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Transition of the African Power System to Renewable Energies – A Case Study

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Abstract—Africa's power system faces many challenges: Half of all Africans are without access to electricity, the infrastructure needs investments to strengthen its reliability and lessen the frequent electricity disruptions, adaptation of the system for one of the world's highest power consumption growth rates and an urge to transition the currently highly fossil-fuel dependent system to renewable energies. Based on a detailed representation of the power system, incorporating the unique technical and economic characteristics of the electric power sector, we model a transition to renewable energies in Africa. An addition of 180.2 GW of wind power and 42.1 GW of PV is necessary to cover the current demand in the modeled countries purely by renewable energy sources.

Keywords—renewable energies, load flow, energy system modelling, LEGO, power system, generation expansion

I. INTRODUCTION

Africa, like every other continent, is already facing the effects of climate change. The increase in temperatures lead to changing precipitation patterns and an increase in extreme weather events. Extensive droughts on the one hand and heavy rainfalls leading to floods on the other hand are becoming more and more common. Therefore, limiting global warming to 1.5°C, as stated by the United Nations at the Climate Conference in Glasgow (COP26) in 2021 must be a top priority for the African countries. Otherwise climate change can have severe effects on Africa's already challenging water supply, food security and human health and can lead to negative implications for the economic growth as set out in [1]. To limit its impact on climate change, the need to shift the African power system towards renewable energy sources (RES) is inevitable. Africa's electricity demand is rapidly increasing, with growth rates expected to be between 4.5% and 6.0% per annum until 2040 according to [2]. With the current share of 80% of Africa's electricity generated by thermal power plants using fossil fuels (based on [3]), the system has to become more sustainable in the future.

Existing models for generation and transmission expansion planning for Africa either concentrate on specific parts or countries of Africa only or do not include power flow calculations or just simplified power flow calculations based on one node per zone or country. Examples of these are the publications for Tanzania [4], Nigeria [5], Ethiopia [6] and Malawi [7]. They use the *Open Source Spatial Electrification Tool* (*OnSSET*) [8] which is a bottom up optimization energy modelling tool. *OnSSET* is used to identify the most cost-effective electrification strategy, but does not include operation optimization (unit commitment) or power flow calculations. *OSeMOSYS* [9] is an existing, open-source energy modelling system that is used in *TEMBA* [10] to model generation and transmission capacity expansion including forty-seven African countries. In *TEMBA* every country is represented by one node and therefore lacks inner-country power flows.

With our proposed model in this publication, we want to show that a detailed model of the African power system which includes the unique technical and economic characteristics of the power system is possible. For this approach the open-source *Low-Carbon Expansion and Generation Optimization* (*LEGO*) model [11] is adapted and expanded to include open-source grid data from the OpenStreetMap (OSM) project and combined with power plant data from the World Electric Power Plants Dataset.

The remainder of the paper is organized as follows. Section II gives an overview of the current state of the African power system, followed by the methodology describing the adaption of the *LEGO* model for Africa's power system in section III. Section IV outlines and presents the results of the modelled case study to transition Africa's power system to renewable energies. Finally, section V concludes the paper and gives an outlook on future work.

II. THE CURRENT STATE OF AFRICA'S POWER SYSTEM

The African continent is divided into 5 power pools: North African Power Pool (NAPP) or also often referred to as Maghreb Electricity Committee (COMELEC), Eastern African Power Pool (EAPP), Southern African Power Pool (SAPP), West African Power Pool (WAPP) and Central African Power Pool (CAPP). The goal of these power pools is to enhance electricity trading between its members. This leads to a higher system reliability as member states can help each other out in case of electricity shortages or system failures and a more cost-effective electricity production as the advantages of economies of scale come into effect, therefore making electricity prices cheaper and more affordable. The classification of the power pools can be seen on the in Fig. 1. It should be noted, that the member states of the power pools differ depending on the source or

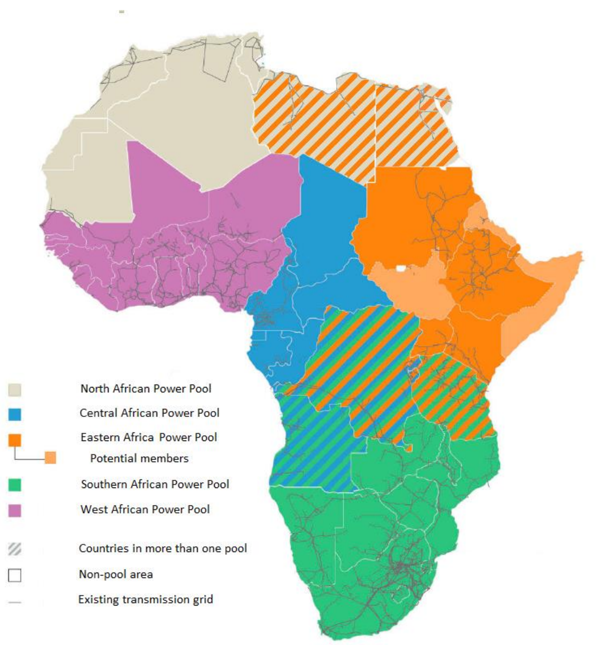

Fig. 1. African power pools and their member states. (Based on [12])

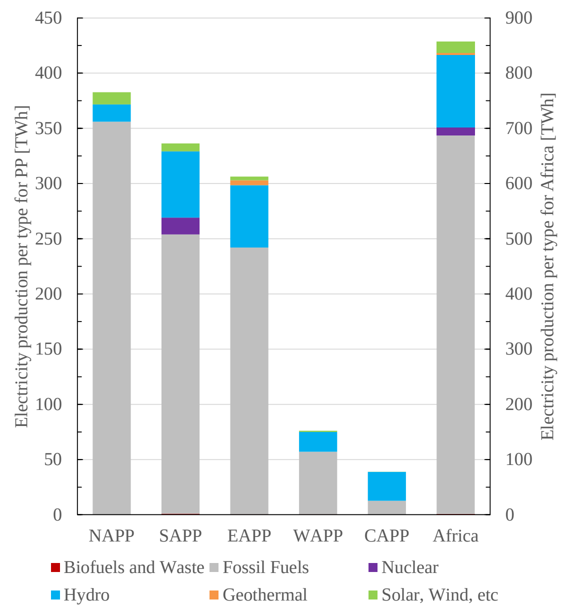

Fig. 2. Electricity production per power pool (left axis) and for whole Africa (right axis). (Based on [3])

publication. In terms of level of development regarding to electricity markets, generation, transmission and distribution infrastructure, the power pools differ greatly. Electricity production per power plant type and power pool as well as whole Africa is shown in Fig. 2. As some countries are members of more than one power pool, the sum of electricity production of the power pools does not sum up to be the electricity production of Africa. The next paragraphs give an overview of the five power pools.

The NAPP and SAPP are the oldest and best developed power pools. The NAPP was established in 1975 as the Electricity Committee of the Maghreb region (COMELEC) and resurrected in 1989 after years of inactivity. Although it has the best infrastructure of all the power pools, due to a missing joined electricity market, electricity trading between NAPP countries is low and done via bilateral agreements. [13] This could change in the future with the planned start of the Maghreb electricity market in 2025 [14]. With 93% of its electricity production generated by oil, coal or gas power plants in 2019, it is heavily dependent on fossil fuels. Renewables in the form of hydro, solar and wind only account for 7%. Total generation sums up to 382 TWh in 2019. (Based on [3])

The SAPP was created in 1995 and established the Short-Term Energy Market (STEM), a platform for short term electricity trading, in 2001. While the STEM was discontinued in 2006, a new day-ahead market was introduced in 2009 and an intra-day market in 2016. [15] This makes the SAPP the most advanced power pool, but further development is hindered by insufficient generation and interconnection capacities [13]. In 2019 total electricity production was 336 TWh. The share of fossil fuels was 75%, hydro was second largest with 18% followed by nuclear (5%) and solar and wind power (2%). (Based on [3])

The EAPP was established in 2005 but because of differences between Ethiopia and Egypt about the Grand Ethiopian Renaissance Dam (GERD), Egypt resigned from the EAPP in 2016 [15]. According to the official website of the EAPP Egypt is still shown as a member of the EAPP and therefore we include it as well. As reported by [16], a centralized day-ahead trading market will start in mid to late 2023. The statistics based on [3] show a total production of 306 TWh of which 70% comes from fossil fueled power plants, 19% from hydro, 1% from geothermal and 1% from solar and wind generators.

The WAPP, established in 2011, is small in terms of total electricity generation compared to the beforementioned power pools, with only 76 TWh. Fossil fuels have a share of 75%, hydro 25% and solar and wind 1% (based on [3]). Trading between members is done via bilateral agreements [13].

The fifth and by far the smallest and least developed power pool is the CAPP. Infrastructure is mostly basic, but it is expected that the electricity demand will increase significantly in the years to come. Trading between countries is low, as market rules still have to be developed. [13] From the 28 TWh of electricity production, hydro has a share of 68% and fossil fuels come second with 32% (Based on [3]).

Total electricity production in Africa in 2019 was 857 TWh of which 685 TWh (79.9%) were produced by fossil-fueled power plants, 131 TWh (15.2%) by hydro power plants, 20 TWh (2.3%) from solar and wind generators, 15 TWh (1.8%) from nuclear power plants, 4 TWh (0.5%) by geothermal and 2 TWh (0.2%) from biofuel and waste generators. (Based on [3])

III. Methodology

For this contribution, the current state of the African electricity sector (based on the year 2019) using the *LEGO* open-source model (available at https://github.com/IEE-TUGraz/LEGO) is replicated. For a detailed intro to the *LEGO* model the reader is referred to [11]. In short *LEGO* is an electricity economic simulation model that can be used for operational decisions like unit commitment as well as for cost-minimizing generation and/or transmission expansion planning. The model includes different options that can be turned on and off as needed. For example, these allow to run the model as a single node network or with considering the power grid via DC- or simplified AC-optimal power flow calculations and demand side management options. Also, political constraints like minimum green production, minimum firm capacity or maximum carbon budget can be considered. The flexible temporal framework of *LEGO* makes it possible to run it with chronological data or with representative periods.

In order to build a digital twin of the African electricity sector input data for the electricity grid, power plants and temporal data (demand, solar and wind profiles) are needed. The methodology used to collect this data is described in the following subsection. A standard PC (Intel Core i7 11th Gen with 2.80 GHz and 32 GB of RAM) using the GAMS version 39.1.1 with the Gurobi solver is used. The model is run as a mixed integer problem (MIP) with power flow calculated with a DC-OPF.

A. Grid Data

The used grid data is based on open-source data from the OpenStreetMap (OSM) project. In order to make that data usable for our model the *GridTool* [17] is used. This tool uses the input data from OSM, identifies the substations (called nodes) with a heuristic approach, simplifies the data and saves the resulting nodes and power line data in a format that is usable by energy simulation models like *LEGO*. The result of this is illustrated in Fig. 3, showing the electricity lines with their different voltage levels. This system is made up with 1470 nodes and 2441 electricity lines. As can also be seen in Fig. 3 grid data is not available for every country. Especially for the underdeveloped CAPP data is mostly missing. In further course, only countries are considered where grid data is available, making it 35 African countries. Another thing worth mentioning is that the rest of the power pools are easily identifiable as interconnections between them are limited.

For power flow calculations technical line parameters are needed. The voltage levels are directly taken from the OSM data and transferred to the final data by the *GridTool*. The *GridTool* also calculates the line lengths based on the real route of the electricity line before they get simplified to just a straight connection between a start and an end node. For impedance and thermal power limits, typical values for the corresponding voltage levels are chosen.

B. Power Plants Data

Getting power plant data for all 35 considered African countries proved to be difficult. Different open-source power plant databases were evaluated. The Global Power Plant Database [18] is very incomplete for the African continent and missing data for many countries or the installed power plant capacity is too small. The databases from Open Power System Data covering conventional [19] and renewable power plants [20] do not cover the African continent. Therefore, the commercial power plants database from [21] is integrated into the model. As this database does not include exact GPS coordinates of the power plants, but only information about the city in which they are located, an intermediate geocoding process was needed. A Python script was written that reads all the power plants and translates the city to longitude and latitude information using the geocoder package. Information about the feed-in node into the power grid of the power plants are also not available. The assumption is made, that the power plants feed-in to the closest node from the grid dataset within their country. For this a geographic information system (GIS) software called ArcGIS is used using the Spatial Join tool with the match option to find the closest geodesic node. As can be seen in Fig. 4, where the grey lines indicate the connection of the power plant to the feed-in node, 73% of all power plants are within 50 km to their feed-in node. Exceptions are in countries where the grid information is not very good.

C. Temporal Data

For temporal data like demand, wind and solar profiles, the LEGO model can either work with chronological (hourly) data or with representative periods like representative days. With representative days the temporal

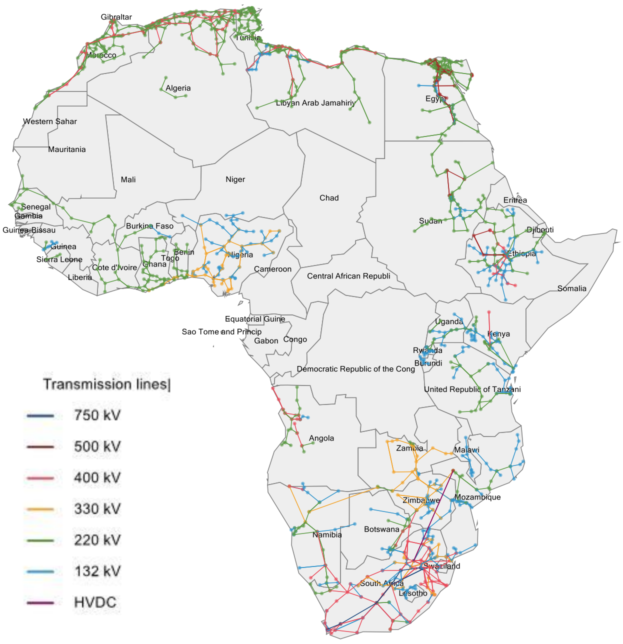

Fig. 3. Resulting electricity grid using the GridTool with OSM data.

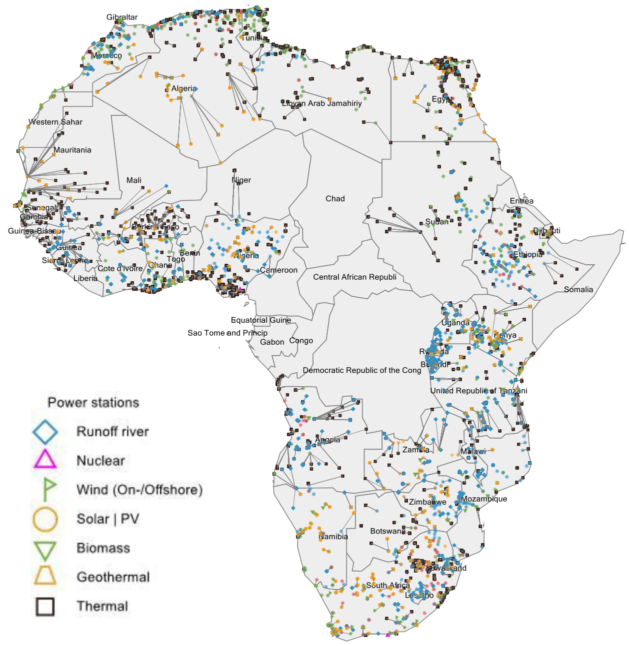

Fig. 4. Power plants assigned to their feed-in node.

data has to be clustered. The result of the clustering assigns every day of the year to one representative day that best depicts this real day. Representative days have the advantage, that instead of simulating a whole year with 8760 hours, the processing is reduced to the amount of representative days chosen times 24 hours. E.g. when choosing seven representative days, only 168 hours have to be simulated. This, of course, comes with the cost of reduced accuracy. Choosing more representative days leads to a result that better reflects the reality, but also needs more processing time. As this case study is the first run of this African model, it is done with one representative day. The k-medoids clustering technique is used based on the hourly demand profiles and hourly wind and solar capacity factors for every country. The hourly demand profiles are synthetic based on the yearly demand from [3] and hourly profiles from [22]. Hourly capacity factors that reflect the profiles for wind and solar for every node of the grid data have been downloaded from [23] and implemented into the model.

IV. Case Study

Before running the case study to transition the African power sector to RES, the model was run to simulate the year 2019. The comparison of the electricity production per power pool (only including the simulated countries) in Fig. 5 shows that the production of *LEGO* is lower compared to actual data from [3]. This is mainly due to two factors. First, due to clustering with k-medoids with one representative day, one actual day is chosen to represent all 365 days of the year. This day has to represent demand as well as wind and solar profiles as good as possible. As there is not one actual day that can do that exactly, inaccuracies are unavoidable. The demand of the day chosen by the clustering algorithm multiplied by 365 is lower compared to the actual demand. The actual yearly demand of the 35 simulated countries is 672 TWh, the demand of the representative day times 365 is only 636 TWh. (Note: The sum of the electricity production of the 4 power pools is different, because some countries are members of more than power pools.) This issue can be improved by clustering and simulating with more representative days (see chapter V). Second, because only countries with available grid data are simulated, electricity production for export in those countries is not considered.

For the case study to transition Africa’s power sector to renewable energies, wind and PV candidate power plants are added to the model. This allows the model to add up to 10000 wind power plants in 1 MW increments and 20000 PV generators in 0.5 MW increments to each node. Corresponding investment costs per technology are also added. Furthermore, the restriction for minimum green electricity production is set to 100%. (Nuclear power is not considered as green in this case study.) To show how much added RES capacities would be needed to get to a renewable power system, the demand is kept the same for this case study. Table I shows the already installed renewable power plant capacities of the 35 simulated countries as well as results for the added wind and solar capacities and the produced electricity per RES type in the 100% renewable case. To transition Africa’s current power system to renewable energies additional 180 GW of wind and 42 GW of solar capacities would be needed. Subsequently, wind would produce 431.9 TWh, followed by hydro with 107.1 TWh, solar with 97.0 TWh and biomass with 0.4 TWh. To compare the results with Fig. 5, the electricity produced per power pool is shown in Fig. 6 for the four power pools considered in the simulation.

V. Conclusion and Outlook

Transitioning Africa’s power system to renewable energies is of major importance in view of our climate goals, especially considering one of the highest electricity demand increase rates worldwide over the next years and decades. Switching a system from adjustable thermal power plants to variable renewable energies is not only a technical challenge but also a financial one. Therefore, it is of utmost importance to plan such things carefully in advance. In order to do so, a digital twin of the African power system can help to try out different strategies and see their effects on the

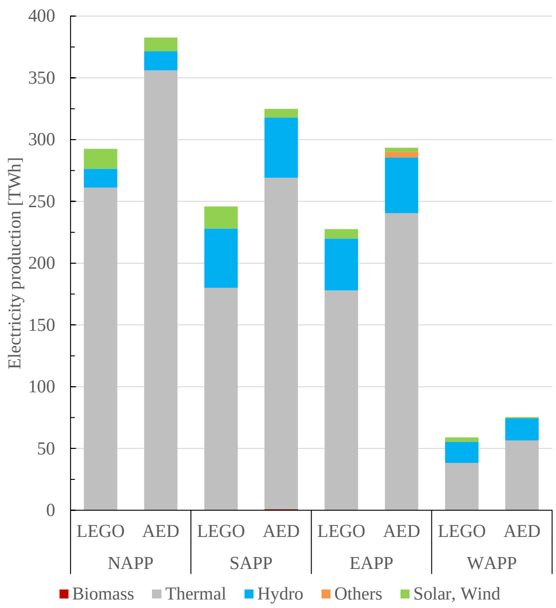

Fig. 5. Comaprison of electricity production per power pool (only simulated countries) between LEGO results and data from the African Energy Database [3].

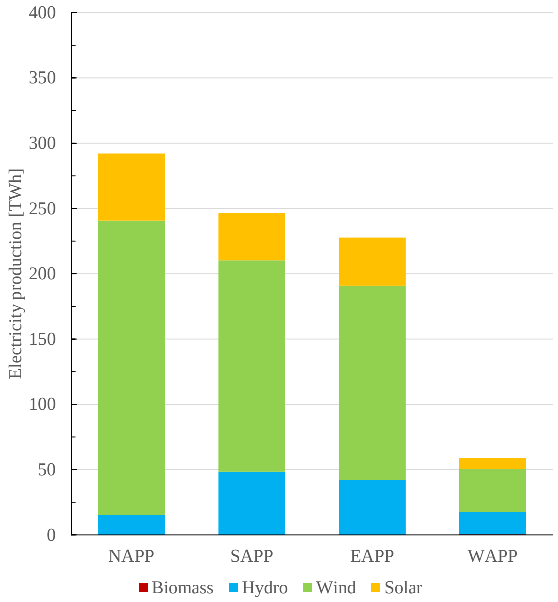

Fig. 6. Electricity produced per power pool, when only allowing RES.

TABLE I. EXISTING RENEWABLE POWER PLANTS, ADDED WIND AND SOLAR GENERATORS TO REACH 100% RES AND PRODUCED ELECTRICITY.

	Existing RES [MW]				**Added RES [MW]**		**Produced electricity per type [GWh]**				
	Biomass	***Hydro***	***Wind***	***Solar***	***Wind***	***Solar***	***Biomass***	***Hydro***	***Wind***	***Solar***	***SUM***
Algeria	-	276	80	462	21 334	5 078	-	153	31 096	11 535	**42 784**
Angola	51	7 012	100	-	180	-	-	5 941	149	-	**6 090**
Benin	-	1	-	-	129	-	-	4	90	-	**94**
Botswana	-	-	-	201	2 249	-	-	-	7 251	393	**7 643**
Burkina Faso	5	105	-	130	1 601	29	-	149	878	172	**1 199**
Burundi	-	126	-	8	67	-	-	189	17	7	**213**
Côte d'Ivoire	-	1 147	-	25	3 849	-	-	1 590	6 858	26	**8 474**
Djibouti	-	-	20	52	-	-	-	-	1	82	**83**
Egypt	67	3 558	1 090	1 044	34 869	15 987	-	13 121	120 022	34 638	**167 781**
Eswatini	140	225	-	10	-	-	-	234	-	21	**255**
Ethiopia	203	20 668	495	0	764	-	-	9 638	1 534	0	**11 173**
Ghana	24	2 060	500	405	-	-	-	6 333	556	515	**7 404**
Guinea	-	1 559	-	88	-	-	-	308	-	-	**308**
Kenya	159	1 282	1 159	639	737	-	-	3 676	3 293	1 085	**8 054**
Lesotho	-	81	150	20	-	-	-	554	82	48	**684**
Libya	-	-	88	1	3 763	414	-	-	14 128	864	**14 992**
Malawi	17	1 048	-	-	400	147	-	2 846	669	251	**3 766**
Mali	30	572	1	74	1 648	615	157	947	1 600	995	**3 699**
Mauritania	-	-	34	34	1 000	-	-	-	613	12	**625**
Morocco	-	2 356	1 858	1 309	11 249	-	-	1 870	42 728	2 460	**47 058**
Mozambique	27	7 238	-	42	7 688	167	-	14 468	19 840	402	**34 710**
Namibia	60	872	204	126	3 957	-	-	1 457	13 831	254	**15 542**
Niger	-	130	-	-	3 298	-	-	9	3 477	-	**3 486**
Nigeria	14	10 608	40	1 095	21 477	3 205	-	6 700	10 256	3 827	**21 081**
Rwanda	2	210	-	22	-	-	-	228	-	37	**265**
Senegal	48	120	158	61	1 780	4 007	179	374	1 553	2 800	**4 907**
Sierra Leone	33	409	-	31	-	-	-	160	-	-	**160**
South Africa	335	5 244	2 840	3 056	35 241	11 538	-	4 184	99 745	32 688	**136 617**
Sudan	243	2 287	0	0	2 067	-	-	9 101	6 328	0	**15 429**
Tanzania	144	3 825	200	60	668	-	-	2 487	3 485	104	**6 076**
Togo	-	214	24	-	8 911	-	-	552	7 946	-	**8 498**
Tunisia	-	62	438	10	6 958	851	-	-	17 028	1 791	**18 819**
Uganda	124	2 855	-	35	-	-	-	3 570	-	56	**3 626**
Zambia	67	5 958	130	264	1 345	-	-	12 745	6 659	444	**19 848**
Zimbabwe	99	2 314	-	716	3 007	34	-	3 483	10 169	1 508	**15 159**
SUM	**1 892**	**84 422**	**9 609**	**10 021**	**180 236**	**42 069**	**336**	**107 073**	**431 881**	**97 013**	**636 601**

system. This can lead to more efficient investments and better system stability. In order to do so, a detailed model of the African power system is developed including the power grid, power plants and location based renewable profiles using the open-source *LEGO* model. The model is set up with one representative day and is then used for a case study to transitions Africa’s power system to 100% RES. The results show that the addition of 222 GW of wind and solar capacity would be needed. The vast majority of investment currently goes into wind power plants, as these also can be used to cover demand during night hours. In a future update, candidate battery storages could be added to make PV investments more valuable to the system, as the energy could be stored and used in hours without sun.

Currently the work is done to simulate more than one representative day, to better depict variances in demand and renewable production over the course of a year. Furthermore, we will improve the candidate power plants for renewable investments. In the future these candidate power plants will represent the available solar and wind potential per node and limit the capacity that can be added per node. Additionally, demand side management could be enabled and its potential explored. Instead of setting a minimum goal of production from RES a maximum CO_2-budget could also be considered. In addition, a minimum firm capacity could be set to enhance system reliability. With the groundwork for a holistic model of the African power system done and work to improve it even more underway, trying out different scenarios for a sustainable power system and making Africa fit for the future can start.

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