Strategic low-cost energy investment opportunities and challenges towards achieving universal access (SDG7) in each African nation

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Research Article

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Abstract

Strategic energy planning to achieve universal access and cover the future energy needs in each African nation is essential to lead to effective, sustainable energy decisions to formulate mitigation and adaptation climate change policy measures. Africa can not afford a cost-increasing green energy transition pathway towards achieving SDG7. In this analysis, least-cost power generation investment options using energy systems analysis enhanced with geospatial data for each African nation are identified, considering different levels of electricity consumption per capita (Low, High) and costs of renewables (New Policies, Renewable Deployment scenarios). The power generation capacity needs to increase between 211GW (NPLs) and 302GW (RDHs) during 2021-2030 to achieve SDG7 in Africa, leading to electricity generation to rise between 6,221PJ (NPLs) - 7,527PJ (NPHs) by 2030. Higher electricity consumption levels lead to higher penetration of fossil fuel technologies in the power mix of Africa. To achieve the same electricity demand levels, decreasing renewables' costs can assist in a less carbon-intensive power system, although higher capacity is needed. However, Africa is still hard to achieve its green revolution. Depending on the scenario, grid-connected technologies are estimated to supply approximately 85%-90% of the total electricity generated in Africa in 2030, mini-grid technologies roughly 1%-6%, and stand-alone technologies 8%-11%. Solar off-grid and solar hybrid mini-grid technologies play an essential role in electrifying the current un-electrified settlements in residential areas. Natural gas will be the dominant fossil fuel source by 2030, while the decreasing costs of renewables make solar overtake hydropower. Higher penetration of renewable energy sources in the energy mix creates local jobs and increases cost-efficiency. Approximately 6.9 million (NPLs) to 9.6 million (RDHs) direct jobs can be created in Africa by expanding the power sector during 2020-2030 across the supply chain. Increasing the electricity consumption levels in Africa leads to higher total system costs, but it is estimated to create more jobs that can ensure political and societal stability. Also, the decreasing costs of renewables could further increase the penetration of renewables in the energy mix, leading to a higher number of jobs.

1 Introduction

Energy access is important for economic growth and social prosperity [1]. At the 2015 UN General Assembly, the 2030 Agenda for Sustainable Development (SDGs) with 17 goals, 169 targets and 232 associated indicators was approved and addresses the economic, social and environmental pillars of development by 2030. Specifically, SDG7 target focuses to "Ensure access to affordable, reliable, sustainable and modern energy for all" with its sub-targets: 7.1 is universal access to affordable, reliable, sustainable and modern energy services, 7.2 is defined as a substantial increase in the share of renewable energy in the global energy mix and 7.3 to increase the global rate of improvement in energy efficiency by 2030 [2]. The International Council for Science identifies goal 7 as the second most interconnected goal, with links to goals SDG1, SDG2, SDG3, SDG6, SDG8 and SDG13 [3]. The established goals are universal. However, each country is developed its own national Sustainable Development Goal targets based on their country´s policy plans, National Determined Contributions (NDCs) for development and the region´s Agenda 2063 strategic framework [4], [5]. Also, these policies have collective implications, which are likely to affect Europe´s energy goals in promoting sustainable energy, energy systems security, and climate-neutral by 2050 [6].

Africa has abundant energy resources. Nevertheless, it is the least electrified region in the world. Specifically, electricity access steadily increased from 44% in 2010 to 56% in 2019, with North Africa almost fully electrified (99%) and Sub-Saharan Africa (SSA) increasing its share from 33–48% in the corresponding years. Thus, approximately 579 million people are without access to electricity in the region, where 81% and 37% live in urban and rural areas correspondingly. In the past decade, the rate of achieving electricity access in SSA has exceeded population growth (except from 2016 to 2018) with Congo, Gabon, Ghana, Kenya and Rwanda to contribute more to this trend, presenting the highest increase in their electricity access the last ten years [7]. However, as the population growth in Sub-Saharan Africa is increased by 2.7% in the same period, together with the impact of the COVID-19 pandemic, achieving universal access in the region by 2030 (only ten years left) is proven notably challenging in practice [8], [9]. Specifically, Nigeria, the Democratic Republic of Congo and Ethiopia are the largest deficit countries in Africa [8]. Also, as the population in Africa is expected almost to double in the next thirty years, reaching 2 billion in 2050 (Shared Socioeconomic Pathways 2 (SSP)) tackle the energy access challenges is essential for sustainable development [10], [11].

Each African country has a different supply mix of domestic energy reserves and renewable potential, economic and population growth, national policy plans and energy security targets, resulting in policy-makers and energy planners managing several conflicting factors for energy system expansion [12]. Strategic use of a nation´s domestic energy resources is essential in its energy transition. A universal integrated energy systems planning approach identifying the evolution of each African nation´s energy system is needed to tackle the increased energy demand for structural transformation, the rising population and the adverse impacts of climate change in Africa. Energy access needs to be aligned with its nation´s energy transition to meet reliable and affordable electricity security and emissions reduction. The energy transition is complex and has several implications for a nation´s economy and future development.

Energy models have been used for many years as tools to provide pathways for sustainable development either on a global, continental, or country scale analysis [7], [13]. Energy system analysis and electrification planning using medium-to-long term cost-optimization energy modelling tools [13]–[17] can address the challenges mentioned above as follows. They can provide insights on energy options such as centralized versus decentralized power system technologies, grid expansion, identify least-cost investments to satisfy future energy demands (achieve universal energy access) and also inform part of SDGs [1], [18]. Analytical approaches and tools are needed to support policy analysis in countries to assess interactions among the SDGs and establish clear metrics and targets tailored to national priorities [19]. Specifically, without energy system modelling tools is not clear how progress towards SDG7 can be addressed [18]. The modelling tools can also inform how universal access in each country can be better achieved by addressing uncertainties around the evolution of fossil fuel prices, renewable energy technology (RET) costs and demand projections, assisting governments, policy makers and funders to identify proper financing mechanisms and strategic investments [20]. They can also measure the socio-economics (e.g., job creation) of different energy transition pathways [21], [22]. Lastly, considering the spatial dimension of energy access (location and size of un-electrified population, geophysical parameters and technology costs) can improve the medium-to-long-term assessments of least-cost power system expansion in an energy model [23]–[25].

Several techno-economic studies have been conducted in the past in a continental, regional and national scale to address the future challenges associated with the evolution of the energy system in Africa. **Trotter et.al** [26] conducted a literature review on quantitative and qualitative electricity planning and implementation research approaches on Sub-Saharan Africa on a national, regional and continental scale. Their review indicates that 63% out of 306 relevant peer-reviewed journal articles favour renewable energy technologies for the identified challenges, mentioning success factors for electrification in sub-Saharan Africa to include adequate policy design, sufficient finance and favourable political conditions. On a continental scale, using a cost-optimization tool OSeMOSYS [27], **Taliotis et al.** [28] modelled the electricity system of each African country (45 in total) and linked it via electricity trade links to examine scenarios of power plant investments by exploiting trade potential in the continent during 2010-2040. They show that an enhanced trading scheme could reduce electricity generation costs. However, only the electricity sector on a national scale is modelled and not the rest of the sectors to satisfy the nation´s whole energy demand and examine the associated implications leading to changes in the electricity generation costs. Furthermore, only the electricity trade links included in the model and not other trades (e.g., gas) and the number of power-generating technologies are less than our study, decreasing the model's granularity. **Bazilian et al.** [29] examined various energy access scenarios in Sub-Saharan Africa by 2030 using the OSeMOSYS framework to model the electricity sector. Although in this study, a detailed analysis of the energy demand projections is presented, missing from **Taliotis et al.** study [28], other fuel demands are not included in the study to better capture the evolution of the energy system in Africa and the geospatial allocation of power generation technologies is missing. In another study, a cost-optimization modelling framework MESSAGE-SPLAT used to model only the power system of two regions (Eastern and Southern Africa) and examine scenarios associated with their energy transition and not the rest [30].

Puig et al. [31] suggested an action agenda for Africa´s electricity sector identifying economic opportunities associated with the power-sector reform, energy access and investing in Sustainable Development Goal 7. Expansion of investments in off-grid and interconnected clean-energy mini-grids are one of those.

Enhancing energy systems analysis with geospatial data, **Mentis et.al** [20] in their study developed a bottom-up geospatial electrification tool (OnSSET) to examine least-cost electrification strategies for each Sub-Saharan country considering investment options (grid extension, mini-grid, stand-alone systems) for different electricity consumption levels. Nevertheless, the OnSSET model, which also uses the TEMBA model as an input for the grid cost, is further improved in this study using the open-access Global Electrification Platform (GEP) [32]. Also, the authors in their research did not present the grid-connected power generation mix for the different universal access scenarios and the analysis of the electricity demand projections primarily focused on connecting the un-electrified population. Similarly, **Longa et al.** [33] applied geographic information system analysis coupled with an integrated assessment modeling to study electricity access in Africa through scenario projections until 2050, focusing on climate policies (2.0ºC). They conclude that universal electricity access in Africa cannot be achieved by 2030 but primarily until 2050. Also, they conclude that off-grid renewable energy technologies are essential to increase significantly the electrification of rural areas. However, the study only examines the electricity supply system of 48 African countries and the citizen's willingness to pay for electricity. In our study, the analysis is broader covering the whole energy supply system of the African countries together with energy demand projections by 2040. Also, the focus is except from defining the least-cost electrification mix for each country also informing indicators relevant to SDG7 and its sub-targets and provide insights on job creation potential in Africa. Other studies also focused either on a regional or a national scale analysis. **Falchetta et.al** [34] modelled only the electricity supply system of East Africa (OnSSET) to estimate least-cost pathways to achieve universal access by 2030 under different electricity consumption levels. Nevertheless, this study doesn't consider the trade implications with the other power pools and doesn't include a detailed representation of the grid power generation mix and consequently how the grid cost is affected. **Rocco et. al** [35] and **Pappis et al.** [25] examined energy access scenarios for Tanzania and Ethiopia, accordingly modeling only the power sector using OSeMOSYS and geospatial data to determine the electricity demand projections and the optimal allocation of power generation technologies. Similarly, the analysis is conducted only on a national level, without considering the trade implications on a continental scale. Only the power sector is modelled and the scenarios are limited by only examining energy access considering policy and environmental goals and not the evolution of other fuels.

The **Africa Energy Outlook 2019** [36] focused on electricity access in Sub-Saharan Africa by examining two scenarios, the Stated Policies and the Africa case, the period 2018-2040. Although the study covers the whole of Africa, the detailed electricity supply system of only 11 sub-Saharan countries was modelled using both a cost-optimization tool and a geospatial electrification tool (OnSSET). In the Stated Policies scenario, hydropower is expected to be the primary fuel source by 2040, while its share declines as natural gas and other renewables expand. Contrary, in the Africa case, hydropower is being overtaken by natural gas. Solar PV capacity increases significantly, almost 40%-70% of all new capacity additions in the power system in each scenario, respectively. Geospatial analysis shows that the least-cost way to achieve universal access by 2030 is decentralized systems powering half of the electricity connections (nearly 440 million people) and extending the main grid. In the Stated Policies scenario, Ethiopia, Ghana, Kenya, Rwanda, Senegal and South Africa are expected to reach full access by 2030 [36] [8]. However, the **Tracking SDG7: The Energy Progress report 2021** [8] shows that although Africa continues to progress toward SDG7 still a lot of effort is required to reach the goal by 2030 (Stated Policies). The projections show that under current and planned policies and before the start of the COVID-19 crisis, about 555 million people would still lack access to electricity in 2030. Almost 20 countries would have less than half of the population electricity access while ten less than one in four (e.g., Chad, the Democratic Republic of Congo, Malawi, Niger and Somalia) [8]. To bridge the gap, almost 85 million people per year need to gain access from 2020 (the access rate to triple) to 2030. IEA´s and IRENA´s [37] scenarios estimate that achieving SDG7 would require annual investments of approximately $680 billion to renewable energy by 2030, around $45 billion spent in energy access and $625 billion to energy efficiency [8].

Lastly, few studies have been conducted to track the progress towards achieving SDGs in African countries [38], [39]. Also, another aspect to examine relevant to the energy transition on a global, regional or national level is the associated job creation potential of achieving universal access, which is missing from the literature [21], [22], [40]–[42].

Based on the existing literature, this study builds on previous efforts by **Pappis et al.** [43] modelling the electricity supply system of all African countries (48 in total) and linked it via electricity and trade links, including also all fuel demands and fuel exports, to examine scenarios relevant to achieving universal access (Table 1). The results are provided on an annual basis from 2015 to 2030. This study also considers the geospatial allocation of power generation technologies missing from the previous analysis on Africa and examines different research questions.

In this study, therefore, we tried to address the research gaps in the current literature by examining the following research questions: First, how can an African country could identify energy pathways that are least-cost but also consider the nation´s priorities in terms of achieving universal access, the geospatial allocation of power generation investments, financial capacity, technological maturity, environmental and policy constraints, and demand growth in different sectors? Second, what the outputs of these least-cost energy pathways using energy system modelling tools would mean for SDG7 and its sub-targets (rate of success) in each country? and Third, what will be the socio-economic benefits focusing on job creation of these energy transitions in Africa. In this study, an electrification least-cost investment outlook on a continental, regional and national scale for Africa, using energy systems analysis enhanced with geospatial data, is developed for 2015-2030. Four scenarios developed (New Policies Low, New Policies High, Renewable Deployment Low, Renewable Deployment High) focusing on different energy access consumption levels (low, high) and examining the effect of decreasing the costs of renewables in the energy transition in Africa. The four scenarios examined in this study investigated the implications of the future energy transition in Africa on the electricity supply mix, the total system costs, achieving SDG7 and its sub-targets, the associated environmental and socio-economic implications. The different universal access scenarios were examined to analyse the economics and demographic factors as demand drivers to boost electrification in each African nation. A critical dimension of achieving SDG7 in Africa, except the different electricity consumption per capita levels each African country wants to achieve, is the evolution of renewable technology costs. Africa can not afford a cost-increasing green energy transition pathway.

The analysis estimates the cost-optimal mix of electrification technologies and fuel supply consistent with the corresponding whole energy system development pathways using the OSeMOSYS tool [27] and captures the spatial distribution (split of grid, mini-grid and stand-alone technologies) of future electricity connections in the residential areas using the open-access Global Electrification Platform (GEP) [44]. In that way, grid, off-grid and mini-grid energy systems' role in meeting SDG7 can be examined and provide insights into energy transition and its associated challenges. An accounting model was developed to create an index with indicators to inform each African country's SDG7 and sub-targets. Lastly, an input-output model was used to measure the socio-economic transition focusing on job creation in Africa. The open-source nature of this analysis (data, model, code, results) assists in the transparency and freely reproducibility of the research. The analysis provides results at continental, regional and national scale in an integrated way for the whole of Africa to inform national policy analysis (Nationally Determined Contributions [4], Clean Development Mechanism [45]), SDG7 and other closely interlinked targets (SDG1, SDG3, SDG11, SDG13, SDG14) [2] and be used by academics, researchers and policy analysts in their research and capacity building activities. The outcomes of this study can assist each African nation in strengthening risk mitigation associated with future renewable energy projects and ensuring their financial viability.

Table 1
List of African countries per power pool (with the ISO 3166-1 alpha-3 [46] country code in brackets).

Central Africa (CAPP)	Eastern Africa (EAPP)	Northern Africa (NAPP)	Southern Africa (SAPP)	Western Africa (WAPP)
Cameroon (CMR)	Burundi (BDI)	Algeria (DZA)	Angola (AGO)	Benin (BEN)
Central African Rep. (CAF)	Djibouti (DJI)	Libya (LBY)	Botswana (BWA)	Burkina Faso (BFA)
Chad (TCD)	Eritrea (ERI)	Mauritania (MRT)	Lesotho (LSO)	Côte d'Ivoire (CIV)
Congo (COG)	Ethiopia (ETH)	Morocco (MAR)	Malawi (MWI)	Gambia (GMB)
Democratic Rep. of Congo (COD)	Kenya (KEN)	Tunisia (TUN)	Mozambique (MOZ)	Ghana (GHA)
Equatorial Guinea (GNQ)	Rwanda (RWA)		Namibia (NAM)	Guinea (GIN)
Gabon (GAB)	Somalia (SOM)		South Africa (ZAF)	Guinea Bissau (GNB)
	Sudan (SDN)		Swaziland (SWZ)	Liberia (LBR)
	South Sudan (SSD)		Zambia (ZMB)	Mali (MLI)
	Tanzania (TZA)		Zimbabwe (ZWE)	Niger (NER)
	Uganda (UGA)			Nigeria (NGA)
	Egypt (EGY)			Senegal (SEN)
				Sierra Leone (SLE)
				Togo (TGO)

2 Methods

The methodology used to conduct this research is implemented in four stages. Firstly, the existing energy model for Africa developed using OSeMOSYS [47] has been further updated and calibrated to represent the off-grid technologies (mini-grid, stand-alone) and the residential electricity demand for the currently un-electrified settlements in Africa. Also, the previous model does not consider the geographical characteristics of the resources and the residential electricity demand's spatial dimension to identify the least-cost split between on- and off-grid technologies. Thus, in the second step, the Global Electrification Platform (GEP) [44] (based on the OnSSET model [48]) is used and calibrated to be aligned with the techno-economic assumptions and electricity demands considered in the OSeMOSYS model for Africa. In the third step, the residential electricity demands of the currently un-electrified settlements and the associated power generation mix satisfying these demands as an output of the GEP analysis are used as inputs in the OSeMOSYS-Africa model. By doing this linking each tool´s limitations are overcomed at some level. The final OSeMOSYS model provide an integrated electrification investment outlook. It provides the least-cost optimal mix of on-grid and off-grid technologies considering the Geographical theory and Geographic Information Systems (GIS) in electrification planning together with a least-cost long-run energy planning tool to cover each Africa´s country's future electricity demand in all sectors. The fourth step identifies the targets directly or indirectly related to energy infrastructure and the linkages between model outputs and the SDG targets. An accounting model is developed having as inputs the modelling results of the OSeMOSYS model and outputs indicators that can be used to assess the effects on achieving the SDG7 target. Lastly, the modelling results of the OSeMOSYS model are used as inputs in an input-output model to estimate the job creation potential during the energy transition of the African continent.

The modelling tools, input data, model assumptions, and the energy system pathways examined by 2040 under this study are presented in the following sections, Appendix and Supplementary Material.

Table 2
Summary of the modelling tools used in this study.

OSeMOSYS	GEP	Other models
1) Energy supply system	1) **Electricity supply system**	1) **Accounting model**
i) Import & extraction technologies	i) Grid extension	i) SDG7 index
ii) Centralized & decentralized technologies power generation technologies	ii) Mini-grid	
iii) Transmission & distribution network	iii) Off-grid technologies	
iv) Fuel conversion technologies		
2) Energy demands	2) **Electricity demand**	2) **Input-output model**
i) Electrified (others)	i) Residential (current un-electrified settlements)	i) Job creation potential during the energy transition of the African continent
ii) Residential (currently un-electrified settlements)		
iii) Other sectors (coal, heavy fuel oil, light fuel oil, natural gas, biofuel & waste, coal, natural gas)		

2.1 Description of the modelling tools

2.1.1 Cost-optimization framework for long term energy planning (OSeMOSYS)

The open-source energy modelling system (OSeMOSYS) tool is a freely available optimization modelling framework for medium to long-term energy planning [27]. It is a bottom-up modelling framework that uses linear-optimization techniques to satisfy an exogenously defined energy demand. OSeMOSYS has been employed in the scientific literature [21], [33] and in academic teaching and capacity building for energy planners to provide insights on possible transformation trajectories of both country to continental-scale energy systems [49]. The objective function equation consists of the sum of discounted operational and capital costs. The energy system consists of final energy demands distinguished between various end-use services, transmission and distribution networks, power generation technologies (on-grid and off-grid), energy trade links, conversion technologies, and technologies representing imports and extraction of energy resources. The modelling results can include power generation capacity, production by technology, operation and maintenance costs, and emissions on an annual level with a timely resolution for some of the variables.

2.1.2 Geospatial electrification outlook (GEP)

The OnSSET tool considers population settlements and, for each one, determines which is the least-cost technology to meet the electricity demand (grid, mini-grid, or stand-alone). The Levelized Cost of Electricity (LCOE) is calculated for each technology option, considering the investment, operation and maintenance, and fuel costs in each African country. The technology that can meet the demand at the lowest LCOE is selected as the least-cost technology option in that settlement [20]. The OnSSET tool has been used in national electrification studies (Malawi [50], Kenya [51], Tanzania [52], Afghanistan [53]) and regional electrification studies for the whole of Sub-Saharan Africa ([20], [54]). The latest Global Electrification Platform explores least-cost electrification strategies for 58 countries [32]. Integrating the spatial dimension of energy access (location and size of un-electrified population, geophysical parameters and technology costs) can improve the medium-to-long-term assessments of least-cost power system expansion [23]–[25].

The formula used to calculate the Levelized cost of generating electricity for each technology is the following:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

In year t, I_t is the investment cost, $O\&M_t$ are the operation and maintenance costs, F_t are the fuel expenditures, and E_t is the generated electricity. Further, r is the discount rate and n corresponds to the technology's lifetime. The average LCOE of all grid-connected power generation technologies is calculated to estimate the input grid cost to OnSSET.

OnSSET is not an energy system-wide optimization model, and it considers only the future connections of the current un-electrified settlements in the residential areas. Thus it does not represent the evolution of the grid-based electricity generation mix, which is a modeling outcome of the OSeMOSYS tool. The analysis of the grid components is missing from GEP [32].

By linking the two tools, OSeMOSYS and GEP, the electrification mix between grid (in terms of share), mini-grid and off-grid technology-specific which supplies the residential electricity demands in the current un-electrified population defined in GEP is fed into the OSeMOSYS model to identify the least-cost electrification mix (grid components) [20], [25], [51].

2.1.3 Index framework informing SDG7

In this study, the targets and the associated sub-targets of Sustainable Development Goal 7 are informed for each one of the African countries based on the modelling outputs of the energy transition for each scenario in 2030. An index framework is created based on the SDG7 targets focus, as presented in Table 3. The share of renewables and the amount of CO_2 emissions are defined only for the power sector. The energy intensity is estimated as the total primary energy supply per GDP. The lifetime of fossil fuel resources (%) is calculated as the production of fossil fuel reserves during 2015-2030 per each country´s total amount of identified fossil fuel reserves. The import dependency (%) is calculated as the total net imports (imports minus exports) of coal, crude oil, oil products and natural gas as a share of the total primary energy supply in 2030.

Table 3
SDG7 targets and their description [55].

Featured SDG Target	**Target Explanation**	**Indicator**	**Target and indicator**				
			Renewables (%)	**CO2 emissions (Mt)**	**Energy Intensity (Energy production/GDP)**	**Lifetime of fossil fuel resources (%)**	**Import dependency (%)**
Target 7.1	By 2030, ensure universal access to affordable, reliable and modern energy services.	**7.1.1** Proportion of population with access to electricity **7.1.2** Proportion of population with primary reliance on clean fuel and technology for cooking					
Target 7.2	By 2030, substantially increase the share of renewable energy in the global energy mix.	7.2.1 Renewable energy share in total final energy consumption	X	X		X	X
Target 7.3	By 2030, double the global rate of improvement in energy efficiency.	7.3.1 Energy intensity measured as a ratio of primary energy supply to gross domestic product			X	X	
Target 7.A	By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology.	7.A.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including hybrid systems.	X	X			X
Target 7.B	By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support.		X	X	X		X

2.1.4 Job creation potential

An analytical approach for the energy supply system of Africa is adopted to estimate direct energy jobs creation corresponding to the value chain of the energy transition of Africa. The methods by **Rutovitz et al. (2015)** [41], [42] are applied and adjusted to estimate job creation for the African continent using the associated techno-economic assumptions of the modeling inputs of this study. The Employment Factor (EF) method was applied amongst the other methods [56] primarily due to its simplicity and effectiveness in estimating direct employment associated with energy generation, storage, flexibility options and transmission and distribution of electricity. The EF approach is preferable to other methods since it can be modified for specific contexts and applied over a range of energy scenarios [57]. The total direct jobs are estimated considering a sum of jobs in manufacturing, construction and installation, operations and maintenance, fuel supply associated with electricity, decommissioning of energy plants at the end of their lifetimes and transmission and distribution of electricity [42]. This approach is briefly presented in Figure 1 and the methodology is further explained in detail in the Supplementary Material A.

2.2 Scenarios

The following four scenarios are examined for the modelling period 2015-2040 but providing results only until 2030, focusing on achieving universal access in Africa by 2030. The changes in the input parameters among the scenarios will provide a broader understanding of how universal access can be achieved in Africa and identify low-cost investments in power generation technologies. As the African nations aim to decrease their carbon dioxide emissions in the future (NDCs), how renewables can assist in this transition and the evolution of their costs is a challenge that needs to be examined. The national electrification rates of each African country are considered in this analysis. The National policies and SDG7 targets for each one of the African countries are collected and analyzed in each of the scenarios. The scenarios consider the national policies modelled as RET targets for each African country adopted until 2020. The main differences among the New Policies and the Renewable Deployment scenarios are the electrification mix for the current un-electrified settlements in the residential areas derived using the OnSSET-GEP tool [20], [32] and lower costs for renewables. In the model, electricity to the current un-electrified settlements in the residential areas starts supplying from 2020 onwards. The energy transition pathways examined under the Renewable Deployment scenario assist in addressing the challenges associated with SDG7, SDG1 (no poverty), SDG3 and SDG11 (reducing impacts of air pollution) and SDG13 (tackling climate change). In addition, different electricity consumption levels (Low, High) for the un-electrified settlements in the residential areas are considered for each of these scenarios (Figure 2). The modeling assumptions can be found in the Appendix and the Supplementary Material A. The detailed fuel demand projections are presented in the Appendix.

- New Policies – Low un-electrified settlements residential demand scenario (NPLs): Universal access by 2030 is achieved under different electricity consumption per capita targets for each African country, depending on their current electricity consumption levels. The low demand scenario considers tiers of electricity in rural household areas of Tier 1 while in urban households areas similar to the current per capita consumption in each country. The Electrification Tiers (1-5) are defined by ESMAP´s Multitier framework [58]. The scenario considers the future implementation of current commitments on power generation projects and electricity and gas interconnectors.
- New Policies – High un-electrified settlements residential demand *scenario (*NPHs*)*: the only difference with the NPL scenario is the different tiers of electricity in the household's current un-electrified settlements in the residential areas. In this scenario, the rural household areas which are currently un-electrified reach Tier 3. Respectively, the households in urban areas get to one Tier higher than each African country's respective electricity consumption per capita.
- Renewable Deployment – Low un-electrified settlements residential demand *scenario (*RDLs*)*: It aims to combat climate change by considering lower renewable energy technology costs than the New Policies scenarios and examining their effect. The electrification mix is different than the New Policies scenario. In this scenario, the current un-electrified settlements get Tiers of electricity similar to the NPLs scenario.
- Renewable Deployment – High un-electrified settlements residential demand scenario (RDHs): The techno-economic assumptions are similar to the RDLs scenario. The electrification mix is different than the New Policies scenario. The demand projections are similar to the NPHs scenario meaning that the un-electrified settlements in the residential areas will get higher Tiers of electricity than the SDLs scenario.

3 Results

Overall technology (installed capacity) mix

Overall, to fully electrify Sub-Saharan Africa and meet the future energy needs of the continent, the total installed capacity in the continent needs to increase from 178GW in 2015 to 389GW (NPLs), 473GW (NPHs), 403GW (RDLs) and 492GW (RDHs) in 2030 depending on the scenario. This capacity growth is primarily due to changes in electricity demand levels and renewable technology costs. Specifically, the capacity of fossil fuel technologies increased from 143GW in 2015 to 195GW (50%) in NPLs, 212GW (45%) in NPHs, 198GW (49%) in RDLs and 214GW (43%) in RDHs, in 2030. Natural gas constitutes most of the fossil-fuel installed capacity. In the opposite case, most of the renewable capacity in the continent is based on hydropower, although the capacity of solar technologies grows very fast. As the costs of renewables decrease further by 2040, the share of fossil fuels in the power system of Africa decreases even more in the Renewable Development scenarios than in the New Policies ones. Also, as the electricity demand increases between the scenarios (Low to High), higher investments in fossil fuel technologies are required to satisfy the final electricity demand levels since renewables are not always available to generate electricity.

Solar off-grid and solar hybrid mini-grid technologies are expected to gradually penetrate the power system in Sub-Saharan Africa and play an essential role in its future energy transition. The current un-electrified settlements will start getting electricity in 2020. This growth in electricity levels results in 2030 in an increase of the installed capacity of primarily solar off-grid technologies of 56GW (14%) in NPLs, 78GW (16%) in NPHs, 72GW (18%) in RDLs and 101GW (21%) in RDHs and solar hybrid mini-grid technologies of 12GW (3%) in NPLs, 40GW (8%) in NPHs, 15GW (4%) in RDLs and 44GW (9%) in RDHs.

Most of the total installed capacity in the continent was located in SAPP of 61GW (34%) in 2015. Nevertheless, to achieve SDG7 in Africa by 2030, the EAPP is estimated to represent most of the continent´s installed capacity, around 37% in all scenarios due to currently low electricity access levels and high population increase. This energy transformation in EAPP is led by hydropower investments in Ethiopia, Sudan, Tanzania, and Egypt's fossil fuel and solar technologies growth. Also, CAPP is expected to have the higher share of renewables in the continent, mainly due to hydropower and solar potential. The overall technology mix in Africa among the scenarios from 2015 to 2030 is presented in ***Figure 3*** and for each power pool in ***Supplementary Material B***.

Energy supply mix – Electrification mix

To fully electrify Africa and cover the continent's future energy needs, the total primary energy supply in the continent from 674 Mtoe in 2015 increased to a range of 1,312Mtoe (RDLs) to 1,374Mtoe (NPHs) in 2030, depending on the scenario (***Figure 4***). In the Renewable Development scenarios, less supply of fossil fuels is needed as in the New Policies scenarios (***Supplementary Material B***). Although by 2030, the penetration of renewables in the electricity mix of the continent does not significantly change, as their cost decreases in the Renewable Development scenarios than the New Policies scenarios by 2040, this transition is more evident.

The total electricity generation in Africa increased from 2,704PJ in 2015 to 6,221PJ (NPLs), 7,527PJ (NPHs), 6,188PJ (RDLs) and 7,487PJ (RDHs) in 2030, depending on the scenario. Out of the total electricity generation, the fossil fuels share constituted 81% in 2015, decreases to 63% (NPLs), 60% (NPHs), 63% (RDLs) and 60% (RDHs) in 2030. Natural gas is estimated to be the primary fossil fuel in the continent in the next decade. In the opposite case, hydropower was the dominant renewable power source in 2015. It remains by 2030 in the low demand scenarios (NPLs, RDLs), while in the high demand scenarios (NPHs, RDHs), solar power is the dominant power source. Specifically, solar off-grid and solar hybrid mini-grid are expected to play an essential role in the electrification of the current un-electrified settlements in residential areas. Depending on the scenario, grid-connected technologies are estimated to supply approximately 85%-90% of the total electricity generated in Africa in 2030, mini-grid technologies approximately 1%-6%, and stand-alone technologies 8%-11%. As the costs of renewables decrease in the Renewable Development scenarios, higher penetration of stand-alone solar technologies is expected by 2030 (***Supplementary Material B***).

Specifically, on a power pool level, NAPP is expected to increase its electricity generation from almost 590PJ in 2015 to 1,282PJ (NPLs), 1,301PJ (NPHs), 1,283PJ (RDLs) and 1,292PJ (RDHs) in 2030. The fossil fuel share is expected to decrease from almost 94% in 2015 to approximately 66% in all scenarios by 2030. The nations will continue to base their power generation in gas power plants in the next decade while solar gradually penetrates the power mix in Algeria, Morocco and Libya. In most scenarios (NPLs, RDLs, RDHs), stand-alone solar technologies will represent 13% of the electricity mix while in NPHs 17% in 2030.

In SAPP, the electricity generation increases from 989PJ in 2015 to 1,642PJ (NPLs), 1,939PJ (NPHs), 1,637 (RDLs), 1,930 (RDHs) in 2030. The fossil fuel share decreased from approximately 81% in 2015 to 74% in NPLs, 75% in NPHs scenarios and 73% in RDLs, RDHs scenarios in 2030. Most electricity generation is based on coal power plants, while hydro and solar gradually increase their share in the electricity mix. Solar stand-alone technologies are estimated to supply the electricity in the power pool of 74PJ (in NPLs), 102PJ (in NPHs), and 116PJ (in RDLs), 156PJ (in RDHs) in 2030.

In CAPP, the electricity generation increases from 91PJ in 2015 to 209PJ (NPLs), 388PJ (NPHs), 201 (RDLs) and 380PJ (RDHs) in 2030. Most of the electricity supplied in the power pool was based on hydropower, almost 62% in 2015. Nevertheless, achieving universal access in the power pool increases fossil fuel share from 38% in 2015 to 45% (NPLs), 34% (NPHs), 45% (RDLs) and 41% (RDHs) in 2030. High electricity consumption levels (NPHs, RDHs) lead solar power to generate most of the electricity instead of hydro. The current low electricity access levels and the high population in the Democratic Republic of Congo, Cameroon and Chad have collective implications. In all scenarios, oil-based generation declines in the power pool throughout the years. However, it is replaced by coal which starts supplying electricity from 2023 onwards primarily due to investments in the Democratic Republic of Congo and gas-based generation in Cameroon. In this power pool, the role of electricity interconnectors is highlighted to achieve universal access. Specifically, the gas-based generation is higher in the Renewable Development scenarios than in the New Policies ones, under respective electricity demand levels . This energy transition is due to the increase in the electricity supplied by gas power plants in Cameroon to satisfy part of its domestic consumption while its electricity imports from Chad decline by a significant margin. As electricity demand levels increase between the scenarios, DRC, except for covering part of its domestic electricity consumption from coal-based power plants and solar hybrid mini-grid systems, imports more electricity from Angola, Congo, Rwanda, and Zambia to also maintain its electricity exports at similar levels(cumulatively around 108PJ).

In EAPP, the electricity generation increases from 786PJ in 2015 to 2,241PJ (NPLs), 2,640PJ (NPHs), 2,224PJ (RDLs) and 2,633PJ (RDHs) in 2030. The fossil fuel share decreases from 79% in 2015 to 58% (NPLs), 52% (NPHs), 58% (RDLs) and 53% (RDHS) in each of the scenarios in 2030. Gas is expected to be the dominant fuel in the region in the next decade as in 2015, mostly of the gas-based electricity generation in Egypt, while coal from 2023 onwards increases its share in the electricity mix by a big margin due to coal investments in Egypt. Egypt needs to import coal in the future to generate electricity due to its limited availability of identified domestic coal reserves, affecting its import dependency. However, the government could use its natural gas reserves instead to strengthen the reliability of the power system and not be affected by the fluctuation of fossil fuel prices. Except for fossil fuel investments in Egypt, the RET-based generation in the country is expected to increase by almost seven times. As electricity demand increases, Egypt decreases its imports cumulatively from 2015-2030 while it increases its natural-gas-based electricity generation. In Ethiopia, although the RET share increases significantly, specifically hydropower, solar and geothermal, among the scenarios relatively as electricity demand increases, in the NPHs and RDHs scenarios, the country also starts producing electricity from natural gas power plants from 2028 onwards. To cover the increased fuel needs in the future (NPHs, RDHs), the country also reduces its electricity net exports to neighboring countries to even higher levels than the current onesin the NPLs, RDLs. The country also assists Kenya in achieving universal access. Hydropower and solar are the dominant fuels in Ethiopia, Kenya, Sudan, Tanzania and Uganda by 2030. , Tanzania is another country where as electricity demand increases (NPHs, RDHs) the country further exploits its domestic coal reserves to increase its coal-based electricity generation from 2022 onwards and decrease its net imports cumulatively almost by 30% (2015-2030). In the opposite case, under higher electricity demand levels (NPHs, RDHs), Rwanda increased their electricity generation by increasing their gas-based electrity generation from 2021 to increase its electricity exports primarily to Tanzania and Uganda. . However, this energy transition comes at the cost of increasing its carbon dioxide emissions.

WAPP presents the highest increase in its electricity generation between 2015 and 2030 in Africa. The electricity generation increases from 247PJ in 2015 to 847PJ (NPLs), 1262PJ (NPHs), 842PJ (RDLs), 1253PJ (RDHs) in 2030. The fossil fuels share decreased from 72% in 2015 to 56% in NPLs, NPHs and 58% in RDLs and 56% in RDHs in 2030. Gas is the dominant fuel in the region primarily due to investments in Cote D Ivoire, Ghana, Nigeria and Ghana by 2030 with an increased share of hydropower in Nigeria, Cote D Ivoire and Guinea, and solar off-grid and mini-grid technologies. As electricity demand rises among the scenarios, Nigeria is estimated to increase its coal-based power generation in 2022. However, the country decreases its net exports between 2015-2030 to satisfy the high increase in its domestic electricity consumption leading the electricity importers Benin and Niger to increase their gas-based and hydropower generation in the future.

The energy balances on a continental level for the different scenarios the period 2015-2030 are presented in ***Supplementary Material B***.

Investment needs for achieving universal access in Africa

The total system costs of an energy system consist of the capital investments, operating and maintance and operating fuel costs for all grid-connected, mini-grid and off-grid technologies and the transmission and distribution (T&D) infrastructure. Thus, the minimum total system costs required to fully electrify Africa and cover the future electricity needs in the continent in the period 2020-2030 amount to 2,973 billion USD at the Renewable Development Low scenario (lowest electrification level). In the opposite case, the maximum total system costs correspond to 3,489 billion USD at the Renewable Development High scenario at the same period. At the New Policies Low and High scenarios, the total system costs are 3,002 billion USD and 3,447 billion USD accordingly the period 2020-2030. Most of the overall system costs are constituted by the operating fuel ranging from 58%-66% depending on the scenario, as the share of fossil fuels decreases between the Renewable Development and the New Policies scenarios. The operation and maintance costs account for approximately 5% of the total system costs, while the capital costs for transmission and distribution on an average of 9% the period 2020-2030. The higher penetration of off-grid technologies in the Renewable Development scenarios leads to lower investments in the T&D network than in the New Policies scenarios. Higher electricity demand levels and lower renewable technology costs lead to higher capital investments in off-grid technologies during 2020-2030. However, higher capital investments on grid-connected technologies are needed in the Renewable Development High scenario. On average, roughly 61,696 (RDLs)179 – 82,338 (NPHs) billion USD annually are needed on capital investments in the power sector (technologies, T&D) during 2020-2030. The relatively high costs of the gradual penetration of off-grid systems in the power system of Africa in the Renewable Development scenarios are offset by the lower operating fuel costs and the lower T&D costs (lead by high losses in the T&D network). The economic dimension of the evolution of the power system in Africa across the scenarios during 2020-2030 is presented in ***Figure 5***.

The average cost of generating electricity per kWh each year in each African country's scenarios is presented in ***Table 4***, over the periods 2015 - 2020, 2020 - 2030. The costs in each country may vary among the scenarios since there are cases (as presented in ***Section 3.2***) a nation to increase its generation costs in assisting another country in satisfying its future electricity needs. The total system costs in this study are minimized on a continental scale and not on a country level. The average cost of generating electricity is the yearly ratio between the expenses incurred during that period (investment, operation, carbon tax) and the electricity generated. Higher average costs of generating electricity are primarily in the New Policies scenarios than the Renewable Development scenarios primarily due to higher penetration of fossil fuel technologies resulting in higher fuel operating costs. On the other hand, higher upfront capital investments are required for renewable technologies in the Renewable Development scenarios.

Table 4. *The average cost of generating electricity per kWh over the periods (2015-2030,) (cent USD/kWh). The costs are discounted assuming an average discount rate of 8%; they include the power supply grid-connected technologies.*

Country/scenario	2015-2020				2020-2030			
USD/kWh	NPLs	NPHs	RDLs	RDHs	NPLs	NPHs	RDLs	RDHs
Algeria	6.9	6.9	7.0	7.0	7.3	7.2	7.4	7.4
Angola	8.3	8.2	8.3	8.2	7.1	7.3	7.1	7.2
Benin	9.7	9.5	9.7	9.5	11.6	8.9	17.7	10.4
Botswana	5.4	5.4	5.4	5.4	5.8	5.7	5.0	4.8
Burkina Faso	15.4	15.4	16.1	16.1	16.2	15.7	17.3	17.3
Burundi	6.0	6.0	6.0	6.0	6.7	6.0	6.6	10.3
Cameroon	5.2	5.2	5.2	5.2	5.1	5.4	5.3	5.5
Central African Rep.	8.2	8.2	8.2	8.2	7.2	7.3	7.1	7.2
Chad	11.5	11.0	11.0	11.2	23.0	22.4	8.7	13.2
Republic of Congo	5.3	5.3	5.2	5.3	5.6	5.9	5.6	5.9
Democratic Republic of Congo	1.9	1.9	1.9	1.9	2.7	3.3	2.6	3.3
Cote d Ivoire	5.9	5.9	5.8	5.8	7.0	7.5	6.5	7.6
Djibouti	11.3	11.3	11.3	11.3	8.0	8.1	8.0	8.1
Egypt	6.2	6.2	6.2	6.2	7.2	7.2	7.1	7.2
Equatorial Guinea	5.6	5.5	5.7	5.7	4.9	4.8	5.5	5.5
Eritrea	9.7	9.7	9.8	9.7	8.2	7.2	8.3	7.2
Ethiopia	6.3	6.1	6.3	6.1	10.4	7.8	10.4	7.8
Gabon	5.4	5.4	5.4	5.4	5.3	5.4	5.3	5.4
Gambia	7.7	7.5	7.5	7.6	8.1	8.0	8.1	8.0
Ghana	6.2	6.2	6.2	6.2	6.6	6.6	6.5	6.6
Guinea	9.5	9.4	9.5	9.1	13.9	12.1	14.0	11.7
Guinea Bissau	12.4	12.5	12.5	12.5	11.8	10.5	11.6	10.6
Kenya	6.4	6.4	6.5	6.5	9.4	8.2	9.6	8.4
Lesotho	1.3	1.3	1.3	1.3	2.5	3.5	1.9	3.1
Liberia	8.8	8.4	10.4	8.6	9.1	8.9	7.6	8.9
Libya	8.1	8.1	8.1	8.1	7.5	7.5	7.6	7.6
Malawi	3.7	3.7	3.7	3.7	6.1	6.4	6.1	6.2
Mali	10.7	10.7	10.7	10.7	7.0	7.0	7.0	7.0
Mauritania	8.7	8.6	8.8	8.8	9.9	9.6	9.9	9.7
Morocco	7.2	7.3	7.1	7.3	9.8	9.0	9.9	9.9
Mozambique	2.1	2.1	2.1	2.1	4.6	5.4	4.0	5.2
Namibia	2.5	2.5	2.6	2.6	4.5	4.7	4.3	4.6
Niger	9.2	9.1	9.2	9.2	26.7	8.0	9.3	9.1
Nigeria	5.9	5.9	5.9	5.9	6.2	6.4	6.2	6.4
Rwanda	5.1	5.1	5.2	5.2	8.9	10.2	8.3	10.6
Senegal	7.5	7.5	7.5	7.5	7.7	7.6	7.7	7.6
Sierra Leone	8.6	8.6	8.6	8.6	6.3	6.4	6.2	6.4

Somalia	10.1	10.1	10.1	10.1	6.6	6.6	6.6	6.6
South Africa	5.1	5.1	5.2	5.2	4.7	4.8	4.7	4.8
Sudan	4.9	4.9	4.9	4.9	7.4	7.5	8.0	7.9
South Sudan	9.9	9.9	9.9	9.9	6.4	6.4	6.4	6.4
Swaziland	1.9	1.9	1.9	1.9	3.9	4.4	3.9	4.3
Tanzania	5.4	5.4	5.4	5.4	6.0	6.0	6.1	6.0
Togo	4.5	4.5	4.5	4.5	5.9	6.7	5.8	6.6
Tunisia	6.7	6.7	6.8	6.7	6.9	6.8	7.0	7.0
Uganda	4.9	4.7	4.9	4.7	5.4	5.7	5.2	5.8
Zambia	2.8	2.7	2.8	2.7	3.9	3.9	3.8	3.9
Zimbabwe	5.0	5.1	5.0	5.0	8.6	8.5	8.1	7.7

Sustainability insights for achieving SDG7 in each African nation

Achieving SDG7 in each African nation by 2030 will have different implications for the targets and sub-targets associated with SDG7 and each nation´s energy transition. The modelling results below can assist each country in understanding the conflicting objectives among the evolution of the power system with the energy indicators mentioned above. Specifically, although Benin, Cote D Ivoire, Equatorial Guinea and Ghana will increase their renewable energy targets by 2030, this energy transition consumes most of their respective fossil fuel reserves to cover their future energy needs, negatively affecting their net import dependency in the future. As a result of this analysis, the evolution of some indicators: the share of renewables, CO_2 emissions, energy intensity (energy production/GDP), the lifetime of fossil fuel resources and import dependency calculated for each African country is presented in ***Table 5***.

Table 5. *Tracking SDG7 targets, sub-targets and indicators for each African country among the scenarios in 2030.*

Country/ Scenario	Renewables electricity share out of final electricity generated (%)[1]				CO_2 emissions (Mt)				Energy Intensity (Energy production/GDP) (MJ/2010 USD) [2]				Consumption of fossil fuel reserves (%)[3]				Net import dependency of the energy system (%)[2]			
	NPLs	NPHs	RDLs	RDHs	NPLs	NPHs	RDLs	RDHs	NPLs	NPHs	RDLs	RDHs	NPLs	NPHs	RDLs	RDHs	NPLs	NPHs	RDLs	RDHs
Angola	66%	57%	72%	64%	37	40	36	38	3.8	4.2	3.7	4.0	85%	85%	84%	85%	-366%	-321%	-367%	-345%
Benin	70%	76%	69%	78%	14	15	14	15	9.2	10.1	9.2	10.0	63%	100%	63%	100%	95%	91%	94%	92%
Botswana	35%	36%	35%	37%	11	13	10	10	4.3	4.9	4.1	4.2	2%	2%	2%	2%	60%	53%	63%	61%
Burkina Faso	90%	93%	90%	95%	12	14	12	12	4.2	5.0	4.2	4.4	-	-	-	-	95%	97%	95%	91%
Burundi	100%	99%	99%	99%	2	3	2	3	2.5	5.3	2.5	4.9	-	-	-	-	84%	85%	85%	90%
Cameroon	33%	31%	38%	29%	10	10	10	12	2.3	2.7	2.3	2.8	28%	31%	30%	34%	39%	34%	40%	32%
Central African Rep.	83%	95%	76%	95%	1	2	1	1	1.7	3.9	1.5	3.3	-	-	-	-	87%	95%	80%	94%
Chad	98%	99%	96%	99%	1	5	1	3	1.1	3.2	0.8	1.7	50%	50%	50%	50%	-981%	-263%	-1369%	-588%
Congo	32%	27%	31%	24%	9	10	9	10	3.8	4.2	3.8	4.2	46%	47%	46%	47%	-374%	-331%	-374%	-331%
DRC	50%	66%	59%	65%	18	38	16	34	3.7	7.4	3.5	6.6	41%	50%	38%	50%	40%	59%	49%	54%
Cote d Ivoire	39%	34%	42%	33%	28	32	28	33	5.1	5.7	5.0	5.8	100%	100%	100%	100%	95%	95%	95%	97%
Djibouti	54%	94%	57%	93%	1	1	1	1	4.3	4.4	4.3	4.0	-	-	-	-	77%	74%	79%	79%
Equatorial Guinea	81%	81%	66%	66%	50	50	50	51	39.1	39.1	39.2	39.2	98%	98%	98%	98%	98%	98%	99%	99%
Eritrea	88%	94%	87%	94%	1	1	1	1	4.5	5.8	4.4	5.2	-	-	-	-	88%	75%	89%	76%
Ethiopia	100%	98%	100%	98%	31	35	31	32	3.2	3.9	3.2	3.6	1%	1%	1%	1%	74%	68%	74%	66%
Gabon	66%	69%	66%	67%	3	3	3	3	2.6	2.7	2.7	2.8	65%	65%	65%	65%	-645%	-639%	-641%	-616%
Gambia	63%	79%	61%	78%	1	1	1	1	2.5	2.8	2.5	2.6	-	-	-	-	93%	91%	93%	89%
Ghana	46%	37%	47%	38%	32	43	32	42	5.5	6.7	5.5	6.6	91%	92%	91%	92%	81%	94%	82%	93%
Guinea	88%	92%	88%	91%	11	11	11	11	4.0	4.4	4.0	4.3	-	-	-	-	93%	89%	93%	88%
Guinea Bissau	92%	97%	91%	93%	1	1	1	1	4.1	5.0	4.1	4.6	-	-	-	-	95%	95%	95%	92%
Kenya	55%	82%	60%	82%	42	42	42	42	5.6	6.3	5.5	6.1	-	-	-	-	89%	80%	91%	82%
Lesotho	100%	99%	100%	100%	4	4	4	4	12.0	12.8	12.0	12.5	-	-	-	-	86%	86%	86%	83%
Liberia	70%	84%	25%	84%	3	4	4	3	6.6	7.8	8.3	7.2	-	-	-	-	89%	90%	102%	89%
Malawi	76%	85%	78%	85%	5	7	5	6	3.9	5.4	3.9	4.5	-	-	-	-	68%	71%	70%	63%
Mali	97%	97%	97%	98%	7	7	7	7	5.1	5.6	4.8	5.2	-	-	-	-	69%	66%	73%	68%
Mauritania	38%	39%	35%	37%	14	15	14	15	8.3	8.8	8.4	9.0	11%	11%	11%	11%	-54%	-49%	-51%	-45%
Mozambique	26%	20%	31%	25%	40	55	39	52	8.8	11.7	8.6	11.1	5%	6%	5%	6%	-45%	-33%	-45%	-36%
Namibia	70%	71%	69%	71%	10	10	10	10	9.4	9.2	9.4	9.3	18%	20%	18%	20%	52%	53%	53%	52%
Niger	60%	76%	60%	70%	6	10	6	7	4.1	6.1	4.0	4.6	82%	93%	82%	83%	-6%	88%	-6%	3%
Nigeria	36%	35%	30%	34%	385	394	383	393	5.7	6.1	5.7	6.0	29%	30%	29%	30%	-126%	-119%	-128%	-121%
Rwanda	97%	63%	97%	68%	2	4	2	4	1.3	2.2	1.3	2.0	0%	5%	0%	5%	83%	64%	86%	66%
Senegal	57%	53%	67%	54%	10	12	9	12	3.6	4.2	3.3	4.0	-	-	-	-	93%	93%	90%	93%
Sierra Leone	81%	93%	72%	94%	3	4	3	4	4.0	5.0	4.1	5.1	-	-	-	-	95%	93%	93%	95%
Somalia	98%	98%	93%	98%	6	6	2	6	133.5	133.7	52.4	133.6	-	-	-	-	98%	98%	95%	98%
South Africa	10%	10%	10%	10%	443	464	448	474	8.7	9.1	8.7	9.2	9%	9%	9%	9%	38%	37%	38%	36%
South Sudan	78%	94%	91%	94%	3	5	4	4	-	-	-	-	19%	19%	19%	19%	90%	95%	95%	95%
Sudan	34%	38%	37%	41%	52	55	54	55	4.5	4.9	4.5	4.7	63%	67%	63%	66%	59%	60%	64%	63%
Tanzania	73%	61%	81%	58%	32	49	31	45	3.5	5.0	3.4	4.5	18%	28%	17%	28%	46%	45%	50%	38%
Togo	43%	37%	70%	41%	5	8	4	8	7.6	10.9	6.8	10.1	-	-	-	-	93%	96%	86%	96%
Uganda	79%	89%	97%	80%	7	12	6	8	1.4	2.4	1.3	2.0	1%	1%	0%	2%	68%	68%	72%	53%
Zambia	66%	68%	68%	73%	13	13	13	12	5.2	5.5	4.9	5.1	43%	44%	37%	49%	41%	38%	40%	39%
Zimbabwe	26%	21%	30%	28%	19	26	16	22	26.8	34.7	23.9	30.1	12%	15%	12%	13%	41%	32%	44%	34%

Note: [1] Solar hybrid technologies included in renewables, [2] Total primary energy supply per GDP [59], [3] Production of fossil fuel reserves during 2015-2030 per each country´s total amount of identified fossil fuel reserves, [4] Total net imports (imports minus exports) of coal, crude oil, oil products and natural gas as a share of total primary energy supply in 2030. Negative values correspond to net exporters. The differences in the RET share may occur since the electricity generation is not always the same among the scenarios and the supply mix differs since the electricity trading scheme changes among the scenarios

Environmental implications

The total carbon dioxide emissions of the evolution of the energy system in Africa increased from 1,213Mton in 2015 to 2,797Mton (NPLs), 2,9431Mton (NPHs), 2,793 (RDLs) and 2,919Mton (RDHs) depending on the scenario in 2030. NAPP is estimated to represent most of the continent´s carbon dioxide emissions in the future, although the share of renewable energy technologies increases followed by EAPP, SAPP, WAPP and CAPP (***Supplementary Material B***). Higher electricity consumption levels lead to higher carbon dioxide emissions. However, lower carbon dioxide emissions are emitted as the renewable technology costs decrease (RDLs, RDHs). Thus, a decreased cost of renewables could further assist an African nation in evolving its power sector to achieve universal access and achieve part of the National Determined Contribution greenhouse gas emissions targets.

Socio-economic implications: Job creation

Previous sections show that Africa needs energy to grow, which has environmental implications and is cost expensive. However, this energy transition and electricity access can create several jobs than lost. Different levels of jobs can be created associated with the construction and installation of the power generation technologies to the fuel use and specifically to the use of power generation technologies. In Africa, approximately 6.9 million direct jobs can be created by expanding power generation capacity and T&D network in the NPLs scenario, 8.7 million jobs in the NPHs scenario, 7.0 million jobs in the RDLs scenario and 9.6. million jobs in the RDHs scenario during 2020-2030 across the supply chain of the evolution of the power sector (***Figure 6***). Of this total number of jobs in each scenario, 6.4 million jobs in NPLs, 7.8 million jobs in the NPHs, 6.5 million jobs in the RDLs and 8.7 million in the RDHs scenarios accordingly are associated with the future installation and operation of specific power generation technologies. Solar power is expected to be the dominant technology in creating new employment opportunities (***Figure 7***). It is assumed that the manufacturing happens only locally and is not created from exports to other countries. In the Renewable Deployment scenarios, more jobs are created in the manufacturing (local) sector, construction&installation, and operation and maintenance but lower jobs on transmission since the future installed capacity is less due to higher penetration of off-grid renewable technologies. However, higher fuel jobs are created in the RDLs and RDHs scenarios than in the New Policies scenarios, primarily due to the fuel used in coal power plants until 2030. Increasing the share of renewables can boost employment in Africa, while fossil fuel development can support jobs in different ways. Further increasing the electricity consumption levels in Africa (NPHs, RDHs) is estimated to create more jobs. Solar hybrid mini-grid systems are not included in the analysis of job creation potential.

4 Conclusions

This study highlights the importance of strategic energy planning to achieve universal access in each African nation and cover its future energy needs considering their socio-economic development until 2030. Exploiting the energy resources of Africa strategically to expand its power system can lead to effective, sustainable energy decisions to formulate mitigation and adaptation climate change policy measures. The energy transition is complex and has several implications for a nation´s economy and future development. In this analysis, least-cost power generation investment options using energy systems analysis enhanced with geospatial data for each African nation are identified, considering different levels of electricity consumption per capita (Low, High) and costs of renewables (New Policies, Renewable Deployment). The four scenarios examined in this study investigated the implications of the future energy transition in Africa on the electricity supply mix, the total system costs, achieving SDG7 and its sub-targets, the associated environmental and socio-economic implications. A critical dimension of achieving SDG7 in Africa, except the different electricity consumption per capita levels each African nation wants to achieve, is the evolution of renewable technology costs. Africa can not afford a cost-increasing green energy transition pathway. This study develops country-specific electrification investment outlooks to assist each African nation's government officials and policy makers in strengthening risk mitigation associated with future renewable energy projects and ensuring their financial viability.

The power generation capacity in Africa needs to increase approximately 2 - 2.6 times in the NPLs and NPHs scenarios accordingly, while 2.3-2.8 times in the RDLs and RDHs scenarios, to cover its future energy needs and achieve SDG7 between 2015-2030. Natural gas constitutes most of the fossil-fuel installed capacity in all scenarios. In the opposite case, hydropower is currently the dominant renewable energy technology. It will remain by 2030 if the costs of solar technologies do not significantly decrease in the upcoming decade. Otherwise, as it is shown in the RDLs and RDHs scenarios, solar power can be the leading power generation technology in Africa by 2030, building climate change resilience of the system. Solar off-grid and solar hybrid mini-grid technologies are expected to play an essential role in the electrification of the current un-electrified settlements in the residential areas. The total primary energy supply in the continent is estimated to increase from 674Mtoe in 2015 to a range of 1,312Mtoe to 1,374Mtoe in 2030, depending on the scenario. The total electricity generation in the continent needs to increase by 2.3 times in the NPLs, RDLs scenarios and 2.8 times in the NPHs, RDHs scenarios, respectively, by 2030. The fossil fuels share constituted 81% in 2015, decreases to 63% (NPLs), 60% (NPHs), 63% (RDLs) and 60% (RDHs) in 2030. Higher electricity consumption levels lead to higher penetration of fossil fuel technologies in the power mix of Africa. However, to achieve the same electricity demand levels, decreasing renewables' costs can assist in a less carbon-intensive power system, although higher capacity needs to be installed. Depending on the scenario, grid-connected technologies are estimated to supply approximately 85%-90% of the total electricity generated in Africa in 2030, mini-grid technologies roughly 1%-6%, and stand-alone technologies 8%-11%. Solar off-grid technologies supply electricity approximately 8% (NPLs), 9% (NPHs), 10% (RDLs) and 11% (RDHs) of the total generated electricity in Africa and solar hybrid mini-grid technologies 2% (NPLs), 5% (NPHs), 1% (RDLs) and 3% (RDHs) by 2030.

Achieving lower-higher electricity demand levels and the costs of renewables could transform countries accordingly into net importers or exporters depending on their future energy choices (e.g., Tanzania). Also, based on the future energy investments of each nation, achieving SDG7 in an African country may have collective implications to several factors (e.g., the share of renewables, CO_2 emissions, energy intensity, the lifetime of fossil fuel resources, import dependency) and achieving one target may have conflicting objectives with others on a local level but also a regional one. Benin, Cote D Ivoire, Equatorial Guinea and Ghana are some countries that increase their renewable energy targets by 2030. However, this energy transition consumes most of their fossil fuel reserves to cover their future energy needs, negatively affecting their net import dependency in the future. The outcomes of this analysis, achieving SDG7 in Africa, can provide insights to other SDGs such as SDG1, SDG2, SDG3, SDG6, SDG8 and SDG13 [3].

Higher penetration of renewable energy sources in the energy mix reduces dependence on imported fuels, creates local jobs, and increases cost efficiency. Although higher up-front capital investments in renewables are required, the operating fuel costs are lower in the long term. Thus, the total system costs required to fully electrify Africa and cover the future electricity needs in the continent during 2020-2030 amount to 3,000 billion USD in the NPLs and 3,447 billion USD in the NPHs scenarios while 2,973 billion USD in the RDLs and 3,489 billion USD in the RDHs scenarios. The penetration of solar off-grid technologies in the Renewable Deployment scenarios leads to fewer investments in the transmission and distribution network, preventing the relatively high infrastructure losses and improvements needed to upgrade the network and decreasing operating fuel costs. Nevertheless, improvements on the T&D network are essential to provide reliable electricity to the citizens. On average, roughly 62 – 82 billion USD annually are needed on capital investments in the expansion of the power sector (technologies, T&D) during 2020-2030. Moreover, the countries could partly take advantage of their electricity and gas exports revenues to other countries to financially support their future energy transition.

Despite the gradual penetration of renewable energy and solar off-grid technologies in the continent's energy mix, which is higher as renewable costs decrease, Africa is still hard to achieve its green revolution. Domestic identified fossil fuel reserves and fossil-fuel technologies are still the least-cost options to satisfy future energy needs in Africa and provide resilient power grids. An example is the coal power plants which may be phased out in South Africa but be installed in Egypt in the upcoming years and the gradual penetration of natural gas power plants in Nigeria. Consequently, the total carbon dioxide emissions of the future energy transition in Africa increased from 1,213Mton in 2015 to 2,797Mton (NPLs), 2,943Mton (NPHs), 2,793 (RDLs) and 2,919Mton (RDHs) depending on the scenario in 2030. Thus, a decreased cost of renewables could further assist an African nation in evolving its power sector less carbon-intensive. The continental and national scale insights could inform the National Determined Contributions targets by demonstrating the broader African context of national greenhouse gas emission targets.

Africa needs energy to grow, which has environmental implications and is cost expensive. However, this energy transition and achieving electricity access can create several jobs than lost. In Africa, approximately 6.9 million direct jobs can be created by expanding the power generation capacity and the T&D network in the NPLs scenario, 8.7 million jobs in the NPHs scenario, 7.0 million jobs in the RDLs scenario and 9.6 million jobs in the RDHs scenario during 2020-2030 across the supply chain. The increased share of renewables in the energy transition in Africa can boost job creation, while fossil fuel development can support jobs in different ways. Increasing the electricity consumption levels in Africa (NPHs, RDHs) leads to higher total system costs, but it is estimated to create more jobs. Also, the decreasing costs of renewables (RDLs, RDHs) could further increase the penetration of renewables in the energy mix, leading to a higher number of jobs. Potentially achieving climate change targets in the future (e.g., 2.0^{o}C, 1.5^{o}C), more jobs could be created in Africa, meaning that more jobs can ensure political and societal stability. Also, how the jobs will be created and spread in Africa due to the diversification of the energy mix in each African nation may lead to social and economic disruptions, so strategic energy planning is essential.

National and governmental institutions and universities involved in capacity-building activities could benefit from this open-source study since the provided datasets could strengthen the capacity for developing others and extending existing energy systems models.

The analysis could be further improved. Increase the sub-annual time resolution to better capture the variability in the electricity generated by renewable technologies. However, this is prevented due to the limitation of other input data associated with the model. Include country-specific hydro capacity factors and represent hydropower plants individually instead of aggregating them per size. Hydrological modelling of each planned dams would provide more accurate quantification of dam productivity and impacts. Including an explicit representation of reserve margin into each country's power system would improve the representation of national energy systems. Battery storage for solar PV and pumped hydropower storage are only implicitly modelled due to the macroscopic nature of the study that focuses on Africa’s urgent need for access to energy and computational constraints (e.g., the computational time increases significantly). Better data (e.g., available country information on future power plant investments, energy reserves) and spatial techniques (e.g., soft-link with GIS, 2-3 iterations with GEP) could enhance the modelling results. Disaggregate the final energy demand in sectors and exogenous assumptions around fuel switching and efficiency improvements. Including oil and coal export analysis (rather than assuming exogenous sales levels) is currently excluded from this analysis. Lastly, the NDCs of all countries were collected and analysed in this study but weren´t incorporated since each country's greenhouse gas emission limits are not only related to the energy sector. However, the outcomes of this analysis can be used to inform each country´s NDCs.

Appendix

Methods – Model description

1.1 The Energy Supply system

The energy supply system for each African country is constituted by fuel supply technologies categorized in import and extraction technologies and crude oil refineries. The natural gas imports can be through pipelines or liquefied natural gas terminals. Each country's power system is constituted by centralized and decentralized technologies (stand-alone, mini-grid) (***Supplementary Material A)***. The decentralized technologies are aligned with the ones considered in the Global Electrification Platform (GEP) tool [44]. Electricity interconnector projects between the African countries for imports and exports are considered in the analysis. Also, a transmission and distribution network with the associated losses for each African country is modelled. Lastly, for the non-power sector, only fuel conversion technologies are considered in the analysis and the other sectors are not explicitly modeled. The energy demands are presented in the section ***1.2.1 Energy*** demands ***1.2.1***. The Reference Energy system shows the technologies and fuels considered in each country's energy system in a schematic representation (***Supplementary Material A***).

1.2 Overall Data-model assumptions

The modelling period spans between 2015-2040, providing results on an annual basis until 2030. The last ten years of the modelling period were added to prevent the “edge effects” as they are distorted by the model, considering that as the “end-of-time”. Each year is divided into four seasons and two dayparts to capture the key features of the electricity demand load pattern. The year split is defined at a continental level, so the countries cannot have a corresponding day split (e.g., day and night). The “daypart 1” is between 09:00 - 18:00 (most of the commercial and public services are supposed to operate) and “daypart 2” between 18:00-09:00. “Season 1” corresponds to the period between March-May, “Season 2” between June-August, “Season 3” between September-November and “Season 4” between December-February. Country-specific hourly electricity demand profiles were used to develop average profiles for electricity demand for the models’ temporal split [12].

Country-specific fossil fuel reserves and renewable potential are considered in the analysis. The list of power plants considered into the model is categorized into existing projects which are operational (OPR), committed if the construction is about to start soon (CON) and planned if the power plants are identified as candidates (PLN) for each country´s power system [60]. The power plants are distinguished in old (existing ones until 2014) with lower efficiencies than the new ones. No new future electricity and gas trade flows are considered into the model except the operational and committed ones. To capture the variability of renewable energy generation, hourly wind and solar generation profiles country-specific are used [61] except for hydropower plants where generic capacity factors are considered based on the region's seasonality due to lack of data [62]. In the model, country-specific losses are considered in the transmission and distribution network. Country-specific fuel prices considered in the analysis distinguished in inland and coastal. Lastly, a carbon tax is applied only in South Africa. The techno-economic assumptions of the energy supply technologies and the energy system model overall can be found in ***Supplementary Material A***.

The real discount rate is 8% on a continental level [44]. The monetary unit used is the 2015 United States Dollars (USD). The USD gross domestic product (GDP) deflator from the World Bank Group is used [11] to adjust the fuel prices reported in different years to the base year (2015).

1.2.1 Energy demands

The energy demands considered in the model for the different fuels are: i) electricity, ii) biofuels and waste, iii) coal, iii) natural gas and iv) oil products demand. The electricity demands are categorized in: i) "all sectors" which include the aggregated final electricity consumption and ii) "residential electricity demands of current un-electrified settlements" distinguished in low and high depending on the electricity consumption per capita levels. The fuel exports (coal, crude oil, oil products, biofuels & waste) are exogenously encountered in the model and are based on the average values of the historical year's exports for each country [63], [64]. The fuel exports (non-electricity and gas ones) remain the same across all the scenarios.

To estimate the fuel demands in "(all sectors)" the IBM SPSS Statistics tool was used to conduct a linear regression analysis using historical data (fuel consumption, GDP, population, urbanization) between 1990-2018 and project the values until 2040, using as methods criteria the probability of F. In case the regression analysis didn't fit well between the dependent variable (fuel consumption) and the independent ones (GDP, population, urbanization) then the average growth rate of the power pool was used for that country or the average growth rate of the historical values of the respective country.

The historical fuel consumption between 1990 to 2018 was used from IEA World Energy Balances and UN Department for Economic and Social Affairs Statistics Division [63], [64]. The historical values of GDP derived by the World Bank Group [9] and the projections are compatible with Shared Socio-economics Pathways (SSP2) [65]. The historical and forecasts for the population [59] and urbanization values [66] were derived by the United Nations, Department for Economic and Social Affairs, Population Division 2019 (medium varant scenario).

The "residential electricity demands of current un-electrified settlements" start from 2020 onwards to achieve universal access by 2030. They are categorized in "Low un-electrified settlements residential demand" and "high un-electrified settlements residential demand". The electricity demand projections for low and high electricity consumption per capita levels in rural and urban areas are derived from GEP [44]. The demand projections are based on national electrification rates [8], population projections (medium varant scenario) [59], average household size in rural and urban areas [36] and electrification Tiers based on the Multitier framework defined by ESMAP [67]. Energy efficiency measures are not considered in demand projections.

The assumptions used for the energy demand projections are presented below. The "residential electricity demands of current un-electrified settlements" for each African country and each scenario are presented below. The rest of the fuel demands are in ***Supplementary Material A***.

Assumptions used for energy demand projections (Table 6-9)

Table 6. *Socio-economic assumptions (Population, Real GDP, urbanization) [59].*

Country/Region	Total population (billion)			GDP (billion 2010 US$/yr)			Urbanization		
	2020	2030	2040	2020	2030	2040	2020	2030	2040
Central Africa									
Cameroon	26.5	33	41	40	74	125	58	63	68
Central African Rep.	4.8	5.8	7.1	2	5	10	42	48	54
Chad	16.4	21.1	27	13	25	46	24	27	33
Republic of the Congo	55.2	6.9	8.6	11	34	55	68	72	76
Democratic Rep. of Congo	89.5	117	152	37	75	169	46	52	58
Equatorial Guinea	1.4	1.8	2.3	12	25	33	73	77	80
Gabon	2.2	2.7	3.2	20	24	33	90	93	94
Eastern Africa									
Burundi	11.9	15.4	19.8	2	10	20	14	18	22
Djibouti	0.9	1.1	1.2	2	4	6.5	78	80	82
Eritrea	3.5	4.2	5	1	3.5	6	41	48	54
Ethiopia	115	142	172	72	176	318	22	27	33
Kenya	53.7	65	78	65	115	196	28	33	40
Rwanda	13	16	19	13	27	49	17	20	24
Somalia	15.9	20.6	27	0.1	0.6	1.3	46	52	58
Sudan	43.9	54	66.6	92	161	274	35	40	46
South Sudan	11	13.5	16.5				20	24	30
Tanzania	59.7	77	100	65	137	254	35	42	49
Uganda	45	58	73	48	95	185	25	31	38
Egypt	102	119	138	313	775	1225	43	45	49
Northern Africa									
Algeria	43.8	49.8	55.1	191	348	429	74	78	82
Libya	6.8	7.5	8.1	38	60	90	81	84	86
Mauritania	4.6	5.8	7.2	2	14	23	55	63	68
Morocco	36.9	40.5	43.7	132	241	371	64	69	73
Tunisia	11.8	12.7	13.3	60	142	208	70	73	77
Southern Africa									
Angola	32.8	43.5	58.1	95	140	156	67	73	77
Botswana	2.3	2.7	3.1	17	35	45	71	77	81
Lesotho	2.1	2.3	2.5	2	5	8	29	34	40
Malawi	19.1	24	30	12	26	51	17	21	26
Mozambique	31	40	51	21	49	86	37	43	49
Namibia	2.5	2.9	3.4	14	20	29	52	61	67
South Africa	59	65	71	430	654	875	67	72	76
Swaziland	0.001			0.9	5	8	24	27	30
Zambia	18	24	31	29	45	83	45	50	57
Zimbabwe	15	17	21	14	8	14	32	34	39
Western Africa									
Benin	12.1	15.2	19.3	15	21	37	48	54	60
Burkina Faso	20.9	26.7	34.2	17	42	78	31	37	44
Cote D Ivoire	26.4	33	41	45	88	172	52	57	62
Gambia	2.4	3	3.9	2	6	11	63	68	73
Ghana	31	37	44	57	93	160	57	63	69
Guinea	13	16	21	13	40	79	37	41	47
Guinea Bissau	1.9	2.4	2.9	1	3	6	44	48	53
Liberia	5	6	7.6	2	7	15	52	57	63
Mali	20	26	34	16	27	51	44	51	57
Niger	24	33.6	47	14	23	46	17	19	23
Nigeria	206	257	322	487	762	1353	52	59	65
Senegal	16.7	21	26.5	26	39	66	48	53	59
Sierra Leone	7.9	9.5	11	5	11	20	43	48	54
Togo	8	10	12.5	6	10	17	43	49	55

Table 7. *National Electrification rate in 2019 [8].*

Country/Region	National (%)	Urban (%)	Rural (%)
Central Africa			
Cameroon	63	93	24
Central African Rep.	14	32	2
Chad	8	37	3
Congo	48	66	13
Democratic Rep. of Congo	19	41	1
Equatorial Guinea	67	91	2
Gabon	91	98	24
Eastern Africa			
Burundi	11	63	3
Djibouti	61	72	25
Eritrea	50	76	37
Ethiopia	48	93	36
Kenya	70	91	62
Rwanda	38	93	26
Somalia	36	66	11
Sudan	54	81	39
South Sudan	7	13	5
Tanzania	38	73	19
Uganda	41	71	32
Egypt	100	100	100
Northern Africa			
Algeria	100	100	99
Libya[1]	69	100	8
Mauritania	45	82	1
Morocco	100	100	99
Tunisia	100	100	100
Southern Africa			
Angola	43	74	4
Botswana	70	88	28
Lesotho	45	76	32
Malawi	11	46	4
Mozambique	30	73	5
Namibia	55	75	35
South Africa	85	88	79
Swaziland	77	91	73
Zambia	43	80	14
Zimbabwe	41	85	20
Western Africa			
Benin	40	65	17
Burkina Faso	14	62	5
Cote D Ivoire	69	94	42
Gambia	60	80	28
Ghana	84	94	70
Guinea	42	88	16
Guinea Bissau	31	54	13
Liberia	28	46	8
Mali	48	91	15
Niger	19	50	13
Nigeria	55	84	26
Senegal	70	95	48
Sierra Leone	23	51	2
Togo	52	92	24

[1] Note: it is assumed that the electricity access in Libya is almost 100%

Table 8. *Multi-tier Matrix for Measuring Household Electricity consumption [58].*

	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Annual consumption levels, in kWhs	>=4.5	>=73	>=365	>=1,250	>=3,000

Table 9*. Residential electricity demands of current un-electrified settlements in 2030 (GWh).*

Country/Region	New Policies & Renewable Deployment (Low)	New Policies & Renewable Deployment (High)
Central Africa		
Cameroon	1598.2	8407.2
Central African Rep.	461.1	1650.4
Chad	986.1	4649.4
Congo	1169.6	3467.6
Democratic Rep. of Congo	11257.1	38429.1
Equatorial Guinea	564.2	856.2
Gabon	1213.6	1749.5
Eastern Africa		
Burundi	720.2	4300
Djibouti	271.4	407.6
Eritrea	169.5	1089.8
Ethiopia	7106	33638.7
Kenya	6056.8	25586.5
Rwanda	233.4	2531.2
Somalia	1542.4	5251.7
Sudan	7895.4	15286.7
South Sudan	615.3	3091.1
Tanzania	7144.5	26787.3
Uganda	4782.3	20929.4
Egypt	-	-
Northern Africa		
Algeria	-	-
Libya	-	-
Mauritania	480.5	1509.3
Morocco	-	-
Tunisia	-	-
Southern Africa		
Angola	11236	17381.4
Botswana	2409.6	3662.5
Lesotho	273.2	1143.6
Malawi	3308.7	8817.8
Mozambique	3841.3	14321.3
Namibia	1890.6	2199.3
South Africa	15207.7	45136
Swaziland	167.5	799.3
Zambia	5221	9684.8
Zimbabwe	4033.5	8352.3
Western Africa		
Benin	635.6	3746.2
Burkina Faso	608.7	4629.1
Cote D Ivoire	3085.7	10119.1
Gambia	68.6	339.4
Ghana	5497.1	17187.6
Guinea	1034.9	3925.5
Guinea Bissau	58.2	370.7
Liberia	1597.3	2673.3
Mali	606	3714
Niger	1033.4	5967.2
Nigeria	77933.9	128931.3
Senegal	1263	4260.3
Sierra Leone	252.9	1626
Togo	1214	4266.8

Note: The electricity demand between the two scenarios is the same, but the generation mix is different as an outcome of the Global Electrification Platform (GEP) [32].

1.3 Policies

In the New Policies and Renewable Deployment scenarios, the objective is to examine different universal access scenarios by extrapolating the current energy situation into the future and providing energy transition pathways on a national, regional and African level. The scenarios consider only the national renewable policies (***Supplementary Material A***) extracted by the national policy plans of each African country and future investments on power plants and interconnectors, which are in force until 2017, without considering new policies such as National Determined Contributions [4]. The NDCs of all countries collected and analysed in this study but couldn't be incorporated since the greenhouse gas emission limits posed by each country are not only related to the energy sector. However, the outcomes of this analysis can be used to inform each country´s NDCs.

Declarations

Data availability

The dataset used to develop the model can be found in the Zenodo repository [68]. The detailed model results by country, power pool and continental level for the different scenarios can be found in Zenodo repository [69].

Code availability

The OSeMOSYS code used to develop the model for Africa can be found in Zenodo-Github repository [68]. The current version of the TEMBA model takes up to 60 min. to solve using a commercial-grade solver (such as CPLEX or Gurobi) and requires up to 64 GB of memory.

Competing interests: The authors declare no competing interests.

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Figures

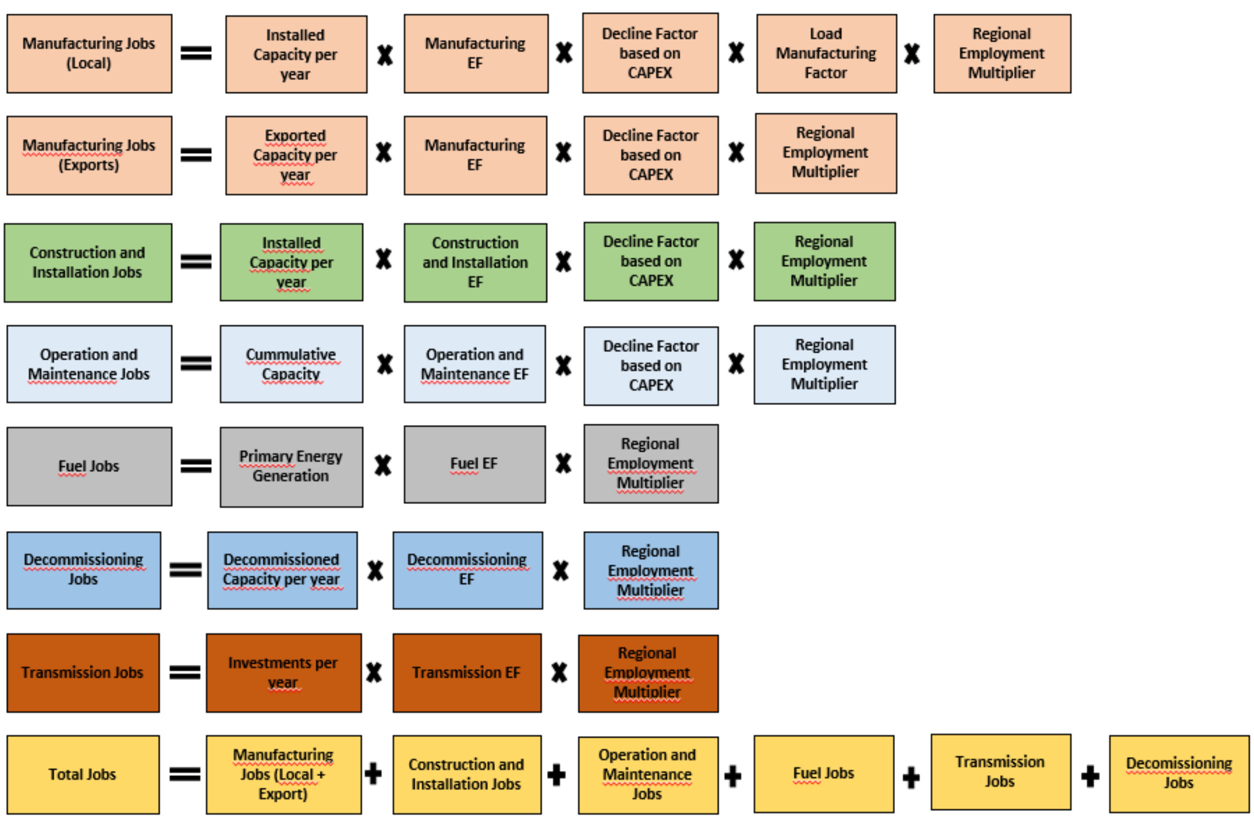

Figure 1

Method for estimating job creation during the energy transition. Abbreviations: Employment Factor (EF), Capital Expenditure (CAPEX) and Operational Expenditure (OPEX).

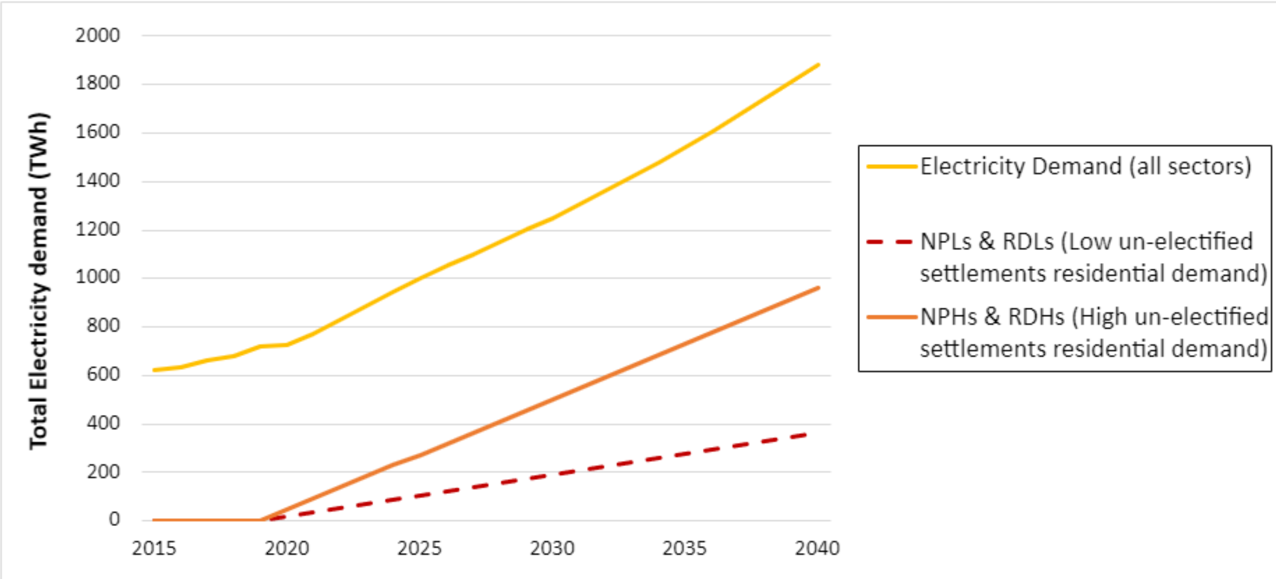

Figure 2

Evolution of the electricity demand (in TWh) among the scenarios at the African level the period 2015-2030.

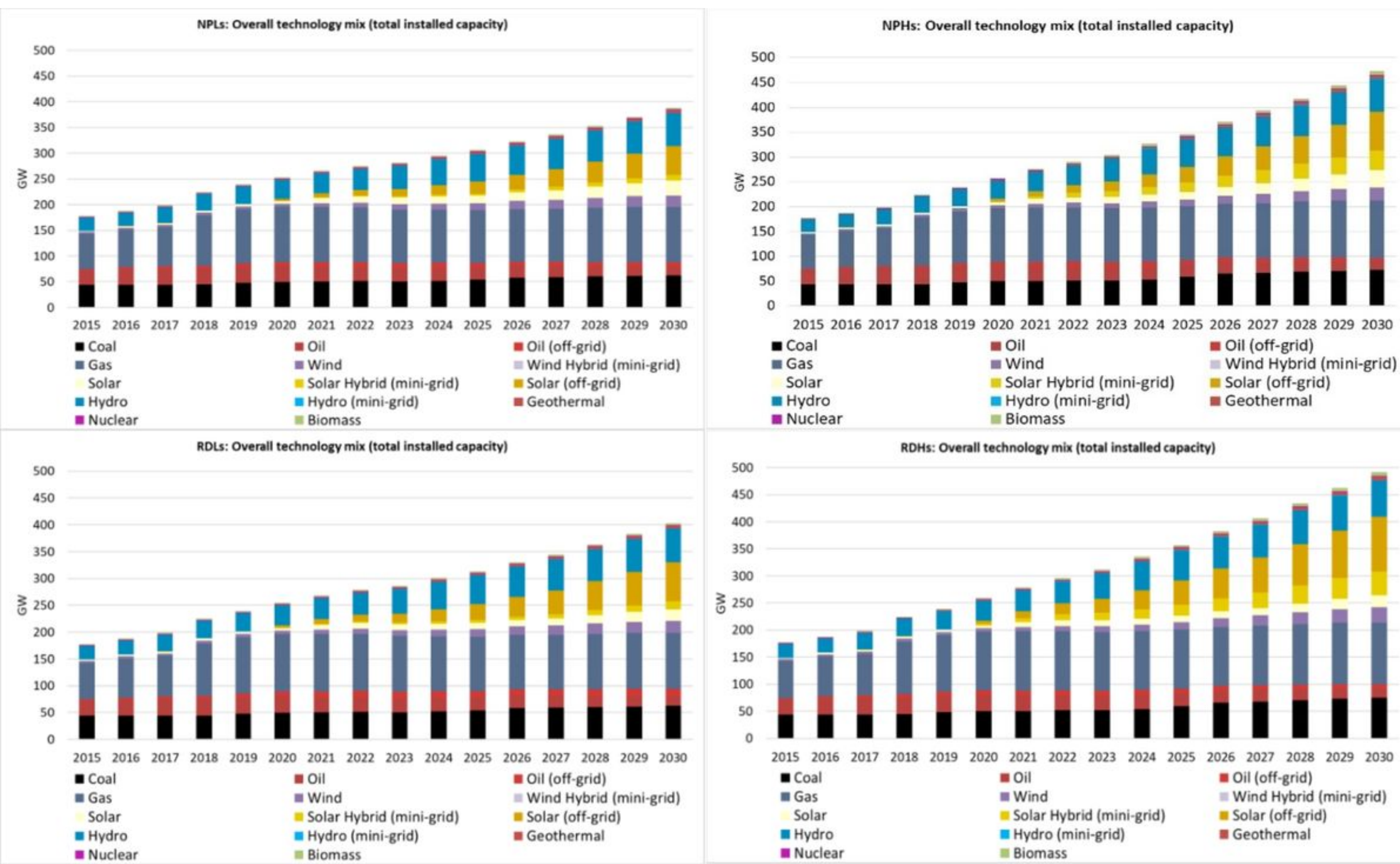

Figure 3

Overall technology mix (total installed capacity in GW) in Africa among the scenarios the period 2015-2030.

Figure 4

Overall electrification mix (in PJ) in Africa among the scenarios the period 2015-2030.

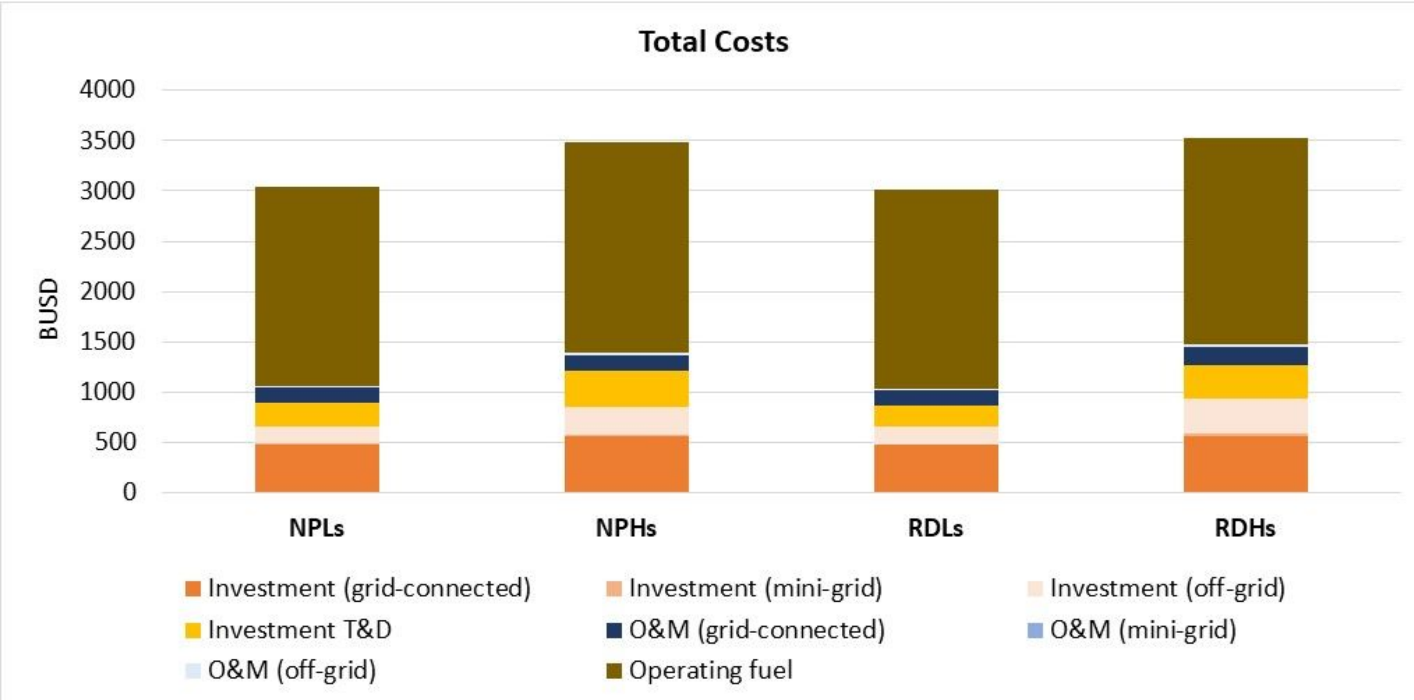

Figure 5

Comparison of the total system costs in the energy sector in Africa among the scenarios (in BUSD) the period 2020-2030.

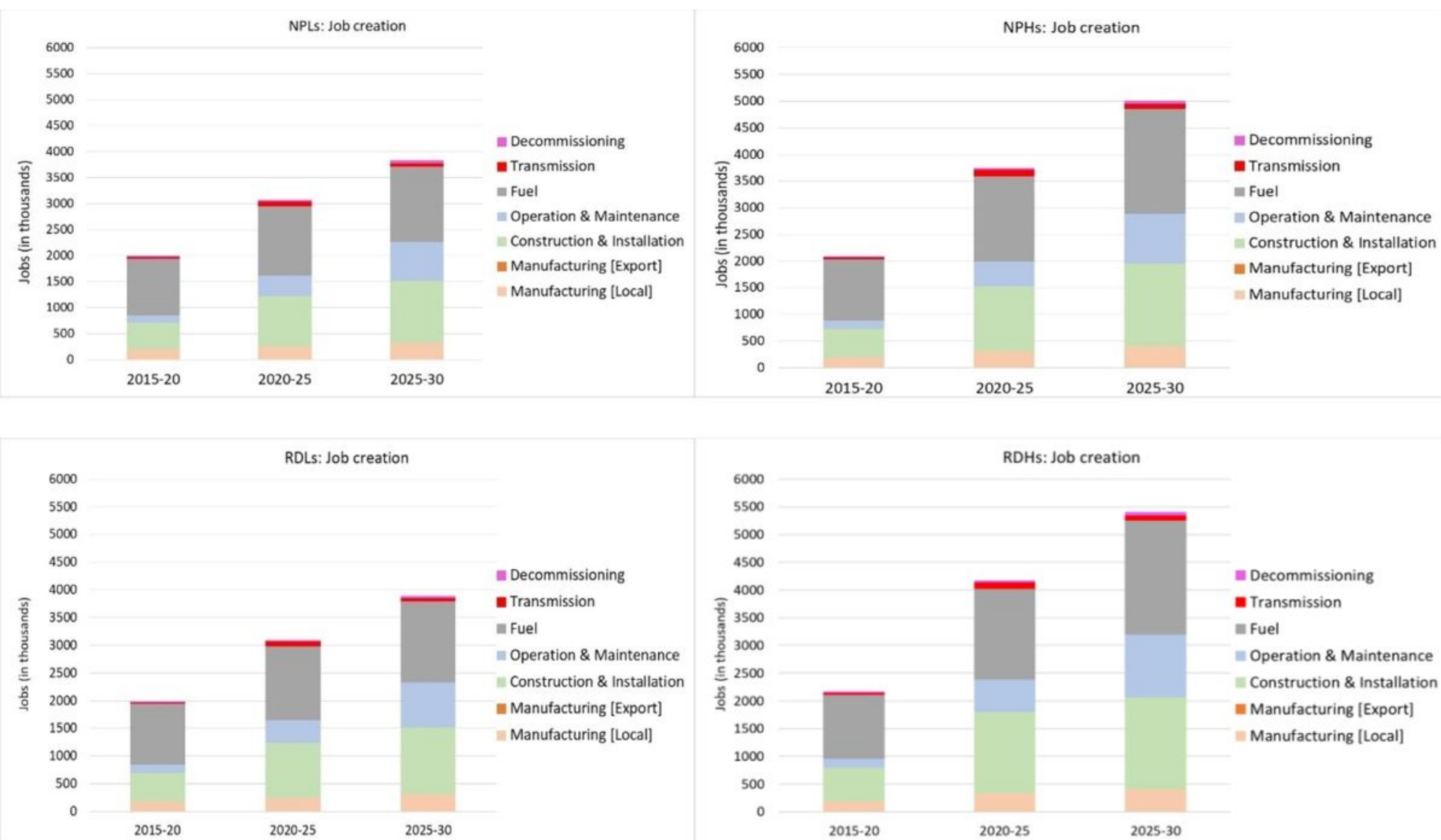

Figure 6

Jobs created (in thousands) in different categories with the evolution of the power system in Africa over the period 2015-2030.

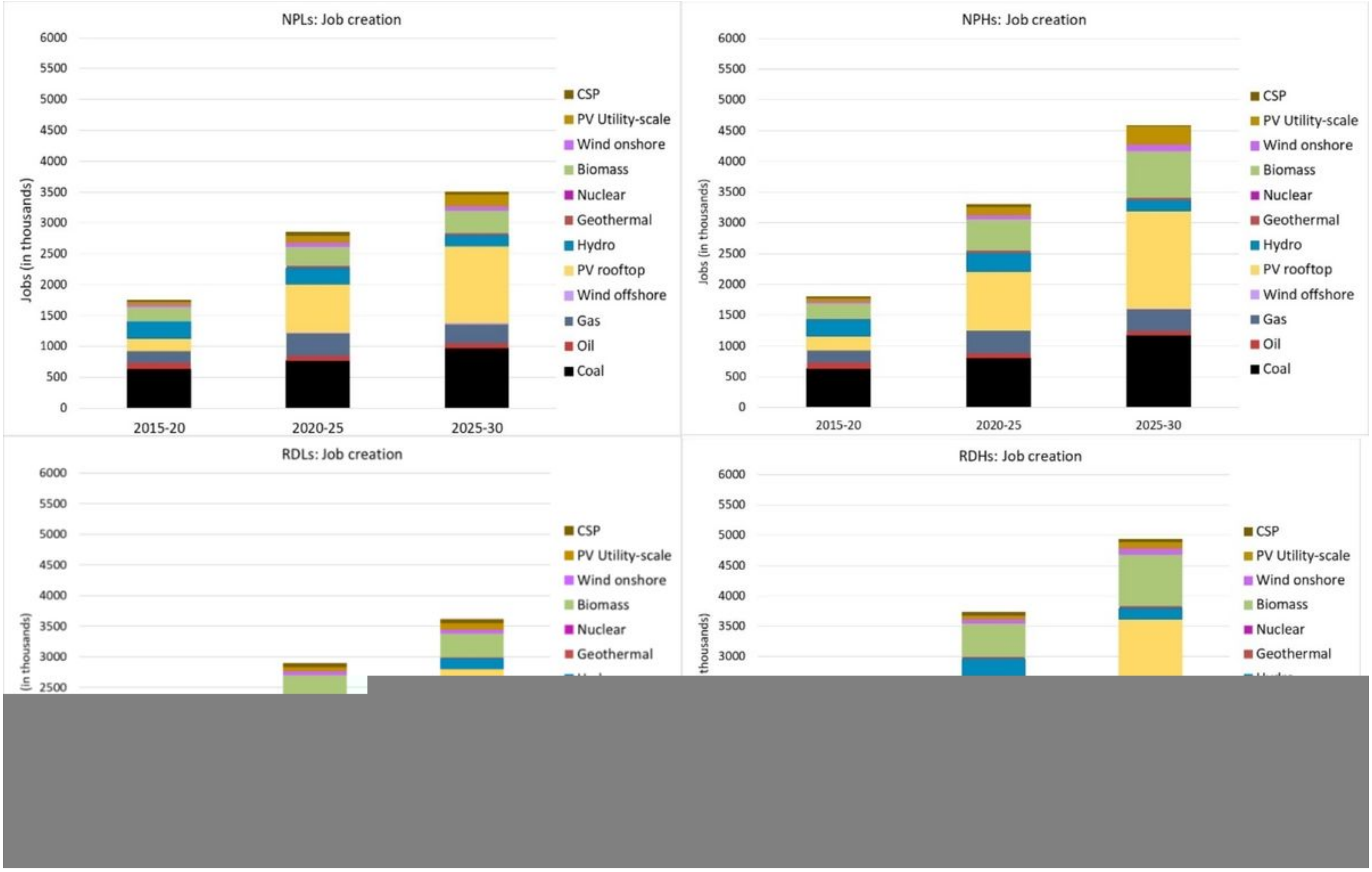

Figure 7

Jobs created (in thousands) by each power generation technology in the evolution of the power system in Africa over the period 2015-2030.

Supplementary Files

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