Electricity Economic Model of the African Continent

Robert Gaugl, Udo Bachhiesl, Sonja Wogrin

Graz University of Technology, Institute of Electricity Economics and Energy Innovation, Inffeldgasse 18, 8010 Graz, +43 316/873-7904, robert.gaugl@tugraz.at, https://iee.tugraz.at

Abstract:

The first part of this paper details the current status of Africa's electricity market with its five power pools. We give an overview of the pathway of the five power pools to form integrated electricity markets, their installed power generation capacity and have a look at the power transmission system.
The second part of this paper shows the path towards modelling Africa's electricity system. To build a model of the African electricity economy, the transmission system, which is based on open-source data, is combined with a database of Africa's existing power plants using a GIS-approach.
The resulting Excel-files containing the electricity grid and the generation infrastructure include all the necessary information and are easily editable and formattable so that they can be used by a wide variety of electricity economic models.

Keywords: electricity economics, simulation model, transmission grid, power plant park

1 Introduction

Africa has the world's lowest electricity consumption with around 535 kWh per capita[1]. Also, Africa is only responsible for around 3.3% [1] of global energy related CO_2-emissions, although it has about 16% [2] of the world's population. With Africa's expected growth of electricity demand, especially in the Sub-Saharan countries where an annual increase of 6.5% is expected (Stated Policies Scenario from [3]), the question arises how the electricity infrastructure (power lines and power plants) has to develop while also trying to transform the electricity sector towards the use of more renewable energy sources.

In Section 2 of this paper we want to give an overview of the current status of the African electricity market. Section 3 shows the path towards building an electricity economic model of the African continent. The first step towards this path is to get and combine data about Africa's electricity grid and power plants. The resulting data should contain the most important data to run electricity economic models with load flow calculations, while also being flexible enough to use the data easily in a wide variety of models.
One such model is ATLANTIS [4], which is a period-based electricity economic model developed at our Institute of Electricity Economics and Energy Innovation. It uses a DC optimal

[1] Based on electricity demand of 700 TWh in 2019 [3] and a population of 1.308 billion [2]

power flow (DC-OPF) calculation and it can be used for long-term scenario calculations. It combines the technical part of the electricity system, including the electricity demand, transmission grid and power plants, with the economic part of the system including the electricity companies, inflation, fuel prices and other economic information.

Another model, where the resulting information could be used, is LEGO [5] which is an open-source model that can be used for short-term unit commitment as well as long-term generation and transmission expansion planning. It can be used with either chronological hourly data or representative periods. It is designed to be very modular and the different modules can be switched on or off as needed. These modules allow for unit commitment constraints, a DC- or (simplified) AC-OPF calculation, inertia constraints and more.

2 Overview of Africa's Electricity Grid and Markets

There are five power pools in Africa, as can be seen in Figure 1, which were established to interchange electricity between the members of the power pools. Some of the countries participate in more than one power pool (see the shaded countries in Figure 1). The goal is to have a greater cross-border trade within the power pools, which should lead to more reliability and to a more cost-effective electricity production. [6]

Figure 1: African Power pools and their member states [1]

For participating countries, it is possible to create a more robust power grid and power market. The advantages of the economies of scale can also be used by pooling resources in generation, transmission and distribution of electricity. In order for power pools to work they require (1) development of cross-border interconnections between the countries in order to connect the national grid to the power pool and to be able to exchange the traded electricity, (2) a common legal and regulatory framework and (3) multi-country organisational structures that plan, harmonise and develop a framework for cross-border electricity trading. [7]

Cross-border electricity trading in Africa already started in the 1950s and 1960s with bilateral agreements, but the success of US and European power pooling as well as the limitations of bilateral arrangements (for example in covering peak demands) and the start of liberalisation of national grids in the 1990s lead to the desire to go beyond bilateral approaches and form the first power pools. [6]

Table 1 shows the power generation capacity by power pool in the year 2015. The list of countries in the power pools for Table 1 is shown in Table 2. Countries that are in more than one power pool are only included in one of the power pools in Table 1 to avoid double counting.

Table 1: Power generation capacity by power pool in 2015 [6]

Region	Coal [MW]	Diesel/HFO [MW]	Gas [MW]	Hydro [MW]	Solar [MW]	Wind [MW]	Geothermal [MW]	Biomass [MW]	TOTAL [MW]
NAPP	2 585	1 866	25 532	1 851	411	952	0	0	**33 197**
SAPP	41 289	2 963	1 375	7 624	1 585	1 010	0	451	**56 297**
EAPP	26	6 130	31 564	8 622	33	793	691	1 727	**49 586**
WAPP	68	3 242	13 292	5 025	55	12	0	50	**21 744**
CAPP	0	658	873	2 886	5	0	0	9	**4 431**
TOTAL	**43 968**	**14 859**	**72 636**	**26 008**	**2 089**	**2 767**	**691**	**2 237**	**165 255**

In 2015 Africa had a total installed power generation capacity of 165 255 MW of which gas-fired power plants are the most common with 72 636 MW. Coal power plants still make up the second largest share (43 968 MW), followed by hydropower plants (26 008 MW). The SAPP is the region which has the highest installed capacity (56 297 MW) among the power pools. The CAPP is the least developed power pool in Africa, which can also be seen on the small number of installed power generation capacity of 4 431 MW. [6]

Table 2: List of countries per power pool considered in the analysis for the power generation capacity [6]

NAPP	SAPP	EAPP	WAPP	CAPP
Algeria	Angola	Burundi	Benin	Cameroon
Egypt*	Botswana	Dem. Rep. of Congo*	Burkina Faso	Central African Rep.
Libya	Dem. Rep. of Congo*	Djibouti	Ivory Coast	Chad
Mauritania	Lesotho	Egypt	Gambia	Congo
Morocco	Malawi	Eritrea	Ghana	Dem. Rep. of Congo
Tunisia	Mozambique	Ethiopia	Guinea	Equatorial Guinea
	Namibia	Kenya	Guinea Bissau	Gabon
	South Africa	Libya*	Liberia	
	Swaziland	Rwanda	Mali	
	Tanzania*	Somalia	Niger	
	Zambia	Sudan	Nigeria	
	Zimbabwe	South Sudan	Senegal	
		Tanzania	Sierra Leone	
		Uganda	Togo	

* The country belongs to more than one power pool so it is reported where it does not have an asterisk superscript

Africa has about 90 000 km of transmission lines with a voltage level of 100 kV or above. Compared to the size of the continent, this is very small compared to other continents like Europe. Another problem for better interconnections between the countries is the lack of standardized specifications which is evident from the over 15 different voltage levels between 110 kV and 700 kV in Africa. [1]

For a more detailed analysis of the five African Power Pools including an overview of the prevailing electricity markets and statistics on electricity production and consumption the reader is referred to [8].

3 Electricity Economic Model of the African Continent

The African electricity market sees big increases in electricity consumption in many countries and security of supply is often a problem which leads to planned shutdowns or blackouts. The electricity production is still heavily dependent on fossil fuels as shown in chapter 2. To find the best way to tackle the challenges to make the electricity sector green and still cover the growth in electricity demand and also increase the security of supply while keeping the electricity prices affordable, an electricity economic model of the African continent is developed.

One of the biggest challenges for developing an electricity economic model of the African continent is the scarcity of information about the electricity market available like the existing electricity grid and power plants and defined goals for future developments.

In section 3.1 the methodology of how the open source grid data is gathered and combined with the power plant database is described.

3.1 Methodology

To build a model of the African electricity economy, which also takes load flow restrictions from the existing power grid into account, the electricity transmission network is necessary. Also, the power plants data has to be linked with the grid data to identify the feed-in nodes.

3.1.1 Grid data

Integrating the transmission system by hand on a country by country basis proved to be difficult as it is (a) very time consuming and (b) data availability is scarce. The solution was to develop a custom tool which takes the available grid data from the Open Street Map (OSM) project and converts it into a data format that is commonly used by electricity models with nodes and lines stored in the Excel file format. Nodes define the start and end point of an electricity line. Each node is represented with a unique identifier, the ISO 3166-1 alpha-2 code which represents the country in a two-letter code, the voltage levels of the node and the latitude and longitude information of the node as can be seen in some sample nodes in Table 3.

Table 3: Example of node data

ID [-]	Country [-]	Voltage [kV]	Lat [°]	Long [°]
ZA00001	ZA	132	-33,836828	25,522784
ZA00002	ZA	132	-33,981358	25,467262
NA00003	NA	220	-24,655896	18,033540
NA00004	NA	132	-22,586347	17,365602
NA00005	NA	220	-22,586347	17,365602
NA00006	NA	400	-22,586347	17,365602
ZA00008	ZA	132	-34,000656	24,783672
ZM00009	ZM	330	-15,753791	28,161952
⋮	⋮	⋮	⋮	⋮

The lines are simplified to be just a connection between two nodes. The actual line path is dismissed as it is not necessary for calculations. Lines also have a unique ID, the country in the ISO 3166-1 alpha-2 format[2], the start and end nodes, the voltage levels and the line length (which is calculated using the actual line path before simplification). OSM also has information about the number of systems, so if there are two systems between two nodes the line will be doubled. An example of lines data is shown in Table 4.

Table 4: Example of line data

ID [-]	Country [-]	Node 1 [-]	Node 2 [-]	Voltage [kV]
LTGAO1764	AO	AO03077	AO01277	220
LTGDZ3436	DZ	DZ00934	DZ02105	220
LTGEG3854a	EG	EG00676	EG04730	500
LTGEG3854b	EG	EG00676	EG04730	500
LTGMA0838a	MA	MA00699	MA00709	220
LTGSD2473a	SD	SD00813	SD01024	220
LTGTZ4479	TZ	TZ01391	TZ01160	220
LTGZW1397	ZW	ZW01060	ZW01063	330
⋮	⋮	⋮	⋮	⋮

The resulting power grid of the African continent is shown in Figure 2. Lines with a voltage level of 110 kV and up were queried by OSM and used as input into the custom-made tool.

[2] For cross border lines the value CB is used for the country.

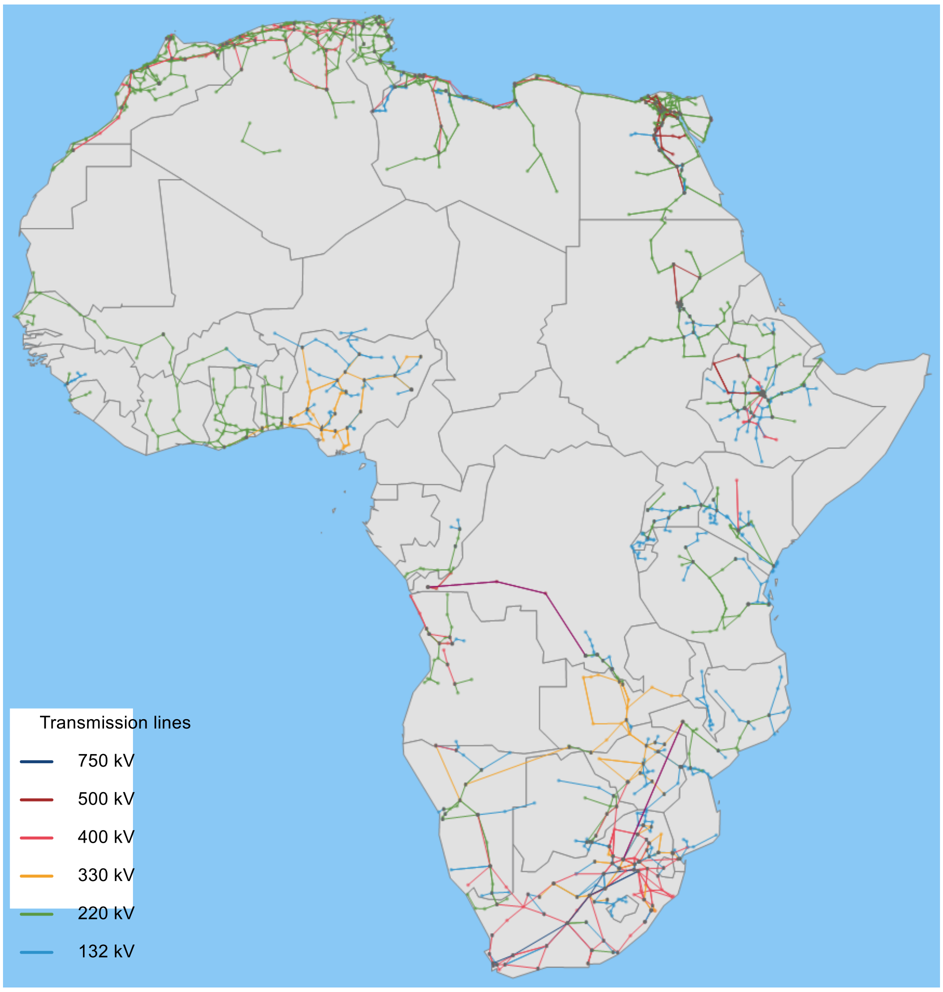

Figure 2: The resulting African power grid for transmission lines of 110 kV and above.

More information about the conversion tool can be found in [9].

3.1.2 Power plant data

The power plant data was taken from the PLATTS database [10]. This database does not contain GPS coordinates for the power plants, but only information about the city in which they are located. In order to get longitude and latitude information, a PYTHON-Script was written that goes through every power plant doing a geocoding process to transform the available address information into GPS coordinates and also simplifying the data to only the necessary information.

As a first approximation it is assumed, that the power plants feed into the transmission node with the closest spatial distance within the country. This is done with the spatial analysis tool in a GIS software called ArcGIS from ESRI. A map of the power plants and their associated feed-in nodes can be seen in Figure 3.

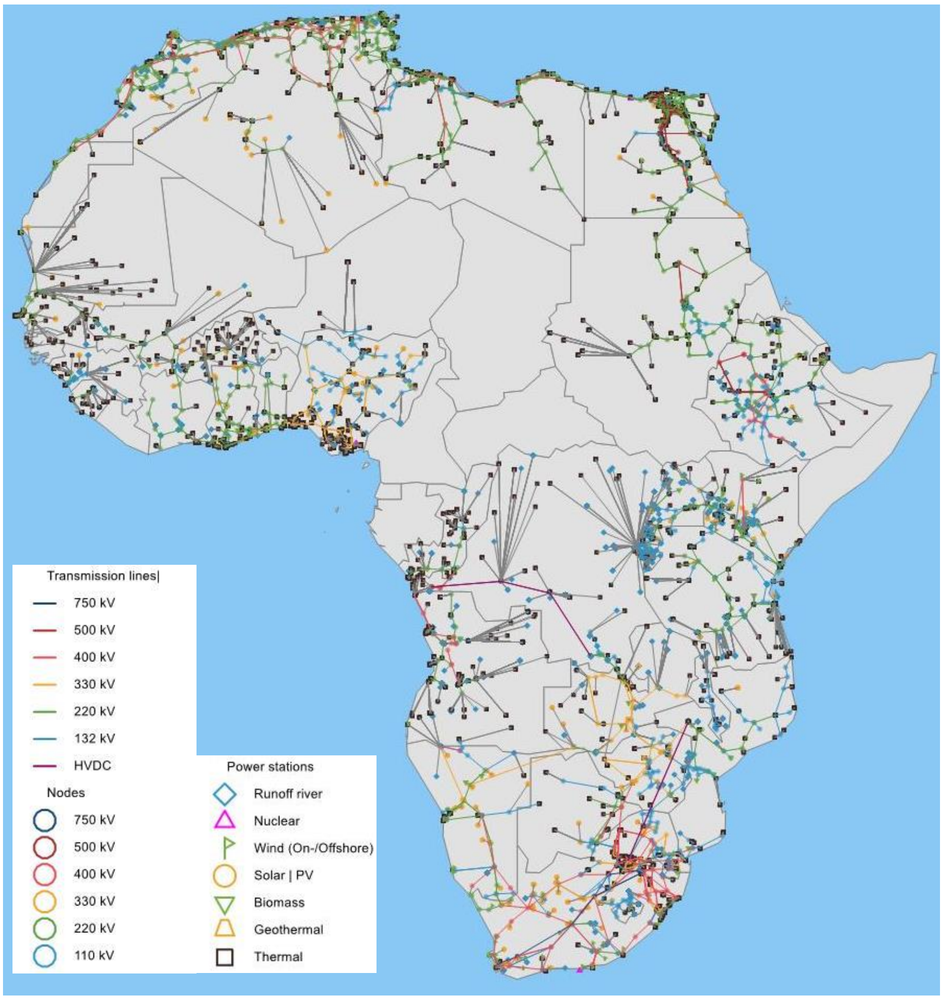

Figure 3: Africa's power grid combined with power plants (grey lines show the associated feed-in node).

4 Conclusion and Outlook

As shown in section 2 the power pools still have a lot of work to do in order to fulfil the goals of enhancing the electricity trading and benefitting from economies of scale, as underdeveloped interconnections and missing legal and regulatory frameworks are still a problem. Bilateral agreements for electricity trading are still the most used trading option in the power pools, with only the South African Power Pool having a working Day Ahead and Intraday market system.

This electricity production in the power pools is also still mostly dependent on fossil fuels, with the exception of the Central African Power Pool, where about two third of the electricity comes from hydro power plants.

In order to perform simulations with electricity economic models, the African grid data from the OSM project is transformed and simplified for modelling usages using a self-developed tool. This grid data is converted and combined with power plants data from the PLATTS database [10], that also runs through a PYTHON-Script to simplify and geocode the power plants.

Figure 4 shows the result of a proof-of-concept simulation done with the electricity economic model ATLANTIS. Please note: These results just show that a simulation can be done with the data and do not reflect any "real world"-case so far, as there is still some data missing about renewable generation profiles, economic data of the countries and more.

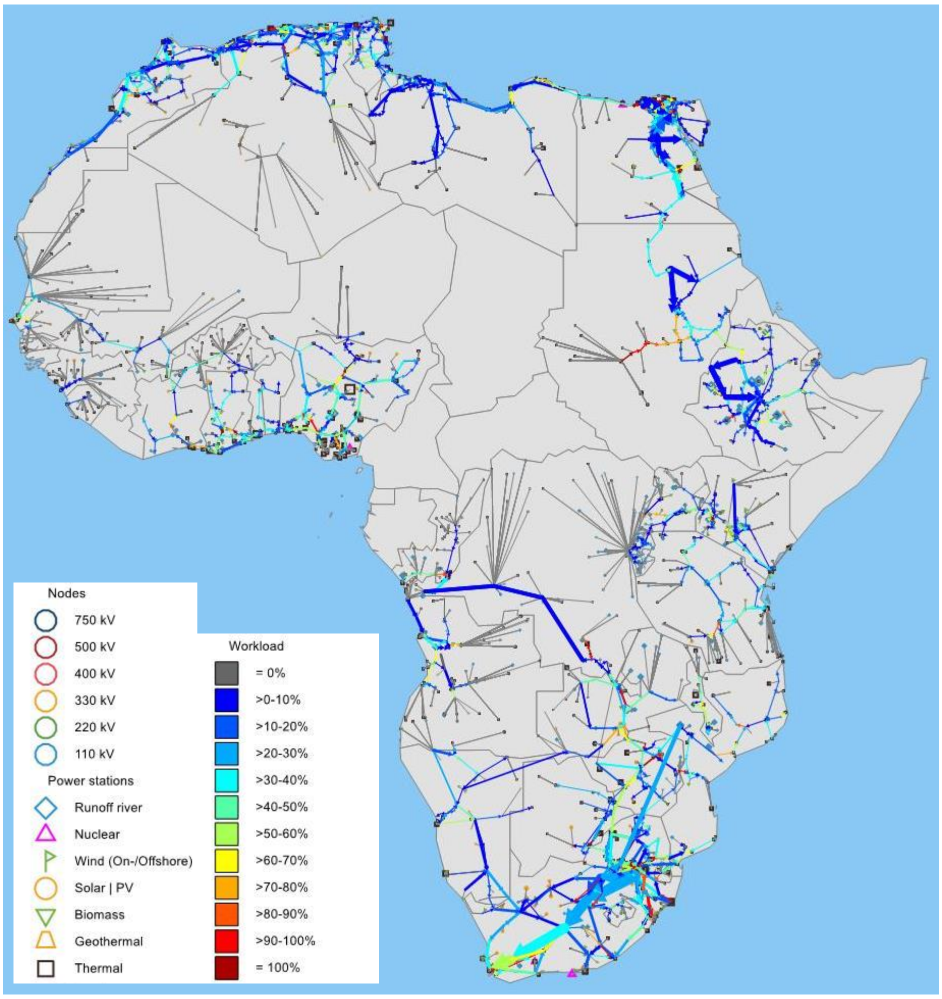

Figure 4: Results from a proof-of-concept simulations in ATLANTIS.

In the next steps, the missing data mentioned above will be completed, the data will be imported into the LEGO model as well and calibrated for a given year. Then some future scenarios will be developed and implemented.

Literature

[1] UNEP, “Atlas of Africa Energy Resources,” 2017.

[2] Worldometer.info, “Africa Population,” Aug. 30, 2021. https://www.worldometers.info/world-population/africa-population/ (accessed Aug. 30, 2021).

[3] International Energy Agency, “Africa Energy Outlook 2019 Africa Energy Outlook 2019,” 2019.

[4] H. Stigler, U. Bachhiesl, G. Nischler, and G. Feichtinger, “ATLANTIS: techno-economic model of the European electricity sector,” *Central European Journal of Operations Research*, vol. 24, no. 4, pp. 965–988, 2016, doi: 10.1007/s10100-015-0413-8.

[5] S. Wogrin, D. Tejada-Arango, S. Delikaraoglou, and A. Botterud, “Assessing the impact of inertia and reactive power constraints in generation expansion planning,” *Applied Energy*, vol. 280, p. 115925, Dec. 2020, doi: 10.1016/J.APENERGY.2020.115925.

[6] A. Medinilla, B. Byiers, and K. Karaki, “Summary African power pools regional energy, national power,” 2019. [Online]. Available: www.ecdpm.org/dp244.

[7] S. Woolfrey, “The Political Economy of Regional Integration in Africa - Common Market for Eastern and Southern Africa,” 2016. Accessed: Aug. 25, 2021. [Online]. Available: Available: https://ecdpm.org/wp-content/uploads/ECDPM-2016-Political-Economy-Regional-Integration-Africa-COMESA-Report.pdf.

[8] R. Gaugl, “Overview of the African Transmission Grid and Electricity Markets,” 2021.

[9] L. Frauenlob, “Optimierte Modellierung von Energieinfrastrukturen mittels automatisierter Datenselektion,” 2019.

[10] S&P Global Platts, “World Electric Power Plants Dataset.” 2018.