared investment opportunities can arise to divide costs of increasing generation capacity and interconnection flow for the benefit of both importing and exporting countries.

REFERENCES

[1] IRENA (2021) 'Planning and Prospects for Renewable Power: Eastern and Southern Africa'.

[2] EAPP (2014) EAPP Regional Power System Master Plan Executive Summary. Addis Ababa.

[3] Federal Democratic Republic of Ethiopia (2019) 'National Electrification Program 2.0 Integrated Planning for Universal Access'. Addis Ababa.

[4] World Bank (2018) ' Kenya National Electrification Strategy'.

[5] Sudan General Secretartat (2007) 'The National Council for Strategic Planning'.

[6] Republic of Rwanda (2016) 'Rural Electrification Strategy'.

[7] Kuyioni, S., and Ong'anda, H. O. (2018). Regional Power Interconnections in East Africa: Current Status, Challenges, and Prospects. Journal of Energy, 2018, 1-10

[8] Mutale, V., & Moriarty, P. (2017). Assessing the Potential of Renewable Energy Integration in East Africa: A Review. Renewable and Sustainable Energy Reviews, 77, 1251-1266.

[9] Lesaoana, M., & Kenyon, T. (2016). The East Africa Power Pool: A Strategic Framework for Regional Power Systems Development. Energy Strategy Reviews, 14, 122-132

[10] Musau, M. P., Odero, N. A. and Wekesa, C. W. (2017) 'Asynchronous Interconnection of the Proposed East Africa Power Pool (EAPP)', IEEE, pp. 7–11.

[11] Musau, M. P. (2018) 'Analysis of the East Africa Power Pool (EAPP) with Renewable Energy Penetration and Proposed Asynchronous Tie Lines', IEEE, pp. 336–341.

[12] Wright, J. G. (2014) 'Developing an Integrated Energy Model for the Eastern African Power Pool (EAPP)', (September).

[13] Energy Exemplar (2019) Concise Modelling Guide, PLEXOS WIKI. Available at: https://wiki.energyexemplar.com/index.php?n=Article.ConciseModellingGuide#ntoc1 (Accessed: 20 April 2023).