ESTIMATING INVESTMENT NEEDS FOR THE POWER SECTOR IN AFRICA 2023-2030

AFRICA REPORT

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GROUPE DE LA BANQUE AFRICAINE DE DÉVELOPPEMENT

Foreword

As a leading financial institution dedicated to fostering economic growth and social progress in Africa, the African Development Bank (AfDB) is at the forefront of efforts to improve infrastructure across the continent, with a particutlar emphasis on the energy sector. Thus, the Bank has played a pivotal role in mobilizing resources, facilitating partnerships, and implementing projects that aim to bridge infrastructure gap on the continent. By addressing the critical need for reliable and affordable energy, the Bank seeks to empower communities, stimulate industrial growth, and enhance the overall quality of life for millions of Africans.

As part of its infrastructure development efforts, the Bank has also launched the Africa Infrastructure Knowledge Program (AIKP) to improve the availability of statistical information on infrastructure development on the continent. The AIKP program aims to provide an effective and sustainable platform for data collection and analysis on Africa's infrastructure sectors, namely: (i) electricity; (ii) transport; (iii) ICT; and (iv) water and sanitation. One unique feature of the AIKP is the estimation of the power sector investments needs drawing on least cost optimization models. These models seek to catalyze a more active and informed engagement of energy stakeholders in the development of energy investments strategies.

The Statistics Department (ECST), in collaboration with the Energy Financial Solutions, Policy and Regulation Department (PESR) of the AfDB, and the Common Market for Eastern and Southern Africa (COMESA) are proud to present the report, «Estimating Investment Needs for the Power Sector in Africa 2023 – 2030» which provides a comprehensive analysis of the financial investments required to bridge energy gap in Africa. The current study has two main objectives: (i) to generate individual country investment needs using mathematical programming models and (ii) to provide an analytical report about the state of the energy sector in Africa and its five regions. Following this Africa main report, five regional reports will delve deeper into the specific needs and opportunities within each region.

This report is not just about numbers, it is about envisioning an achievable future where every African has access to the energy needed to thrive. It is about creating a sustainable pathway to economic development and environmental stewardship. The findings herein underscore the urgent need for concerted action and the profound impact that strategic investments can have on the continent's future.

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Acknowledgement

The report was prepared under the Africa infrastructure Knowledge Program being implemented by the Statistics Department (ECST) in close collaboration with the Energy Financial Solutions, Policy and Regulation Department (PESR), The Common Market for Eastern and Southern Africa (COMESA), and Multiconsult Group.

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The report also benefited from the contributions of Mutliconsult consulting team led by Mr. Ingar Flatlandsmo (Team Leader) and Mr. Jan Ohlenbusch (Energy Modelling Expert).

Executive Summary

This study is a contribution to the ongoing discussion on the costs and implications of addressing the two fundamental energy challenges facing the African continent, namely achieving universal access to electricity in line with Sustainable Development Goal number 7 and expanding power systems to support economic growth without getting locked into a high-emissions pathway.

Specifically, the study aims to derive insights from economic least-cost expansion modelling to:

- Estimate economic least-cost investment requirements and related emissions; and
- Explore existing structural barriers to and enablers of the energy transition.

The headline estimates indicate a Base Case investment requirement of about USD 454 billion, or USD 64 billion per year from 2023 until 2030, if an optimal investment plan is realized[1]. Behind this headline, there are several interesting results and findings.

The timeline for SDG 7 is slipping. Significant progress has been made in electrification across the Continent over the past decade, with the share of connected households increasing from 25.7 percent in the year 2000 to 50.6 percent in 2020[2]. Even so, it is estimated that nearly 195 million new connections will be required from 2023 till 2030 to achieve universal access and keep pace with population growth. The Base Case of this study includes an unprecedented expansion of off- and mini-grid connections through a significant mobilization of private investments and expansion of supply chains, supported by robust and harmonized regulatory frameworks and incentives.

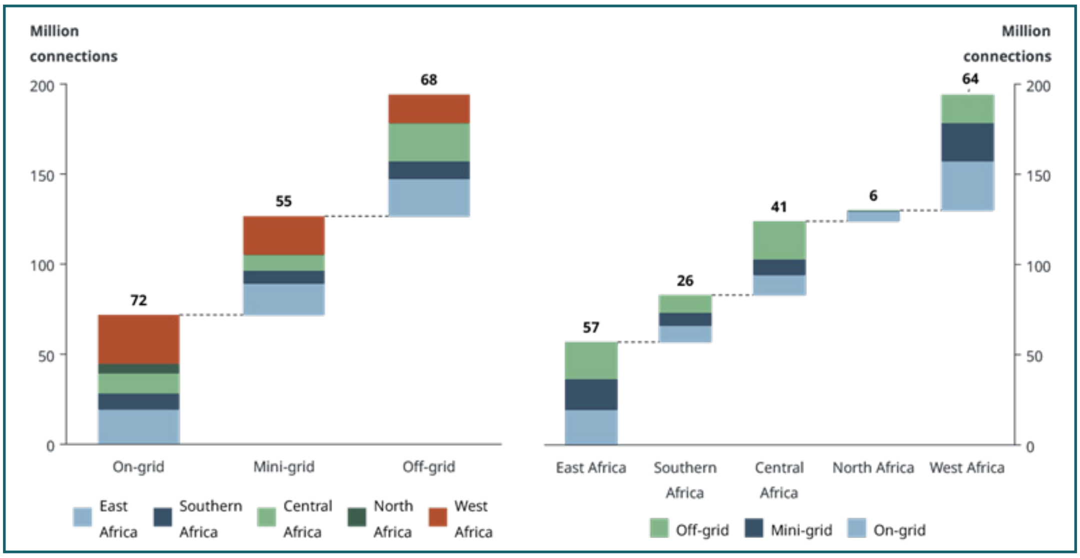

Figure a: New connections in the Base Case by geographical region and type

Most African countries are unfortunately not on track to meet the aspirational goal of SDG 7 by 2030, and even a radical break with business-as-usual may at this time not be enough to overcome the related logistical challenges and costs. The results of the Delayed Access scenario in this Study indicates that moving the goalpost for universal access to 2040 would reduce the number of connections required till 2030 by 70 million, or 36 percent. The largest reduction in absolute numbers would be seen in Western and Eastern Africa. Overall, the number of off-grid connections needed across Africa until 2030 is nearly halved in the Delayed Access Scenario.

[1]All monetary values denoted in USD throughout this report are expressed in terms of 2023 USD, unless otherwise specified.
[2]IEA, IRENA, UNSD, World Bank, WHO. 2023. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC. https://databank.worldbank.org/source/world-development-indicators

The economic least-cost and low-emissions power system expansion pathways for Africa towards 2030 are largely the same. It is forecasted that total net energy demand on the African continent will grow by 44 percent to around 1,200 TWh between 2023 and 2030. While Southern and Northern Africa will see the largest absolute growth, the highest relative increase is expected in Central and Eastern Africa as a result of access expansion.

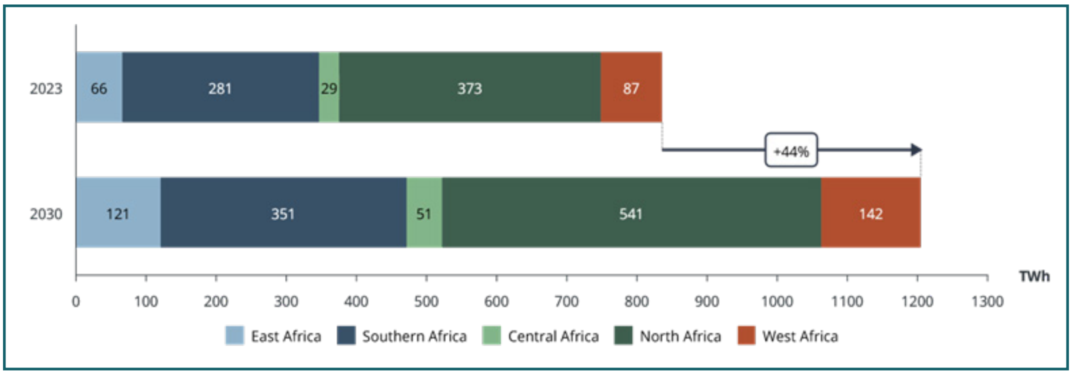

Figure b: Forecasted net demand in 2023 and 2030 by region

The core of the power system expansion analysis in this Study entails optimization of power supply options and interconnection for each country by minimizing system costs to meet the forecasted demand hour-by-hour through the year in realistic wind, solar irradiation, and hydrological conditions. The Base Case results reconfirm the cost-competitiveness of variable renewables, predominantly wind and solar across the Continent. This is true even when accounting for necessary co-investments in spinning and non-spinning reserves, batteries, and interconnectors required to offset the challenges that variable generation pose to power grids.

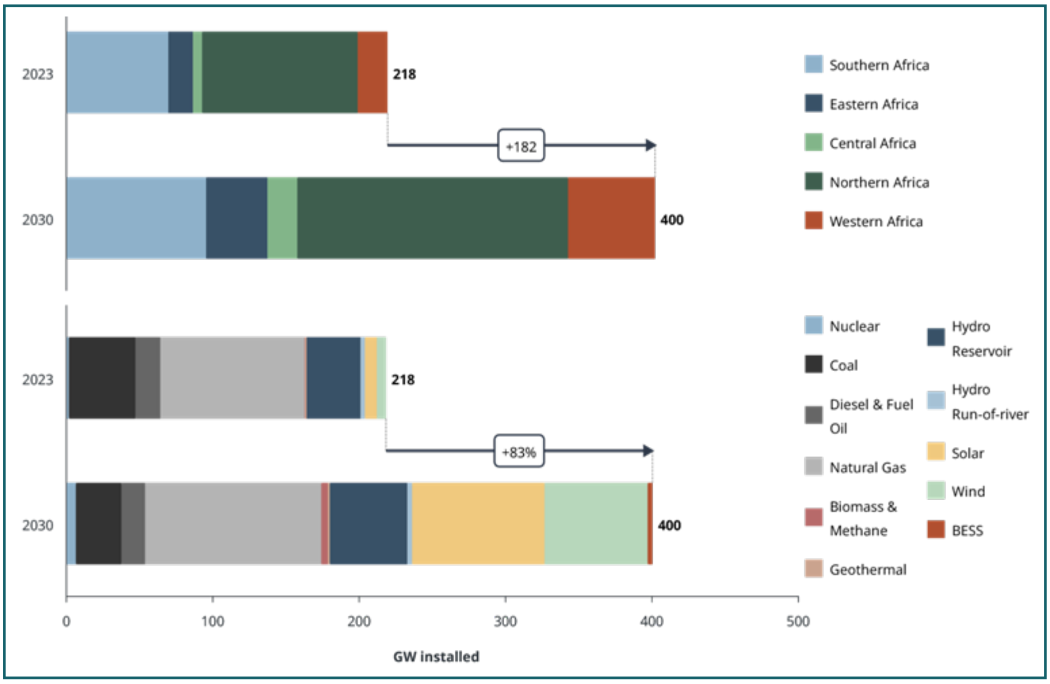

Figure c: Installed capacity in 2023 and 2030 by region and technology

In total, the least-cost Base Case requires a net expansion of generation capacity of 182 GW from 2023 until 2030, 88 percent of which would come from variable renewables such as wind and solar

There is ample room for policymakers to steer the future power systems in Africa. The scenario analyses prepared for this study shed further light on the uncertainties inherent to modelling exercises of this nature, but also provide several interesting insights. The figure below shows the investment needs under different scenarios.

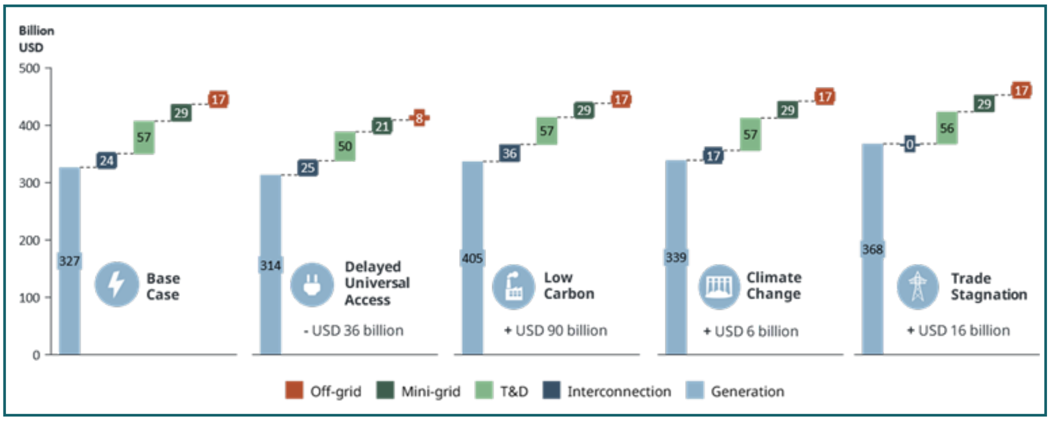

Figure d: Total investment requirements for each scenario from 2023 to 2030

A Trade Stagnation Scenario, where investments in interconnectors are constrained increase the required capacity expansion by USD 16 billion, highlighting the economic benefits of regional integration, as well as its contribution to resilience and energy security.

Further, the low-carbon scenario, where a cost of USD100 per ton of CO2e emitted is applied to internalize the social cost of carbon, increases the investment requirements till 2030 by USD 90 billion, as more existing fossil generation capacity is replaced by renewables. It should be noted that a share of these costs will be off-set by reduced spending on fuel. The resulting emissions reductions of 100 million tonnes per year are, however, modest compared to emission from developed economies.

Finally, the climate change scenario demonstrates how adverse hydrological conditions to African hydropower stations will impact investment needs. It is noted that other impacts of climate change on African power systems are not analysed here.

Public investments must increasingly be leveraged to increase private investments and salvage African utilities. Clearly, the difference between historical investment levels, by some estimated to USD 36 billion per year, and the annual Base Case investments needs of USD 64 billion found in this study cannot be covered by African governments alone[3]. Rather, they will require a combination of public sector lending, international grants, increased private participation, and (cross-) subsidization.

Private sector involvement is particularly vital in off-grid and generation sectors, with a need for risk mitigation and supportive regulatory environments. Multilateral and bilateral development assistance should focus on catalysing private investment in these areas. Lastly, the financial sustainability of African utilities is a pressing concern. Policy makers must prioritize reforms towards cost-reflective tariffs and strengthen support in grid reinforcements and loss reduction measures to ensure a sustainable and resilient power infrastructure.

[3]Africa-EU Energy Partnership (2022): European Financial Flows on SDG7 to Africa. Available at: https://sdg7.africa-eu-energy-partnership.org/wp-content/uploads/2023/02/GIZ_AEEP_Report_Financinal-Flows_2022_WEB.pdf

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List of Abbreviations

AfDB	African Development Bank
AIKP	Africa Infrastructure Knowledge Program
BESS	Battery Energy Storage Systems
CAGR	Compound Annual Growth Rate
COMESA	Common Market for Eastern and Southern Africa
EIA	Energy Information Administration
ESREM	Enhancement for a Sustainable Regional Energy Market initiative
GW	Gigawatt
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	Organization for Economic Cooperation and Development
SCB	Statistical Capacity Building
SDG	Sustainable Development Goals
TWh	Terawatt hours
UN	United Nations

1 About the Study

Africa faces two fundamental energy challenges:

1. **Achieving universal access to affordable, reliable, sustainable, and modern energy services, as set out in the United Nation´s Sustainable Development Goal 7; and**
2. **Increasing the supply of electricity to fuel economic growth and improve livelihoods while avoiding a lock-in to polluting fossil fuels.**

The study of which this report is the main deliverable is a contribution to the ongoing discussion on the enablers and implications of an energy transition which aims to sustainably address these challenges across the African continent. Specifically, the study aims to contribute to the discourse on investment needs and related policy responses in African power sectors towards 2030.

Several other studies also model the African power sectors and investments needs, including the forthcoming Continental Master Plan being prepared for the African Union Development Agency[4], and the International Energy Agency´s (IEA) Africa Energy Outlook. While contending with the same topic, these studies have distinct objectives and analytical angles and therefore deploy different tools and assumptions. It follows that the numbers derived from this analysis inevitably will differ from these other efforts to explore the same issues. This does not imply that other estimates, nor the ones made in this report, are wrong. Instead, this plurality strengthens the discourse on Africa´s energy challenges. It is therefore recommended that the results of this study are read and interpreted in light of the above-mentioned reports.

Approach and methodology

This study builds on a similar analysis prepared for the African Development Bank (AfDB) in 2018, and derives insights from economic least-cost expansion modelling to:

- Estimate economic least-cost investment requirements and related emissions;
- Explore existing structural barriers to the energy transition; and
- Identify enablers that need to be put in place for the energy transition to become a reality.

In addition to the aggregated results and findings of the analysis, this Africa Report also contains details on methodology and policy implications. It is supported by separate regional reports for each of the five regional power pools and the Common Market for Eastern and Southern Africa (COMESA). The regional reports, while stand-alone deliverables, are mainly focused on the results of the access and power system expansion at regional level, and so are best read in conjunction with this Main Report.

Making projections seven years into the future in a market influenced by technological change, political turmoil, cross-border relations, economic growth, and human behaviour is fraught with uncertainty. Several of the methods utilized in this analysis rely on prior statistical analyses, with diligently and carefully selected sources for all data and projections for each input. Whether based on statistical analysis or market research, all projections come with uncertainties. Nonetheless, in utilizing the modelling tools described above, the analyses necessarily arrive at specific investment

[4] The work on a Continental Master Plan was ongoing at the time that this report was issued. For updated information, see: https://nepad.org/continental-master-plan

needs estimates – rather than intervals, as this is not a statistical analysis. This does not imply that these estimates will turn out to be exactly correct or accurate. Instead, these are estimates with no reasonable way to assign probabilities or intervals.

Finally, the core of the power system expansion analysis entails the optimization of power supply options and interconnection for each country by minimizing the system costs to meet the forecasted demand hour-by-hour throughout the year. Thus, the analysis does not take account of the many political realities impacting African power systems, but effectively provides a baseline for planning and eventually monitoring investment in and progress towards SDG7. The scenarios and sensitivity analyses presented throughout this report are meant to shed light on the impact of different policy choices, in keeping with the objectives of the study.

Economic least-cost expansion modelling

Access expansion and load forecasting. A bespoke model has been developed to project access expansion paths across countries and access types. It takes account of, among others, current access rates, population density, poverty, and investment climates for each country to determine the pace and relative importance of grid, mini-grid, and off-grid expansion. Further, the same model also forecasts on-grid demand for each of the African countries, as a function of factors such as economic growth, elasticities of demand, energy efficiency, and level of industrialization, as well as increasing access, and transmission and distribution losses.

Optimization model. The open-source energy system simulation and optimization toolbox PyPSA is deployed for modelling economic least-cost expansion and dispatching for different scenarios. A wide range of technology and geography specific data and assumptions pertaining e.g. to costs, production, resources (water, solar and wind), fuels, and distances are made to determine the investments required in order to meet demand hour-by-hour in each of the African countries. The optimization accounts for region-specific daily demand profiles and solar and wind resource profiles.

Because the optimization model is designed to minimize total system costs, it does not inherently reflect certain technical or practical restrictions that may exist. Thus, a key aspect of the analysis has been that of introducing reasonable restrictions to the model, while maintaining significant opportunity to determine optimal investment paths.

Limitations of the study. It is important to understand that there is significant uncertainty related to the applied inputs and assumptions, including future demand, technological developments, and the cost of different technologies. Therefore, the Base Case, nor any of the other scenarios predicts what will happen in the future. Further, whereas the model does consider power transmission between countries and regions it does not include a detailed grid topology. Therefore, no power flow calculations have been made. These issues would have to be addressed through more detailed studies.

Methodological Note. Please refer to Annex 1 for more details on the applied methodology, sources, and assumptions.

2 Africa's Energy Challenges and Opportunities

Key messages

- Most African countries are not on track to reach universal access by 2030.
- Pre-pandemic per-capita demand in Africa was 477 kWh, one 15th of OECD levels.
- More than 70 percent of installed utility-scale generation capacity in Africa is based on fossil fuels, but abundant renewable energy resources offer a great opportunity.

While each of the African countries have their own unique contexts, the types of challenges they face are often similar. In order to provide a baseline for the analysis presented in subsequent chapters, this section presents a brief overview of the status with regard to some of the most critical electricity challenges facing the Continent.

Access rates are growing, but too slowly. Underlying SDG7 is the recognition that access to modern energy services is a prerequisite for development. More than 625 million people in Africa, or 41 percent of households did not have access to electricity in 20215. For the rural areas, the share of unelectrified households was even higher, at 61 percent.

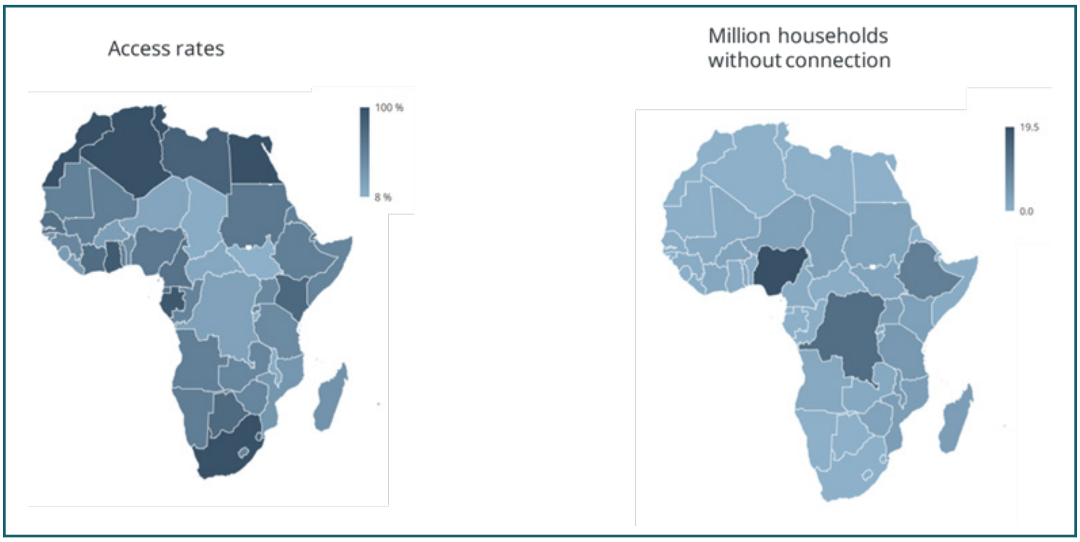

Figure 1: Total access rates and million people without electricity access in 2021

Significant progress has been made in electrification over the past decade, as a mix of modern mini- and off-grid solutions have emerged to supplement grid expansion in rural areas. In fact, the share of connected households in sub-Saharan Africa increased from 25.7 percent in the year 2000 to 50.6 percent in 2020[5]. Even so, most African countries are not on track to meet universal access by 2030. As evident from the map above, the challenge is not evenly distributed across the continent, with the Democratic Republic of Congo, Ethiopia, and Nigeria alone making up nearly 40 percent of unelectrified households.

[5] IEA, IRENA, UNSD, World Bank, WHO. 2023. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC. https://databank.worldbank.org/source/world-development-indicators

Demand for electricity on the African Continent remains low. Pre-pandemic, in 2019, the per capita demand for electricity in Africa reached 477 kWh/year, roughly one 15th of the pre-COVID19 average for the developed OECD countries[6]. These aggregate numbers do, however, hide large differences in electricity demand within the group of African countries. As evident from the map below, a few countries of the extremes of the Continent account for an outsized share of the total consumption.

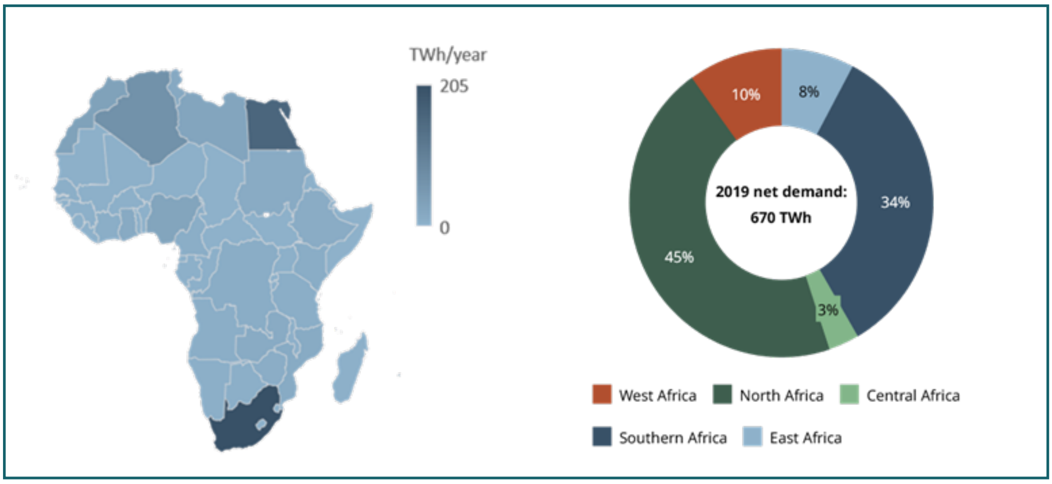

Figure 2: Pre-pandemic (2019) electricity demand by country and region

Electricity services are important enablers of improved livelihoods and economic growth, and while increased demand is not an objective onto itself, expanded electricity access and increased productive use of electricity constitute significant opportunities for the African continent.

National and regional grids are weak. There is a significant need for continued investment in national transmission and distribution grids across the African continent[7]. Many countries suffer from undersupply and poor supply quality which impedes economic growth. On a regional level, several large cross-border transmission projects are under development and the regional power pools are gaining traction, but much remains before African power systems are fully integrated. The fact that many national grids remain isolated entails higher risk and cost of operations, and the value of increased interconnection of the Continent is therefore a key axis of analysis for this study.

Generation capacity is modest in most regions. Estimates made for this study show that there are roughly 218 GW of installed utility-scale on-grid generation capacity on the African continent in 2023[8], as broken down in the figure below. This number is based on a bottom-up mapping exercise conducted for this study, and it is noted that the number may differ from that provided by other sources due to the exclusion of all off-grid and stand-by capacity. Given the distribution of existing demand, it is not surprising that most of the generation capacity is found in the Northern and Southern Africa regions. It is interesting to note that more than 70 percent of installed utility-scale generation capacity is based on fossil fuels such as natural gas and coal. The regional reports published under these studies provide more details on how energy resource availability may impact generation expansion in different regions.

[6] U.S. Energy Information Administration (EIA). Net electricity demand: https://www.eia.gov/international/data/world/electricity/electricity-consumption
[7] IEA (2022). African Energy Outlook 2022: https://www.iea.org/reports/africa-energy-outlook-2022
[8] Generation technologies with an aggregated capacity of less than 5MW in a single country is not considered in the analysis. See Annex 1 for details.

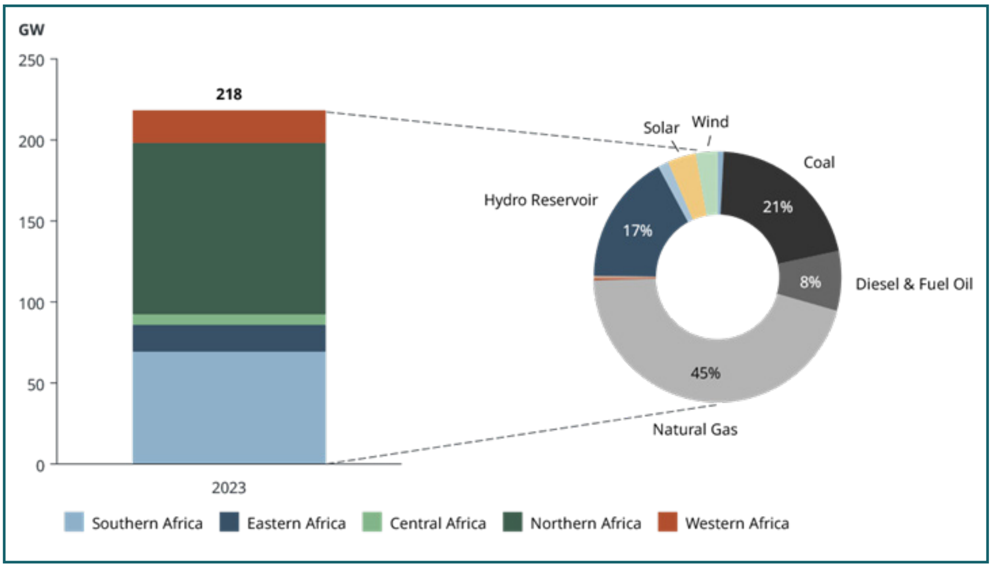

Figure 3: Existing generation capacity by region and technology

African power systems are vulnerable to climate change. While African countries have not contributed significantly to the emissions that drive global climate change, they are among the ones hardest hit by its consequences. Among these are adverse impacts on the power systems, including changed rainfall patterns that negatively impact the ability of existing hydropower plants to meet demand[9]. These effects are explored through a separate simplified scenario analysis in this study.

Emissions are low, but there is a risk of fossil lock-in. The modelled 2023 emissions from fuel combustion in African power sectors are approximately 468 million ton[10]. This is comparable to the total 2021 emissions from electricity generation of Japan, a country of approximately 125 million inhabitants[11]. The lion's share of these emissions come from South Africa as well as a few countries in Northern Africa. The comparatively low emissions numbers imply that a clean development path for the power sector in most African countries is less about cutting existing emissions and more about meeting expected demand growth without locking the countries into high emissions. This constitutes another important axis of analysis in this report.

The road to 2030. In sum, reaching universal access on the African continent while building resilient and sustainable power systems is simultaneously a formidable task and a huge opportunity for the Continent. Over the following chapters, this Report will attempt to quantify the magnitudes of the energy transition and contribute to the discourse on what policies are best suited to make it a reality.

[9] IEA (2020). Climate Impacts on African Hydropower. Available at: https://www.iea.org/reports/climate-impacts-on-african-hydropower
[10] Based on modelling done for this study. Emissions per kWh generated from each technology are obtained from the Intergovernmental Panel on Climate Change (IPCC)
[11] IEA (2024). Total CO2 emissions from energy - Japan. Accessed in March 2024. Available at https://www.iea.org/countries/japan

3 Optimal Power System Expansion

Key messages

- The hope of connecting 195 million new households and achieving universal access by 2030 rests in an unprecedented expansion of off- and mini-grid connections.
- The Reference Scenario sees a 83 percent increase in installed on-grid generation capacity, mainly from wind and solar.
- On a Continent of abundant solar and wind resources, there is little difference between least-cost and low-emissions.

This chapter sets out the Africa-wide results of the study in terms of access expansion and demand forecasting, as well as a Base Case least cost generation and grid expansion that would be required to meet the challenges set out in chapter 2. The Base Case findings are explored and challenged through different scenario analyses. More detailed analyses of regional power system implications can be found in the six regional reports.

3.1 Electricity Demand Towards 2030

The increasing demand for electricity on the African continent towards 2030 will largely be driven by economic growth, population growth, and access expansion. This section presents a forecast of how these forces may impact country-by-country demand for electricity towards 2030[12].

Access expansion

Given the low electrification rates in many African countries, universal access to electricity by 2030 is increasingly becoming an aspirational vision rather than a likely outcome[13]. It is, however, important to remember that the demand for electricity services and access rates in Africa no longer are tied solely to grid expansion. As technology costs fall and business/financing models improve these services, increasingly, can be provided by a continuum of on-grid, mini-grid, and off-grid service levels.

This analysis sets out to assess the costs and investments required to achieve universal access by 2030, leveraging the full continuum of off-, mini-, and on-grid solutions. Each of the African countries has different starting points and will follow a unique path to universal access. Nonetheless, the SDG7 target is so ambitious that most countries must see rapid access expansion, particularly in rural areas, and some form of convergence if universal access is to become a reality by 2030. As seen from the figure below, approximately 195 million new on-grid, mini-grid, and off-grid connections will have to be added across Africa between 2023 and 2030[14], in order to achieve SDG7. By 2030 the number of connections needed to achieve universal access while keeping pace with population growth is estimated to 380 million.

[12] See methodology text-box on page 6 and Annex 1 for details on the forecasting approach.
[13] AfDB president Adesina is among the leaders that has voiced this concern, stating during a meeting held in Berlin in March of 2023 that "the clock is running out" on SDG7 in Africa by 2030.
[14] Population projections from the United Nations World Development Indicators are applied, combined with average person per household numbers from GlobalDataLab. See Annex 1 for further details.

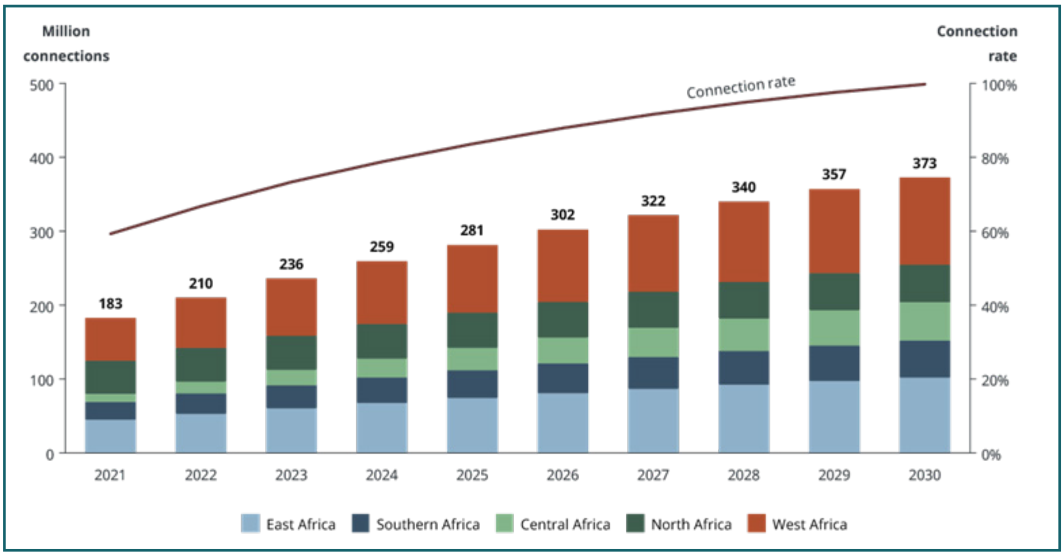

Figure 4: Aggregate access expansion to 2030 by region.

While most countries in North Africa are already close to universal access, the largest access gap is found in Eastern, Central, and Western Africa. Achieving universal access by 2030 in these regions will require an unprecedented expansion of off- and mini-grid connections. This is largely due to the technical and financial challenges entailed in expanding the grid across vast distances in rural areas. In fact, as seen from the figure below, the Base Case results entail that the approximately 195 million connections to be added towards 2030 is nearly equally split along the continuum of off-, mini-, and on-grid connection.

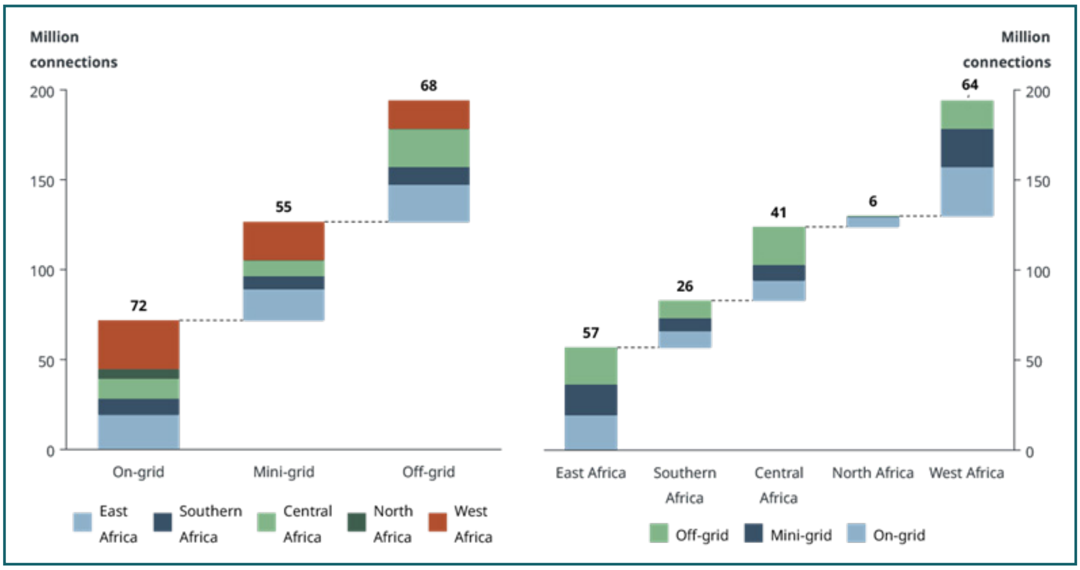

Figure 5: New connections in the Base Case by geographical region and type

Is the timeline for SDG7 slipping?

Questions are increasingly being raised about the feasibility of achieving universal access to electricity in Africa by 2030, as discussed in chapter 2. These concerns are strengthened by the analysis presented in this chapter. Even a radical break with business-as-usual may at this time not be enough to overcome the logistical challenges and costs related to making 195 million new connections before 2030.

To explore the implications of delayed universal access, a simplified analysis has been done whereby the goalpost for SDG7 in Africa has been moved to 2040. The figure below compares how such a shift may impact electrification across regions and connection types.

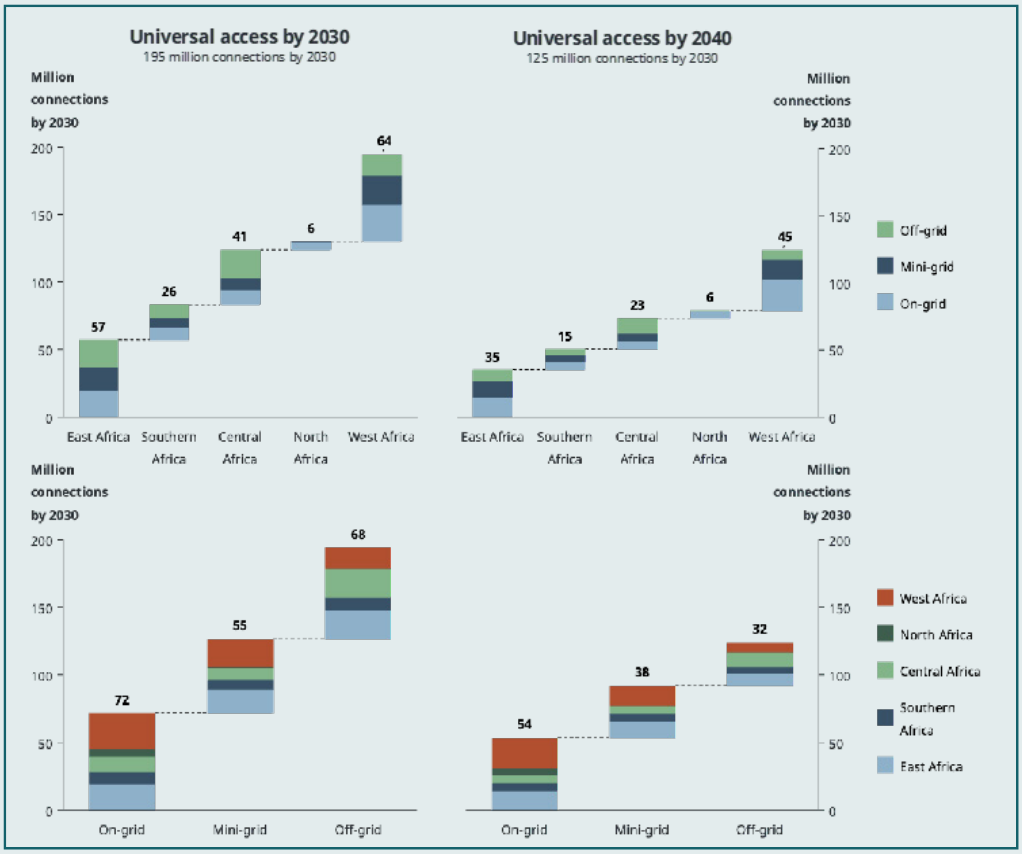

Figure 6: Access expansion in Reference and Delayed Access scenarios

Overall, the total number of connections required by 2030 is reduced by 70 million, or 36 percent. Unsurprisingly, the largest reduction in absolute numbers is seen in Western and Eastern Africa where the access gap is largest. The number of off-grid solutions is nearly halved.

Given the relatively limited impact of access expansion on demand, it is not surprising that delayed access only is modelled to give a two percent reduction in 2030 net on-grid electricity demand from new connection, down from nearly 100 TWh in the Base Case to 79 TWh in the Delayed Access scenario. The implications of delayed access on power system expansion and investment needs are explored further in sections 3.5 and 4.5 respectively.

Demand forecast

2019 has been chosen as a starting point for the demand forecast to avoid the temporary demand shock resulting from the COVID19 pandemic[15]. The combination of economic growth and rapid access expansion is forecasted to imply an increase in net demand from 695 TWh in 2019 to 1,170 TWh in 2030. This implies a Compound Annual Growth Rate (CAGR) of about five percent. Transmission and distribution losses are estimated for each country and added to the net demand[16].

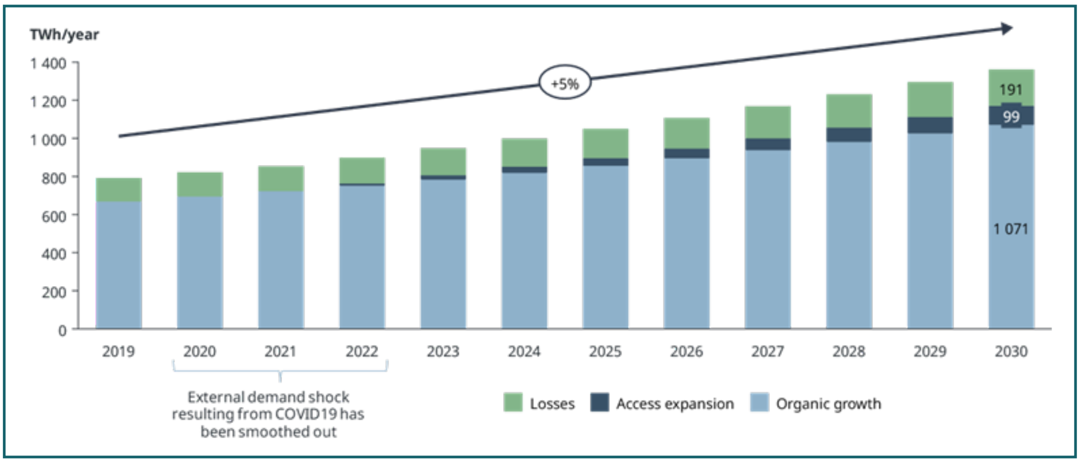

Figure 7: Aggregate demand forecast till 2030

The extraordinary access expansion required to achieve universal access to electricity by 2030 is an important driver of demand, accounting for nearly 100 TWh of additional load by 2030. The lion's share of the demand increase is, however, attributed to economic growth[17]. Overall, an increase in demand of 44 percent is forecasted between 2023 and 2030, as seen from the figure below. While Southern and Northern Africa will see the largest absolute growth, the highest relative increase is seen in Central and Eastern Africa as a result of access expansion.

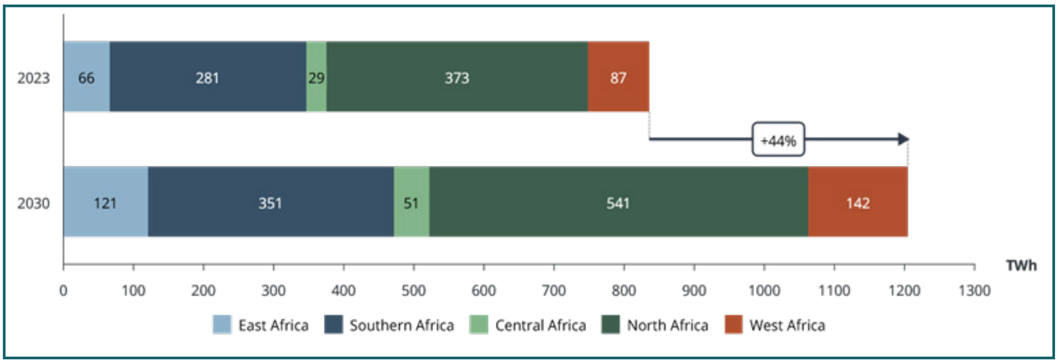

Figure 8: Forecasted net demand in 2023 and 2030 by region

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[15] Demand numbers for 2020 and 2021, while available, are heavily distorted by the demand shock caused by COVID19. Therefore, as most economies are coming back to their pre-pandemic levels, it has been determined that 2019 is the most suitable starting point for the analysis. Please refer to Annex 1 for details.

[16] Average combined transmission and distribution losses are calculated to 18.5 percent for 2019, reducing gradually to 16.3 percent in 2030. Please refer to Annex 1 for details.

[17] Country-by-country GDP forecast from the IMF World Economic Outlook has been applied. Please refer to Annex 1 for details.

3.2 Power System Expansion

The core of the power system expansion analysis comprises the optimization of power supply options and interconnection for each country by minimizing system costs to meet the forecasted demand hour-by-hour through the year in realistic wind, solar irradiation, and hydrological conditions. Thus, the analysis does not take account of the many political realities impacting African power systems, but effectively provides a baseline for planning and eventually monitoring investment in and progress towards SDG7.

Generation capacity

The figure below presents the results of the Base Case in terms of capacity installed in the different African Union regional groupings. A net increase of 182 GW in the Continent-wide generation capacity is required by 2030 in the Base Case, equal to 83 percent of the existing volume. This is a combination of 1) exogenously added projects that are already under construction, and 2) least-cost investments. Approximately 88 percent of the net increase comes from renewable generation sources. In addition to confirming that solar and wind power are the least-cost expansion options in most African countries, this is also a testament to the significant flexible balancing capacities in the shape of natural gas and stored hydro that already exist in many regions.

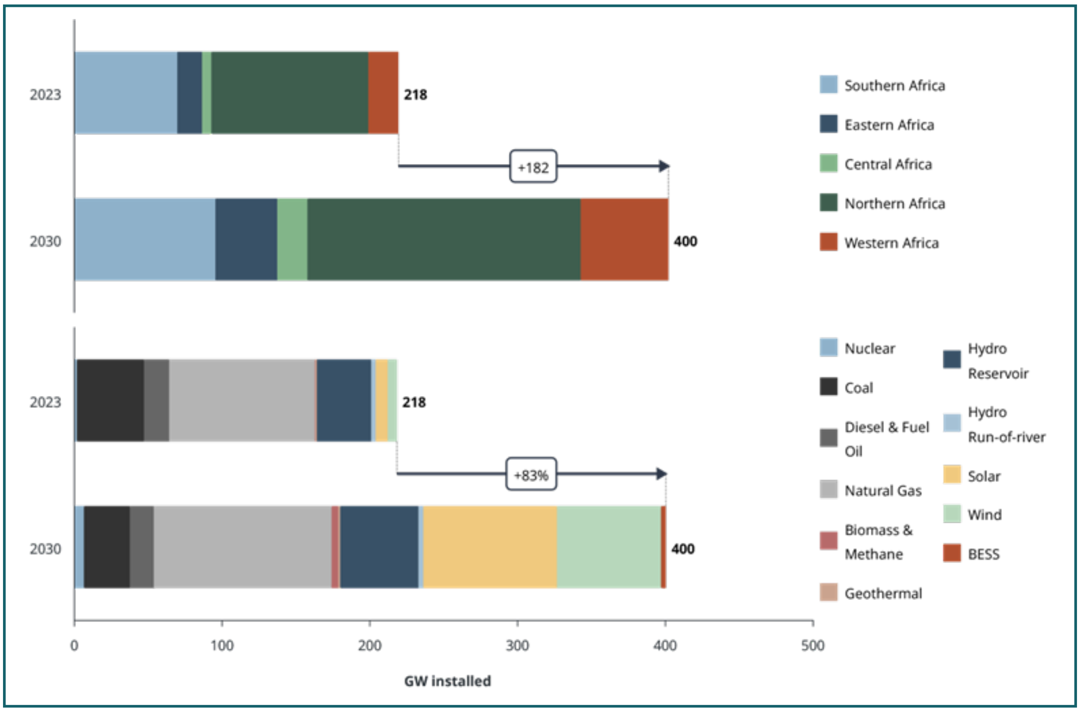


Figure 9: Installed capacity in 2030 by region and technology

At the regional level, it is noteworthy that the installed capacities in Eastern, Central, and Western Africa all would have to grow by more than 150 percent between 2023 and 2030 to meet the forecasted demand growth.

System Operations

The regional integration and optimal system-wide planning allow each region to harness the characteristics of different generation technologies, such as the comparative advantage of cheap variable renewables and the dispatchable capacity of each country[18]. The figure below illustrates how the respective installed capacities in 2023 and 2030 are dispatched optimally to meet demand hour-by-hour throughout the year.

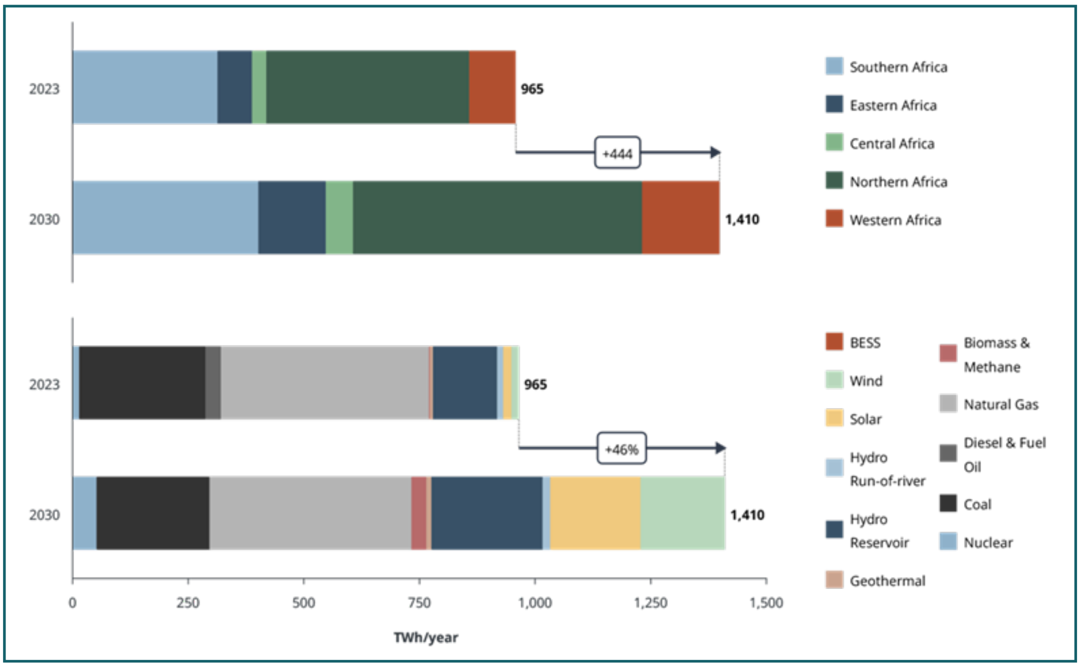


Figure 10: Annual generation in 2030 by region and technology

The reports for the respective power pools and COMESA provide significantly more detail on 2030 generation, including hourly profiles, interconnector investments, and net flows of electricity between interconnected countries and regions[19].

Finally, while investments in domestic transmission and distribution networks are not part of the optimization model, an annual investment need of approximately USD3.3 billion per year is estimated and included in the investment needs between 2023 and 2030. Please refer to Annex 1 for details.

[18] In order to ensure system stability as the share of variable renewable renewables grow, requirements for total reserves and spinning reserve have been included in the system expansion. Please refer to Annex 1 for further details.
[19] The study, for practical reasons, disregards inter-continental interconnectors as it is expected that exports will be supported by dedicated generation expansion. The aim of this study is to meet local demand.

Emissions

In a global context, greenhouse gas emissions from the African continent remain very low both in absolute and per capita terms[20]. This also applies to power generation. In fact, the emissions related to fuel combustion resulting from the generation forecast presented in Figure 10 only amount to 468 million tonnes of CO2 equivalent for 2023 and 398 million tonnes for 2030[21]. Thus, the total emissions from a 2030 power system that will serve nearly two billion people are comparable to the total emissions from electricity generation of Japan[22]. This means that climate mitigation in this context is more about avoiding lock-in to a high-emissions pathway than it is a fuel-switch for existing generation capacities.

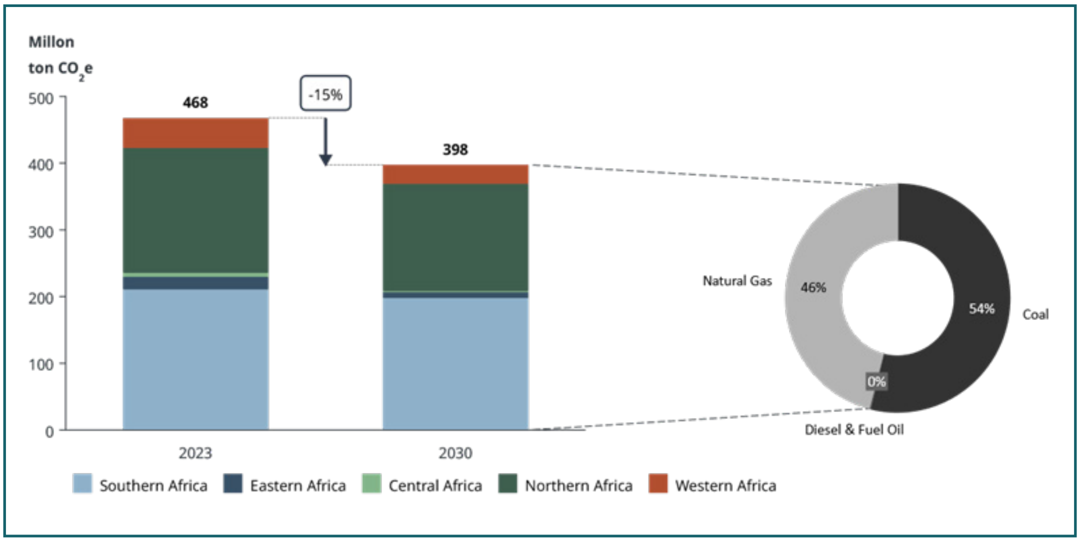


Figure 11: Emissions from power generation in 2023 and 2030 by region and technology

3.3 Scenarios

In order to contextualize and explore the policy implications of the Base Case results, four expansion scenarios have been developed for 2030. These are presented in the table below.

[20] IPCC (2022): Mitigation of Climate Change from Working Group III of the Intergovernmental Panel on Climate Change (IPCC). Available at: https://www.ipcc.ch/report/ar6/wg3/

[21] Estimates based on modelling results and emission intensity numbers from the Intergovernmental Panel on Climate Change. See Annex 1 for details.

[22] IEA (2024). Total CO2 emissions from energy - Japan. Accessed in March 2024. Available at https://www.iea.org/countries/japan

Table 1: Overview of modelled scenarios

Scenario	Issue explored	Narrative description	Change in assumption for 2030 from Base Case
Delayed Universal Access	Delayed realization of SDG7.	The realism of achieving SDG7 by 2030 is increasingly coming into question. This scenario explores the impact of moving the goal post for universal access to 2040.	Continental access rate set to 82 percent for 2030, corresponding to universal access by 2040.
Low Carbon	The impact of pricing carbon emissions.	The impacts of climate change are already being felt across the African Continent. This scenario explores the effects of pricing in the social cost of carbon in system expansion.	A cost of USD100 per ton of CO2equivalent is added[23].
Climate Change	Hydrological shifts caused by climate change.	Climate change is impacting hydrological patterns across the world. This scenario looks at the impact on power systems of more erratic rainfall.	Inflow to reservoir, pumped-storage and run-of-river have been reduced by 30%. Please refer to Annex 1 for details.
Trade Stagnation	Value of cross-border trade.	Increased integration of power systems is a stated policy objective for many African policy makers. This scenario explores how trade impacts costs and resilience of power systems.	Model is not allowed to invest in new interconnector capacity over and above projects under construction.

The figure below shows the continent-wide installed capacity in for each scenario in 2030, as compared to the Base Case.

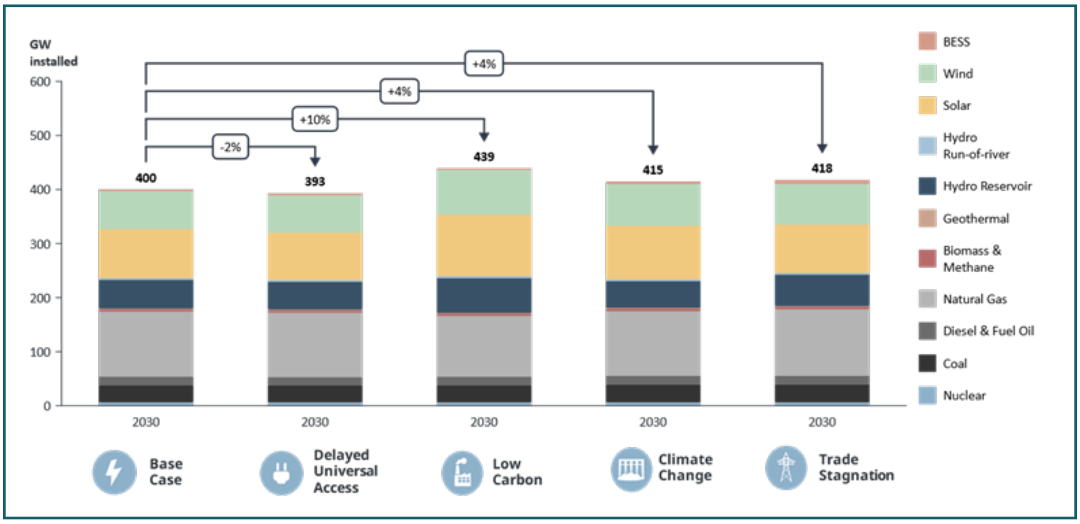


Figure 12: Installed capacities in 2030 in each scenario

[23] The social cost of CO2 is a monetized measure of the long-term damage done by a ton of emissions. The IPCC in a 2018 report suggested that a carbon price of USD100/ton would cut 2030 global emissions by 50 percent. Available at: chttps://www.ipcc.ch/site/assets/uploads/sites/2/2019/03/SR15_FGD_Chapter_4.pdf

The impact of delayed universal access on electricity demand is, as noted in section 3.1, insignificant. It is therefore not surprising that this scenario has very little impact on the required on-grid generation capacity. Other scenarios do, however, provide policy-relevant findings for generation expansion.

Climate change will have significant negative impacts on the power system. The four percent increase in 2030 generation capacity from the Base Case to the Climate Change scenario, mainly from flexible fossil generation sources and Battery Energy Systems (BESS) is a small testament to the significant negative impact that more erratic rainfall patterns may have on regional power systems, particularly in Eastern Africa. It is important to underline that the assumed changes to inflow patterns are simplified[24]. Other studies have looked in more detail at the impact of climate change on African hydropower[25].

Pricing carbon does not reduce fossil investments significantly, but still drives capacity up by 10 percent. Absolute investments in fossil fuel capacity are small even in the Base Case, and the main impact of including the social cost of carbon will therefore be to discourage the use of existing generation capacity for base load. This reduced generation is replaced by additional renewable generation capacity, resulting in a 10 percent increase in installed capacity for the Low Carbon scenario.

Regional trade enables more variable renewables. Installed capacity in the Trade Stagnation Scenario is four percent higher than for the Base Case, mainly from flexible generation sources such as natural gas and reservoir hydro. From this, it can be derived that in addition to reducing overall investment needs in generation, regional integration also enables a larger share of cheap and emissions-free variable renewables in the generation mix.

[24] Please refer to Annex 1 for details.
[25] IEA (2020). Climate Impacts on African Hydropower. Available at: https://www.iea.org/reports/climate-impacts-on-african-hydropower

Reflecting the social cost of emission in planning further increases renewables investments

As discussed in chapter 2, African countries do not carry historical responsibility for climate change, and still have small per capita emissions compared to the OECD countries. Even so, it is interesting to explore how considering the social cost of carbon would impact power systems expansion and emissions. The results of the Low Carbon scenario reveal that a price of emissions of USD 100 per ton of CO2 equivialents would reduce emissions by 102 ton relative to the Base Case in 2030.

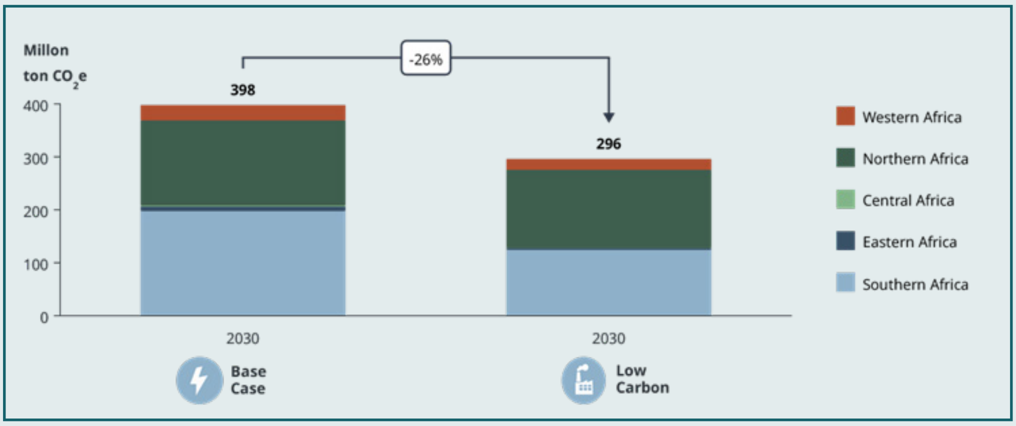


Figure 13: Emissions in Reference and Low Carbon scenarios

Interestingly, because Base Case investments in fossil generation technologies are already minimal, the main impact of pricing in the social costs of carbon would be reduced generation from existing coal, HFO, and natural gas power plants, and even and early phase-out of the same assets. This generation would be replaced by generation from additional renewable assets. This signals that - if the true cost of carbon would be considered in least cost expansion planning - investments in renewables would need to be accelerated further. Accordingly, if the social cost of carbon would be reflected in least-cost planning, emissions from fuel combustion could be reduced by 25 percent.

Nevertheless, it should be noted that in relative terms, this remains a modest amount of emissions. On a Continent of abundant solar and wind resources, there is little difference between least-cost and low-emissions.

4 Investment Needs

Key messages

- For the Base Case, estimated investment of USD 454 are required from now till 2030 to realize SDG7 and meet forecasted demand.
- The largest investments are made in solar and wind generation capacity, particularly in Northern Africa.
- Regional integration allows for better utilization of resources and lowers investment requirements significantly.

This chapter presents the investment required to finance the Base Case access and power system expansions presented in previous chapters. In order to contextualize the investment needs and provide insights for decision-makers, estimates are also presented for the other scenarios.

4.1 Investment Needs Until 2030

It is estimated that a total investment of USD 454 billion, or USD 64 billion per year, is required from now till 2030 to achieve the Base Case access and power system expansion laid out in chapter 3. This aggregate number is broken down as seen in the figure below.

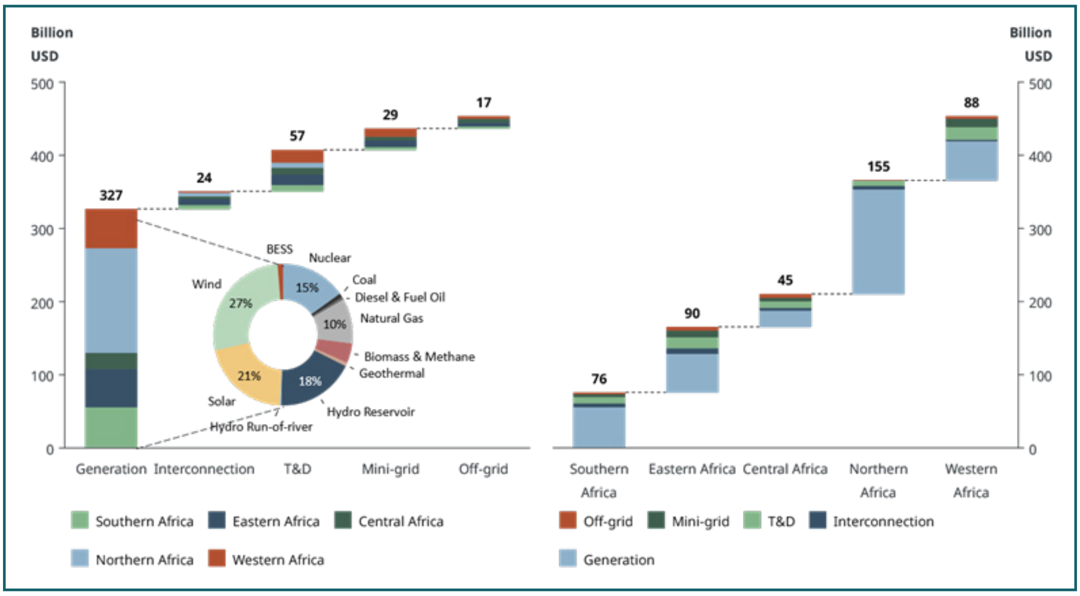


Figure 14: Investment needs by region and category

Wind and solar generation dominate generation investments. Around 48 percent of total generation investments in the Base Case are expected to be made in solar and wind power plants, underscoring the increasing importance of variable renewable energy across the Continent. From a regional perspective, Northern Africa stands out, with investment needs in generation that alone account for nearly USD 143 billion, or 31 percent of the total investment needs for the Continent until 2030. A significant share of this amount comes from the El Dabaa Nuclear Power Plant which currently is under construction in Egypt. The fact that an individual power plant makes up a significant share of the total investment needs for a continental power system that by 2030 will serve nearly two billion people is a striking testament to the fact that development of African power sectors is a long-term endeavour.

The combined expenditure of off- and mini-grid connections is higher than grid expansion costs[26]. Total access expansion costs till 2030 in the Base Case are estimated at USD 74 billion. Even though new connections, as seen in section 3.1, are split roughly into one third each of on-, mini-, and off-grid connections, the investment requirements for mini-grids are nearly double those for off-grid solutions. This is explained by the higher quality and cost of mini-grid connections. On-grid access expansion costs are bundled with investments in existing transmission and distribution grids but are comparable to those for mini-grids.

Regional integration provides good value-for-money. Given the significant economic value of regional integration documented in section 3.2, it is noteworthy that the total investments estimated to make them a reality only is USD 24 billion[27].

4.2 Scenarios

The figure below presents estimated investment needs for each of the four scenarios presented in section 3.3. It is interesting to note that the changes made to underlying assumptions trickle through to the investment needs in very different ways.

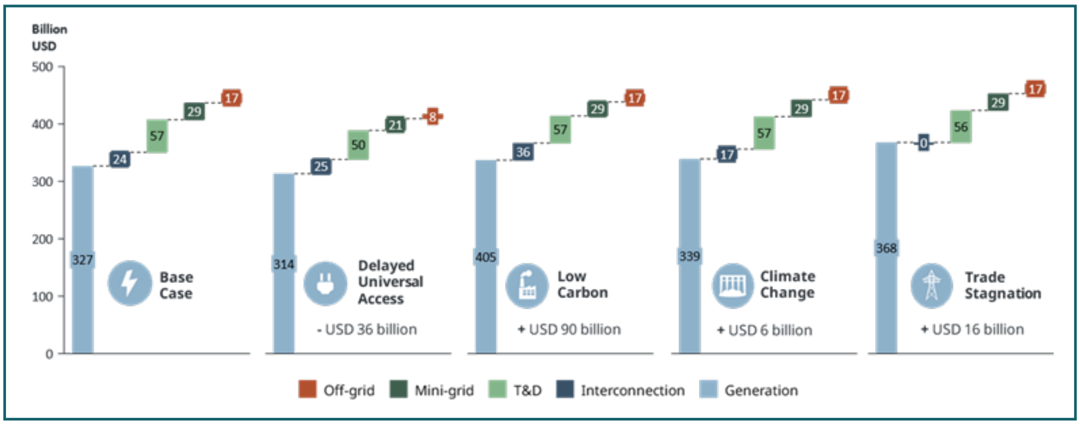


Figure 15: Total investment requirements for each scenario and by region in the Base Case

Delayed universal access only reduces 2030 connection costs. The modelled investment costs for the delayed access scenario, where the goalpost for SDG7 in Africa is moved to 2040 reduces the required investment costs till 2030 by USD 36 billion. Given the limited impact that these changes have on grid demand, it is not surprising that generation and interconnector investments are not significantly impacted.

Approximately USD 24 billion of the 36 billion in reduced investment needs stem directly from a lower number of grid-, mini-grid, and off-grid connections in the Delayed Universal Access scenario.

[26] Cost estimates for mini- and off-grid connections include assets needed for access (e.g. mini-grid generators).
[27] Cost estimates for interconnectors are based on standardized per kilometre assumptions rather than specific costs from feasibility studies. Please refer to Annex 1 for details.

This means that, compared to the Base Case, there will be a residual investment need to achieve universal access after 2030. The structure and composition of these residual investments have not been modelled. It is, however, reasonable to assume that they are higher than USD 24 billion, as the distribution of connections can be expected to shift from off-grid to mini-grid, and from mini-grid to on-grid connections over time.

Africa´s least-cost expansion path is one of low emissions. Given the relatively low investments made in fossil energy even in the Base Case, it is notable that the Low Carbon scenario is the one which has the largest increase in investment needs, USD 90 billion higher than the Base Case. A significant amount of this increase is related to additional investments in solar and wind on top of the already significant capacities installed of these technologies in the Base Case. The increased investments are partly off-set by approximately USD five billion in annual savings on fuel, operations, and maintenance costs for the fossil generation capacity which is being phase out. Whereas the consideration of social cost of carbon would require an even stronger acceleration of investments in renewables, it should be emphasized that the least-cost expansion pathway for African power systems already is one of reducing emissions.

Climate change will drive up the cost of system expansion. The accelerating climatic change that already is being experienced across the African continent will impact the supply and demand for electricity and power systems at large in many ways. An important aspect will be that of changing rainfall patterns, which is expected to have adverse impacts in countries that rely on hydropower to meet their generation and balancing needs. It is therefore not surprising that the Climate Change Scenario results in investment needs that are USD six billion higher than the Base Case.

Regional integration remains a good investment. Regional integration is, as stated in section 3.2, good value for money. This is evidenced by the fact that that the reduced interconnector investments in the Trade Stagnation more than outweigh the increased investment requirements in generation, leading to a net increase in investment needs of more than USD 16 billion.

5 Implications for Policy Makers

Key messages

- The private sector must be enabled to bridge the gap in off- and mini-grid connections.
- For African power systems, the least-cost pathway leads to low emissions.
- To bridge the annual estimated funding gap of USD 25 billion per year, public financing will have to be leveraged to increase private investments.

There is, as demonstrated by the different scenario analyses presented through this report, ample room for policymakers to impact the future of African power systems. This chapter highlights some important takeaways from a policy perspective.

Universal access by 2030 requires strengthening and harmonization of regulations, subsidies, and approaches to market creation for solar home systems and mini-grids across the Continent. The last hope of achieving universal access by 2030 now rests in an unprecedented expansion of off-grid solutions such as solar home systems and mini-grids across much of the Continent. Achieving the extraordinary scale required over only seven years will, however, require the mobilization of private investments and supply chains at presentenced levels. Both the regulations and incentives of these spaces remain immature in too many African countries and coordinated efforts at the Continental level will be required to reach the numbers required and with sufficient quality. An example of such initiatives is the COMESA lead Enhancement for a Sustainable Regional Energy Market initiative, which aims to harmonize a broad spectre of regulations and incentive structures across the Eastern Africa, Southern Africa, and Indian Ocean regions.

Changing rainfall patterns will require increased investments in balancing. This study only explores a simplified sub-set of the challenges that climate change will create for African power systems. The Climate Change scenario highlights how changing inflows to hydropower reservoirs will require increased investments in flexible generation technology and battery storage to enable the continued expansion of low-cost variable renewables at the rate required to meet demand without increasing emissions. While the security of supply remains a national responsibility, the regional power pools could play a vital role in furthering our knowledge and putting in place measures to address this issue.

By embracing least-cost solutions, Africa is helping mitigate climate change. The analysis clearly demonstrates that cheap and emissions-free renewable technologies are the least-cost generation expansion option for most African countries. Equally important, existing flexible generation capacities in the shape of natural gas and reservoir hydro mean that large amounts of variable renewables can be integrated without significant negative impacts on the security of supply. Low-cost variable renewables will surely put already struggling sections of national grids under increased strain, but the foreseen investments in utility-scale battery solutions will help alleviate this situation along with domestic transmission and distribution investments and regional integration. Therefore, unless decision-makers are tempted to diverge from the least-cost pathway, African power systems are likely to see a rapid decline in emissions from already low numbers.

The process of empowering and enabling the regional power pools must be accelerated. The sizable increase of interconnector capacity entailed in the Base Case highlights the importance of scaling up investments in interconnectors and enabling cross-border trade across the Continent. An interesting finding is that the role of regional integration in allowing for an increasing share of low-cost variable renewable is likely as important as the contribution that integrations give in terms of volume of power exchange. To realize these economic benefits, policymakers must accelerate the integration process and empower the regional power pools.

A change of investment pace is required, and available public funds are insufficient. Estimates made by the Africa-EU Energy Partnership[28] estimate the inflow of investments to African power sectors between 2014 and 2020 to EUR 195 billion, or approximately USD 35 billion per year broken down as indicated in the figure below.

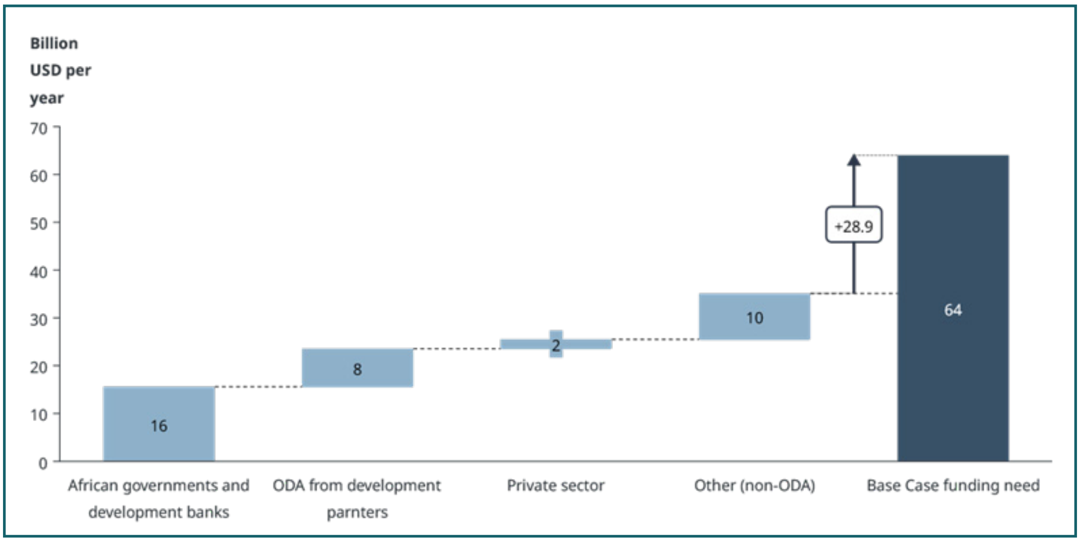


Figure 16: Average annual commitments to SDG7 in Africa 2014-2020 against estimated annual funding needs till 2030.

Public investments must increasingly be leveraged to increase private investments and salvage African utilities. Clearly, the gap between historical investment levels and the needs estimated in this study of USD 64 billion per year till 2030 cannot be covered by African governments alone. Rather, they will require a combination of public sector lending, international grants, increased private participation, and (cross-) subsidization.

Up till 2030 private investment should not be expected to make significant contributions in the transmission and distribution space, where low-cost public-/multilateral lending likely will have continue to carry the lion's share of the investment. In the off- and mini-grid space there is, however, if properly regulated and subsidized, significant room for the private sector to play an active role even in the short run. The same is the case in generation, where, if risks are properly mitigated, private investments can play a crucial role in most African countries[29].

[28] Africa-EU Energy Partnership (2022): European Financial Flows on SDG7 to Africa. Available at: https://sdg7.africa-eu-energy-partnership.org/wp-content/uploads/2023/02/GIZ_AEEP_Report_Financinal-Flows_2022_WEB.pdf
[29] CPCS/Multiconsult (2021): Guideline Report on Procurement of Renewable Energy Capacity. Available at: https://rerasadc.com/wp-content/uploads/2021/07/Draft-Guidelines-for-Renewable-Energy-Incentive-Mechanisms.pdf

Therefore, multilateral, and bilateral development assistance should increasingly be deployed to attract private investments, primarily in generation and mini-grids, as well as creating markets for high-quality off-grid solutions. Several new and innovative risk-reducing instruments are in place, and bringing these to scale will be imperative for the successful realization of SDG7 in Africa.

Lastly, and perhaps most importantly: Most African utilities are in a precarious financial situation[30]. Unless progress is made towards the cost reflectiveness of end-user tariffs, a sustainable grid expansion is unlikely to emerge. Governments and development partners should prioritize their work with utilities on lending for grid reinforcements, technical/commercial loss efforts and policy/regulatory matters to promote sustainability.

[30] IEA (2022): African Energy Outlook 2022. Available at: https://www.iea.org/reports/africa-energy-outlook-2022

Annex 1

1 Introduction

This note outlines the key assumptions and inputs and provides a high-level introduction to the model used in the 2023 Estimating Investment Needs in the Power Sector in Africa study which has been prepared by Multiconsult for COMESA and the African Development Bank. Rather than a stand-alone deliverable, this memo is a supporting document to the reports published under the study.

1.1 Model overview

The following introduced the overall model, planning horizons and scenarios.

Geographical focus – All African countries are modelled as part of this analysis. All countries are not modelled jointly, but rather sequentially based on African Union country allocation in West, Southern, North, East and Central Africa. However, to allow for appropriate consideration of trade and interconnectors between countries that are in different regions, the entire continent is modelled as a final step based on least-cost investments in interconnectors only.

Planning horizons – 2030 is considered as the planning horizon, with a least-cost investment optimization for the entire year on an hourly basis. In addition, the existing system in 2023 is modelled baseline based on least-cost dispatching to create a baseline.

Scenarios – Besides the base case, a number of scenarios are reviewed. These are listed in the following table. The inputs and assumptions behind the base case are presented in the following chapters of this methodological note.

Table 1: Scenario description

Scenario	Issue explored	Narrative description	Change in assumption for 2030 from Base Case
Delayed Universal Access	Delayed realization of SDG7.	The realism of achieving SDG7 by 2030 is increasingly coming into question. This scenario explores the impact of moving the goal post for universal access to 2040.	Continental access rate set to 82 percent for 2030, corresponding to universal access by 2040.
Low Carbon	The impact of pricing carbon emissions.	The impacts of climate change are already being felt across the African Continent. This scenario explores the effects of pricing in the social cost of carbon in system expansion.	A cost of USD100 per ton of CO2equivalent is added[31].

[31] The social cost of CO2 is a monetized measure of the long-term damage done by a ton of emissions. The IPCC in a 2018 report suggested that a carbon price of USD100/ton would cut 2030 global emissions by 50 percent. Available at: chttps://www.ipcc.ch/site/assets/uploads/sites/2/2019/03/SR15_FGD_Chapter_4.pdf

	Climate Change	Hydrological shifts caused by climate change.	Climate change is impacting hydrological patterns across the world. This scenario looks at the impact on power systems of more erratic rainfall.	Inflow to reservoir, pumped-storage and run-of-river have been reduced by 30%. Please refer to Annex 1 for details.
	Trade Stagnation	Value of cross-border trade.	Increased integration of power systems is a stated policy objective for many African policy makers. This scenario explores how trade impacts costs and resilience of power systems.	Model is not allowed to invest in new interconnector capacity over and above projects under construction.

On-grid only - The energy system modelling exercise only considers on-grid generation and demand. Generation and demand from off-grid sources in considered separately, but not included in the optimization.

1.2 Energy system modelling tool

The model developed for this study is based on the PyPSA (Python for Power System Analysis) framework (Brown et al., 2017). PyPSA is an open-source toolbox for simulating and optimising modern power systems that include features such as conventional generators with unit commitment, variable wind and solar generation, storage units, coupling to other energy sectors, and mixed alternating and direct current networks. PyPSA is designed to scale well with large networks and long time series. The framework has already been used in a number of regional energy system studies, such as for the European continent (PyPSA-EUR), or South Africa (PyPSA-ZA).

The framework has a wide range of functionality from high-level economic optimization to detailed power flow calculations. We use the model to perform total electricity/energy system least-cost investment optimisation as well as least-cost dispatching.

1.3 Limitations

It is important to understand that there is significant uncertainty related to the applied inputs and assumptions, including future demand, technological developments, and cost of different technologies. Therefore, neither scenario predicts what will happen in the future.

- Grid topology & power flow. The model does not include a detailed grid topology, and considers countries only as a single node in the network. Therefore, no power flow calculations are made. Investments and maintenance of these systems are estimated separately, outside the optimization problem.
- Climate Change. Whereas a climate change scenario is considered, this only concerns changing inflow patterns to hydropower plants, and even these impacts are modelled based on simplified assumptions.
- Technology assumptions. A number of assumptions had to be made for each generation technology. It is recognized that these may not represent the exact characteristics of each generator installed, as these will depend on a range of factors, such as purpose, contractual agreements, and design.

- Uncertainty in data. Modelling the power sector in all countries of the Continent requires a massive amount of data and inputs. However, the quality of available data varies greatly between countries and regions. Therefore, datasets that cover all countries have been given preference, in order to ensure that data are available and comparable across geographies. It is recognized that this approach results in a loss of detail for certain countries.

A number of other limitations and simplifications have also been made. These are referenced in the respective sections in this document.

2 Inputs and assumptions

2.1 Regional allocation

All countries were grouped by categorization according to African Union (AU) classification, membership to a power pool, and membership in COMESA. However, for the purpose of modelling, only the AU classification was applied. Notably, a two-step optimization process was followed, first modelling the respective AU regions, and then aggregating the results to the continental level and rerunning the optimization for interconnection for appropriate consideration of cross-region trade.

Table 2: Regional groupings

East Africa	Southern Africa	Central Africa	North Africa	West Africa
Burundi	Angola	Cameroon	Algeria	Benin
Comoros	Botswana	Central African Republic	Egypt	Burkina Faso
Djibouti	Lesotho	Chad	Libya	Cape Verde
Seychelles	Malawi	Congo	Mauritania	Côte d'Ivoire
Eritrea	Mauritius	Democratic Republic of Congo	Morocco	Gambia
Ethiopia	Mozambique	Equatorial Guinea	Tunisia	Ghana
Kenya	Namibia	Gabon		Guinea
Rwanda	Sao Tome and Principe			Guinea-Bissau
Somalia	South Africa			Liberia
South Sudan	Swaziland			Mali
Sudan	Zambia			Niger
Tanzania	Zimbabwe			Nigeria
Uganda	Madagascar			Senegal
				Sierra Leone
				Togo

Notably, intercontinental trade and connections were excluded from the analysis.

2.2 Load forecast

The load forecast is a crucial input to the analysis. A number of sources were reviewed to find the appropriate inputs. This includes a bespoke load forecasting model, developed for the 2018 study, as well as the GlobalEnergyGIS tool (Mattsson et al. 2019).
Particularly, we require two levels of inputs for the modelling:

- Total annual energy consumption in 2023 and 2030. The total energy consumption is based on the bespoke forecasting model, with methodology being outlined in the following pages with blue background.
- Hourly load profile for each hour of the year in 2023 and 2030 by country. The GlobalEnergyGIS tool was used to determine the hourly load profile for each region. This is further described in section 2.2.1 below.

The following section outline the approach to access expansion and demand estimation. Because these inputs are exogenous to the model, but connected to a range of inputs and assumptions, they are presented in this separate section. If details of this sections are not of interest, please jump to Section 2.2.1.

Access expansion

An important input for the demand forecast is access expansion. This is modelled bottom-up deploying a bespoke Excel-based model. The following elaborates on the methodology applied and assumptions made. The complete set of input values can be found in the Excel model, which may be made available by COMESA upon request.

Macro level access ambition. The starting point for the access expansion targets applied in this study is the Sustainable Development Goal number 7, which calls for universal access to electricity by 2030.

Population growth and household size. Year-by-year projections of urban and rural inhabitants in each of the African countries from the United Nations (2023) have been applied. For average household size at the country level, the most recent data from GlobalDataLab (2023) has been applied.

Connection expansion. In order to model timing and connection types within each country, the model applies an algorithm that in addition to 2021 electrification rates considers:

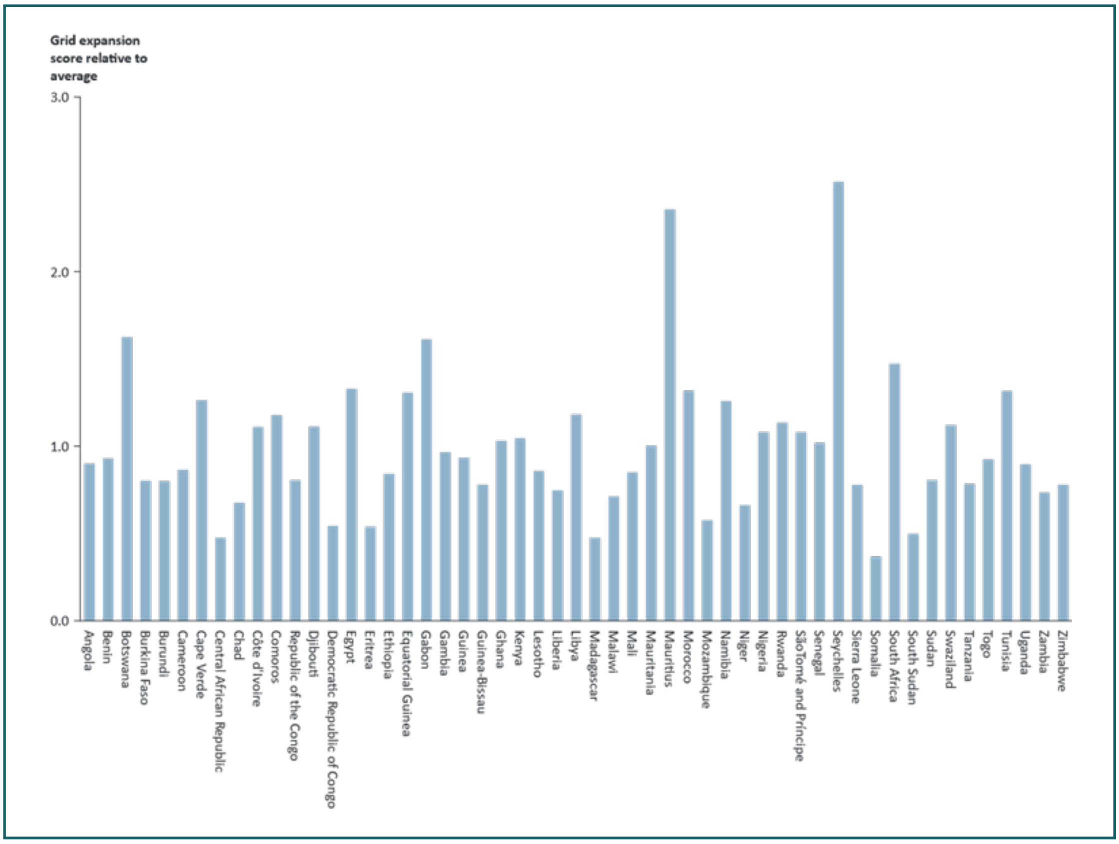
- Population density numbers (World Bank, 2023)
- Share of population living in absolute poverty (Hasell et al., 2022)
- Doing business score (World Bank, 2020)
- GDP/debt ratio (IMF, 2023a)
- GDP/capita (World Bank, 2022)

The table below details how these parameters have been weighted in determining the mix and staging of connection types.

	Population density	Absolute poverty	Doing Business Score 2020	GDP/Debt	GDP/Capita (2022)
Weights - Grid	0.5	1	0.3	0.3	0.5
Weights - Mini-grid	0.2	1	0.8	0.1	0.7

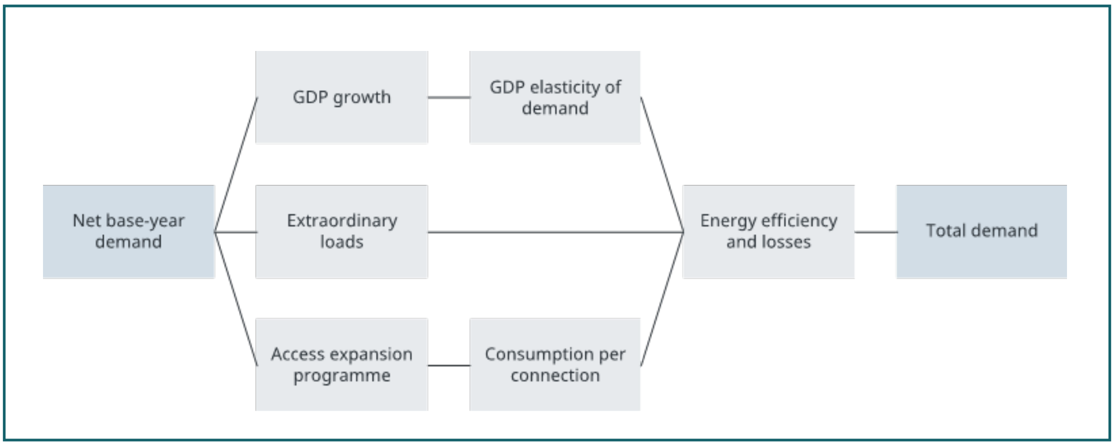
This scoring approach was applied to all countries, with the results illustrated in the figure below. The countries with higher scores can expect to out-perform the average when it comes to the rate of grid expansion, while the countries with lower scores can expect to under-perform.

Figure 1: Grid-expansion index



Demand forecast

The applied total demand projections are, as outlined in the figure below, an aggregate of forecasted demand resulting from i) economic growth and industrialization, ii) the extraordinary access expansion program, and iii) other extraordinary loads.



The key assumptions and data underlying the load forecast exercise are presented and discussed one-by-one below. A number of the assumptions are given for groups of countries which are found to have similar characteristics in terms of their electricity demand. The grouping, which is presented in the table below, builds on an econometric exercise conducted for the Africa Energy Sector Outlook 2040 report prepared for the Programme for Infrastructure Development in Africa (PIDA, 2011).

Table 3: PIDA grouping of countries with similar electricity demand caracteristics

Country	Group
Fragile Low-income countries	Burundi, Central African Republic, Chad, Côte d´Ivoire, Djibouti, Democratic Republic of Congo, Eritrea, Gambia, Guinea-Bissau, Liberia, Mali, Sierra Leone, Somalia, South Sudan, Togo, and Zimbabwe
Non-Fragile Low-income countries	Benin, Burkina Faso, Comoros, Ethiopia, Gabon, Guinea, Ghana, Kenya, Lesotho, Madagascar, Malawi, Mauritania, Mozambique, Niger, Rwanda, Sao Tome and Principe, Senegal, Tanzania, and Uganda
Intermediate Income Countries	Botswana, Cape Verde, Mauritius, Namibia, Seychelles, South Africa, and Swaziland
Resource Rich Countries	Angola, Cameroon, Congo, Equatorial Guinea, Malawi, Nigeria, Sudan, and Zambia

Net base-year demand. The applied base-year (2019) net demand (excluding losses) for each of the African countries is based on numbers presented by the U.S Energy Information Administration (2019). The complete data set can be found in the excel model. 2019 was chosen to avoid the temporary demand shock caused by the COVID19 pandemic.

Validation

Spot-checks have been conducted comparing the applied data set to publicly available sources from AIKP (2023) as well as regulators and utilities in randomly selected countries.

GDP growth. The applied GDP growth numbers from 2019 to 2028 are obtained on a country-by-country basis from the International Monetary Fund (IMF, 2023b) From 2028 to 2030, the long-run GDP growth numbers found in the table below are applied.

Table 4: Applied long-run GDP growth

Group	Long-run GDP growth
Fragile Low-income countries	6.0 %
Non-Fragile Low-income countries	5.0 %
Intermediate Income Countries	3.0 %
Resource Rich Countries	5.0 %
North Africa	4.0 %

GDP elasticity of demand. For numbers on how demand for electricity changes as the economy grows, the GDP elasticity of demand, this study relies on the approximate results of the econometric exercise conducted by PIDA (2011). The applied numbers are found in the table below.

Table 5: Applied GDP elasticities of electricity demand

Group	Elasticities of demand
Fragile Low-income countries	0.85
Non-Fragile Low-income countries	1.35
Intermediate Income Countries	1.20
Resource Rich Countries	1.15
North Africa	1.35

Extraordinary loads. The demand projection model allows for inclusion of extraordinary loads. However, no extraordinary loads are included for the 2023 and 2030 estimate.

Access expansion programme. The GDP elasticity of demand captures the access expansion that has taken place historically. However, it is clear that SDG7 requires a radical break with business as usual. Therefore, it is deemed appropriate to add the increased demand from access expansion to the forecasted organic demand growth. It should be noted that for several poor countries with low current access rates, the expansion program actually contributes the largest relative share of demand growth.

Average consumption per household. The applied numbers for consumption per new connection in the base-year is based on numbers from McKinsey (2015), and presented in the table below.

Table 6: Applied electricity consumption of newly connected households

Group	kWh/connection
Urban	1,200
Rural	400

Energy efficiency. It is assumed that the countries are able to improve the energy efficiency of their economies equal to approximately one percent of total consumption each year, applying improved technologies. This is in keeping with historical trends (Amowine et al., 2019).

Transmission and distribution losses. There is no single updated source available for transmission and distribution losses in each of the African countries. It has therefore been necessary to combine data from different sources. The following sources have been used, in order or priority:

- Africa Infrastructure Knowledge Program Power Statistics Database (AIKP, 2023)
- JRC Technical Report on Energy Projections for African Countries (Papis et. Al, 2019)
- Data from webpages of utilities and regulators
- Other technical studies

A 0.5 percent reduction per year is assumed for combined transmission and distribution losses until they reach 14 percent. Average combined transmission and distribution losses are calculated to 18.5 percent for 2019, reducing gradually to 16.3 percent in 2030. The specific losses and source applied for each country can be found in the excel model.

Validation

Outliers (i.e. surprisingly high or low aggregate loss numbers) in the applied data sets have been verified against the other sources listed.

2.2.1 Hourly load profiles

Determining the hourly load-profiles for such long-term planning horizons is a difficult task, and data is not readily available from previous studies. New approaches are required – and we have therefore applied the GlobalEnergyGIS tool that was developed by Mattsson et al. (2019) to determine hourly renewable energy and load time series for geographical regions based on public datasets.

The model was used to generate hourly synthetic electricity demand for all regions in 2020 and 2030, based on:

- Hour of the day
- Month of the year
- Weekends indicator
- Hourly temperature in population centres
- Monthly temperatures in population centres
- Annual temperature (Mean, 5% and 95% quantile)
- Demand per capita
- GDP per capita

The synthetic demand module estimates the profile of hourly electricity demand in each country. This is done using machine learning, specifically a method called gradient boosting tree regression. This is similar to ordinary regression, except that underlying mathematical relationships between variables are determined automatically using a black box approach.

As the basis for the profile generation the profile generation was configured using, the 2018 weather year, as well as the SSP2 sustainable socioeconomic pathway scenario on development.
Notably, some country data was not available and was replaced by data from neighbouring countries with similar geographical profiles.

2.2.2 Load input data

The output of the analysis is a matrix of 54 (countries) x 8760 (hours of the year). Finally, the load profiles in each region are scaled to the total annual energy consumption (including transmission and distribution losses) in 2023 and 2030.

Validation

The resulting load data has been checked against 2030 load forecasts of IEA and IRENA, which were found to be in a similar range.

2.2.3 Delayed universal access scenario data

An additional scenario was developed to represent delayed universal access. In this scenario, it is assumed that universal access is not achieved in 2030, but rather in 2040. Accordingly, demand from electrification in the demand estimation model is impacted, as electrification targets for 2030 change accordingly. The full T&D model for both the base case and delayed universal access scenario may be made available by COMESA upon reasonable request.

2.3 Transmission and distribution

As noted in the beginning of this note, transmission and distribution infrastructure is not considered as part of the modelling work. However, transmission and distribution impacts model inputs and results in two distinct ways:

- Losses. T&D losses are considered for estimating the gross demand (as stated above in the demand forecast).
- Costs. T&D costs are calculated within the bespoke load forecasting model, particularly relating to grid connection, mini-grid connections and off-grid connections. Costs related to expansion of transmission and distribution grid itself is done ex-post based on model outputs, considering the variable renewable energy share and size of the infrastructure.

Notably, both losses and costs are exogenous to the model, and not included as part of the objective function of the model.

2.3.1 Transmission and distribution losses

As noted above, there is no single updated source available for transmission and distribution losses in each of the African countries. It has therefore been necessary to combine data from different sources. The following sources have been used, in order or priority:

- Africa Infrastructure Knowledge Program Power Statistics Database (AIKP, 2023)
- JRC Technical Report on Energy Projections for African Countries (Papis et. Al, 2019)
- Data from webpages of utilities and regulators
- Other technical studies

A 0.5 percent reduction per year is reduced for combined transmission and distribution losses until they reach 14 percent. Average combined transmission and distribution losses are calculated to 18.5 percent for 2019, reducing gradually to 16.3 percent in 2030. The specific losses and source applied for each country can be found in the excel model.

Table 7: RApplied T&D losses

Country	T&D Losses (2019)	T&D Losses (2023)	T&D Losses (2030)
Algeria	31.60%	29.60%	26%
Angola	13.70%	14%	14%
Benin	24.00%	22%	19%
Botswana	20.60%	19%	15%
Burkina Faso	51.10%	49%	46%
Burundi	25.00%	23%	20%

Country	T&D Losses (2019)	T&D Losses (2023)	T&D Losses (2030)
Cameroon	25.80%	24%	20%
Cape Verde	24.40%	22%	19%
Central African Republic	25.80%	24%	20%
Chad	25.80%	24%	20%
Côte d´Ivoire	19.90%	18%	14%
Comoros	40.00%	38%	35%
Republic of Congo	51.30%	49%	46%
Djibouti	23.90%	22%	18%
Democratic Republic of Congo	16.00%	14%	14%
Egypt	12.30%	12%	12%
Eritrea	24.10%	22%	19%
Ethiopia	23.00%	21%	18%
Equatorial Guinea	32.50%	31%	27%
Gabon	45.40%	43%	40%
Gambia	22.90%	21%	17%
Guinea	23.00%	21%	18%
Guinea-Bissau	52.70%	51%	47%
Ghana	22.90%	21%	17%
Kenya	21.70%	20%	16%
Lesotho	16.60%	15%	14%
Liberia	37.40%	35%	32%
Libya	33.40%	31%	28%
Madagascar	33.00%	31%	28%
Malawi	22.90%	21%	17%
Mali	22.20%	20%	17%
Mauritania	38.20%	36%	33%
Mauritius	9.00%	9%	9%
Morocco	16.60%	15%	14%
Mozambique	16.60%	15%	14%
Namibia	8.20%	8%	8%
Niger	27.10%	25%	22%
Nigeria	16.60%	15%	14%
Rwanda	35.40%	33%	30%
Sao Tome and Principe	33.37%	31%	28%
Senegal	15.50%	14%	14%
Seychelles	8.00%	8%	8%
Sierra Leone	48.20%	46%	43%
Somalia	52.40%	50%	47%
South Africa	12.47%	12%	12%
South Sudan	10.70%	11%	11%
Sudan	30.00%	28%	25%
Eswatini	11.42%	11%	11%
Tanzania	18.70%	17%	14%
Togo	71.00%	69%	66%
Tunisia	17.60%	16%	14%
Uganda	18.70%	17%	14%
Zambia	14.00%	14%	14%
Zimbabwe	19.60%	18%	14%

2.3.2 Costs

Grid connection, mini-grid and off-grid costs. As part of the load forecast, the number of households to be electrified by off-grid, mini-grid, and on-grid solutions was determined. These were then multiplied by the estimated following cost per connection:

Table 8: Applied cost per connection

Group	USD/connection
Grid	400
Mini-grid	600
Off-grid	300

Investment cost in T&D expansion. Investments in T&D expansion are not endogenous to the model. Based on a review of different credible sources, including the latest Africa Energy Outlook, total investment needs were estimated at USD 3.3 billion. The output of the model in terms of share of variable renewable energy and total installed capacity guided the allocation of these costs to the different countries as:

T&D expansion cost of country x = (1 + variable renewable energy share of country x in 2030) / (1 + average variable renewable energy share in 2030) * (installed capacity of country x in 2030 / total installed capacity in 2030) * the total investment amount in T&D expansion.

2.4 Interconnectors and trade

Interconnectors allow for trade in both directions at full capacity listed below. Trade agreements, unidirectional capacity or other trade restrictions are not considered.

Losses. A five percent losses are applied to every cross-border trade via interconnectors, both existing, committed and investment objects.

The following existing and committed interconnector data was applied in 2023 and 2030 and considered fixed. Data is based on the original AIKP study, with additional validation and inclusion of projects under construction. The individual sources are provided in the input sheet to the model

Table 9: Existing and committed interconnector data

Country A	Country B	Capacity (MW)	Status	Commissioning year
botswana	**south_africa**	800	operational	
botswana	**zimbabwe**	600	operational	
congo	**democratic_republic_of_congo**	60	operational	
eswatini	**mozambique**	1450	operational	
eswatini	**south_africa**	1450	operational	
ethiopia	**djibouti**	180	operational	
ivory_coast	**burkina_faso**	327	operational	
ivory_coast	**ghana**	327	operational	

Country A	Country B	Capacity (MW)	Status	Commissioning year
ivory_coast	mali	320	operational	
lesotho	south_africa	230	operational	
libya	egypt	170	operational	
morocco	algeria	1400	operational	
namibia	zambia	300	operational	
nigeria	benin	686	operational	
nigeria	niger	169	operational	
rwanda	burundi	12	operational	
rwanda	democratic_republic_of_congo	385	operational	
south_africa	mozambique	3850	operational	
south_africa	namibia	850	operational	
sudan	ethiopia	200	operational	
sudan	south_sudan	12	operational	
togo	benin	465	operational	
togo	ghana	310	operational	
tunisia	algeria	900	operational	
tunisia	libya	300	operational	
uganda	kenya	445	operational	
uganda	rwanda	305	operational	
uganda	tanzania	70	operational	
zambia	democratic_republic_of_congo	600	operational	
zimbabwe	mozambique	500	operational	
zimbabwe	zambia	1400	operational	
egypt	sudan	300	operational	
ethiopia	kenya	2000	under construction	2025
burkina_faso	ghana	332	under construction	2025
senegal	gambia	350	under construction	2025
guinea	guinea_bissau	350	under construction	2025
guinea_bissau	senegal	350	under construction	2025
ivory_coast	liberia	400	under construction	2025
liberia	guinea	400	under construction	2025
liberia	sierra_leone	400	under construction	2025
sierra_leone	guinea	400	under construction	2025
zambia	tanzania	1000	under construction	2025
tanzania	kenya	1000	under construction	2025
nigeria	niger	650	under construction	2025
niger	benin	650	under construction	2025
niger	burkina_faso	650	under construction	2025
rwanda	burundi	200	under construction	2025

In addition, a number if interconnector investment objects are included in the model as detailed in the figure below. The capacity restrictions are based on the initial AIKP study but have been reviewed and adjusted based on geographical constraints.

Table 10: Interconnector investment objects available to the model

Country A	Country B	Capacity potential (MW)	Annualized capital cost per MW (in 2023 USD)
democratic_republic_of_congo	burundi	500	106782
rwanda	burundi	2000	23158
tanzania	burundi	2000	213564
rwanda	democratic_republic_of_congo	500	38596
south_sudan	democratic_republic_of_congo	500	70759
uganda	democratic_republic_of_congo	500	28304
angola	democratic_republic_of_congo	500	46406
central_african_republic	democratic_republic_of_congo	500	88625
congo	democratic_republic_of_congo	500	19156
eritrea	djibouti	500	46460
ethiopia	djibouti	2000	42455
somalia	djibouti	500	70617
sudan	egypt	2000	72689
libya	egypt	2000	81734
ethiopia	eritrea	2000	89397
sudan	eritrea	2000	40946
kenya	ethiopia	2000	81051
somalia	ethiopia	2000	66318
south_sudan	ethiopia	500	43742
sudan	ethiopia	2000	56607
somalia	kenya	2000	78464
south_sudan	kenya	2000	68186
tanzania	kenya	2000	20584
uganda	kenya	2000	19298
tanzania	rwanda	2000	19298
uganda	rwanda	2000	12865
sudan	south_sudan	2000	60467
uganda	south_sudan	2000	15438
central_african_republic	south_sudan	2000	92445
central_african_republic	sudan	2000	95578
chad	sudan	500	94202
uganda	tanzania	2000	55321
malawi	tanzania	2000	47411
mozambique	tanzania	2000	61432
zambia	tanzania	2000	57210
namibia	angola	2000	43101
zambia	angola	2000	86104
namibia	botswana	2000	60023
south_africa	botswana	2000	31289
zambia	botswana	2000	43421
zimbabwe	botswana	2000	63453
south_africa	lesotho	2000	40228
mozambique	malawi	2000	22349

Country A	Country B	Capacity potential (MW)	Annualized capital cost per MW (in 2023 USD)
zambia	malawi	2000	80832
south_africa	mozambique	2000	43421
eswatini	mozambique	2000	62645
zambia	mozambique	2000	95382
zimbabwe	mozambique	2000	86490
south_africa	namibia	2000	22005
zambia	namibia	2000	22005
zimbabwe	namibia	2000	72345
eswatini	south_africa	2000	22349
zimbabwe	south_africa	2000	19156
zimbabwe	zambia	2000	43819
burkina_faso	benin	2000	75987
niger	benin	2000	45113
nigeria	benin	2000	44698
togo	benin	2000	37036
ivory_coast	burkina_faso	2000	68303
ghana	burkina_faso	2000	21072
mali	burkina_faso	2000	49807
niger	burkina_faso	2000	44538
togo	burkina_faso	2000	86086
ghana	ivory_coast	2000	64493
guinea	ivory_coast	2000	71026
liberia	ivory_coast	2000	88915
mali	ivory_coast	2000	91340
senegal	gambia	2000	81640
togo	ghana	2000	90674
guinea_bissau	guinea	2000	101040
liberia	guinea	2000	65500
mali	guinea	2000	58336
senegal	guinea	2000	40834
sierra_leone	guinea	2000	86204
senegal	guinea_bissau	2000	32758
sierra_leone	liberia	2000	36659
mauritania	mali	2000	63453
niger	mali	2000	69601
senegal	mali	2000	88119
algeria	mali	2000	122755
senegal	mauritania	2000	26180
algeria	mauritania	2000	131125
morocco	mauritania	2000	95501
nigeria	niger	2000	44698
algeria	niger	2000	111393
libya	niger	2000	84652
cameroon	nigeria	2000	93765
chad	nigeria	2000	72357

Country A	Country B	Capacity potential (MW)	Annualized capital cost per MW (in 2023 USD)
central_african_republic	cameroon	2000	79686
chad	cameroon	2000	114602
congo	cameroon	2000	86889
equatorial_guinea	cameroon	2000	41233
gabon	cameroon	2000	34845
chad	central_african_republic	500	73116
congo	central_african_republic	2000	86257
gabon	congo	2000	60178
gabon	equatorial_guinea	2000	68325
libya	algeria	2000	33937
morocco	algeria	2000	27458
tunisia	algeria	2000	40867
tunisia	libya	2000	45975

The cost numbers applied to determine the investment cost is similar to those applied in the AIKP study, only adjusted for inflation. It is briefly described in the following. Rough cost estimates for inter-connectors between countries are estimated based on costs for planned inter-connectors presented in Eastern Africa Power Pool Master Plan (2014), and the distances between the national grids of the respective neighbouring countries. The applied figures are found in the tables below.

Table 11: Applied interconnector investment costs per MW kilometre

Distance between national grids	Capital expenditures (thousand USD per MWkm)
0-150	5.19
151-250	3.28
251-350	1.17
351-550	0.74
551-850	0.83
851-1750	0.62
1751-6000	0.42

The figures above were annualized based on a discount rate of 10 percent and an estimated economic life of 40 years. Further, costs were escalated by the US CPI, retrieved from http://www.bls.gov, considering the December 2017 as reference month (index of 246) and December 2022 as the current reference month (index of 296) – resulting in an inflation adjustment of approximately 20.39 percent. It is assumed that the cost in real USD will remain the same over the time horizon from 2023 to 2030.

2.5 Generators and storage

The following section outlines the inputs and assumptions to all generators and energy storages in the model.

2.5.1 Technologies

A range of technologies were considered in the assignment, using the categorization applied in the initial AIKP study, as detailed in the table below.

Table 12: Generation technologies considered in the study

Type	Sub-type
Diesel	Medium speed diesel engine
Fueloil	Medium speed diesel engine
Diesel	Low speed diesel engine
Fueloil	Steam thermal power plant
Diesel	Steam thermal power plant
Diesel	Simple cycle gas turbine
Fueloil	Simple cycle gas turbine
Diesel	Combined cycle gas turbine
Natural gas	Steam thermal power plant
Natural gas	Simple cycle gas turbine
Natural gas	Combined cycle gas turbine
Methane	Steam thermal power plant
Coal	Steam thermal power plant
Biomass	Steam thermal power plant
Geothermal	Geothermal
Nuclear	Nuclear
Hydro	Hydro run-of-the-river
Hydro	Hydro reservoir
Solar	Solar photovoltaic
Solar	Concentrated solar without storage
Wind	Onshore wind power plant
Hydro	Hydro pumped storage
Wind	Offshore wind power plant
Storage	BESS

A full list of operating parameters for each technology is included in the input sheet to the model.

2.5.2 Costs

The various technologies include a range of cost assumptions, including fuel costs, variable O&M (VOM), fixed O&M (FOM). Fuel costs and variable costs are based on MWh generation, whereas fixed O&M are based on MW installed. All values are expressed in 2023 USD, however, these costs are determined for both time horizons modelled. Data is largely based on the AIKP data, complemented by cost data from the latest LCOE study from Lazards (2023), as well as input from Multiconsult experts on the subject matter where technology cost data was ambiguous. The respective sources of the costs are provided in the input sheet.

Table 13: Applied cost assumptions for generation technologies

Type	Sub-type	FOM 2023	FOM 2030	VOM 2023	VOM 2030	Fuel 2023	Fuel 2030
Diesel	Medium speed diesel engine	30,848	30,848	2.58	2.58	325.96	383.81
Fueloil	Medium speed diesel engine	30,848	30,848	2.58	2.58	163.74	219.39
Diesel	Low speed diesel engine	14,151	14,151	1.13	1.13	318.87	375.46
Fueloil	Steam thermal power plant	63,508	63,508	5.29	5.29	157.61	211.18
Diesel	Steam thermal power plant	63,508	63,508	5.29	5.29	313.76	369.44
Diesel	Simple cycle gas turbine	28,867	28,867	2.41	2.41	363.30	427.77
Fueloil	Simple cycle gas turbine	28,867	28,867	2.41	2.41	182.50	244.52
Diesel	Combined cycle gas turbine	36,084	36,084	3.01	3.01	233.99	275.51
Natural gas	Steam thermal power plant	63,508	63,508	4.63	4.63	96.01	115.40
Natural gas	Simple cycle gas turbine	28,867	28,867	4.63	4.63	111.17	133.62
Natural gas	Combined cycle gas turbine	9,479	9,479	3.88	3.88	71.60	86.06
Methane	Steam thermal power plant	63,508	63,508	5.29	5.29	-	-
Coal	Steam thermal power plant	31,145	31,145	3.75	3.75	25.22	29.03
Biomass	Steam thermal power plant	27,083	27,083	5.29	5.29	14.50	14.50
Geothermal	Geothermal	60,936	60,936	15.00	15.00	-	-
Nuclear	Nuclear	197,703	197,703	4.25	4.25	11.82	11.82
Hydro	Hydro run-of-the-river	47,395	47,395	-	-	-	-
Hydro	Hydro reservoir	47,395	47,395	-	-	-	-
Solar	Solar photovoltaic	27,083	27,083	-	-	-	-
Solar	Concentrated solar	67,707	67,707	-	-	-	-
Wind	Onshore wind power plant	27,083	27,083	-	-	-	-
Hydro	Hydro pumped storage	47,395	47,395	-	-	-	-
Wind	Offshore wind power plant	32,499	32,499	-	-	-	-
Storage	BESS	50,000	50,000	-	-	-	-

Endowments. The generic fuel costs listed above are not applied for all technologies in all geographies. Certain countries have been endowment in natural resources of coal and gas, and these fuel costs have been adjusted as detailed in the table below.

Table 14: Natural resource endowments and related fuel cost adjustments

Coal endowment (25% reduction)	Natural gas endowments (10% reduction)	Natural gas endowments (25% reduction)
Botswana	Benin	Algeria
Mozambique	Mauritannia	Angola
South Africa	Morocco	Cameroon
Zimbabwe	Togo	Congo Republic
		Egypt
		Equatorial Guinea
		Ghana
		Libya
		Mozambique
		Nigeria
		Tanzania
		Tunisia

2.5.3 Variable renewable generation

For variable renewable energy generation, additional time-dependent input was required. Similarly to the demand, these were created using the GlobalEnergyGIS tool by Mattsson et al. (2019).

Solar generation. Hourly solar generation capacity factors were obtained for all countries, based on respective country-shaped polygons using 2018 weather data from the ERA5 satellite. This resulted in a matrix of 8760 hours x 54 countries of capacity factors for solar input. The capacity factor represents the generation potential in MWh of one MWp installed. The Global Energy GIS output includes Class A and Class B types profile, with Class A representing higher-yielding locations for solar PV generation in the respective country. The Class A profile was applied in all countries, as it is assumed that higher yielding sites would be selected for solar investments.

Notably, some weather data was missing or deemed not suitable after validation and was replaced with data from neighbouring countries. The full data is available in the input sheet for the model.

Wind generation. Hourly capacity factors were also obtained were obtained for all countries for wind generation as well – both for on-shore and off-shore (where applicable). This resulted in a matrix of 8760 hours x 54 countries x 2 wind types of capacity factors for solar input. The capacity factor represents the generation potential in MWh of one MW of wind installed. Similarly to the solar capacity factors, the Global Energy GIS output also includes Class A and Class B types profiles for wind, with Class A representing higher-yielding locations. The Class A profile was applied in all countries, as it is assumed that higher yielding sites would be selected for wind investments.

Notably, some weather data was missing or deemed not suitable after validation and was replaced with data from neighbouring countries. The full data is available in the input sheet for the model.

Water inflow. In addition to wind and solar generation, the hydropower run-of-river projects, as well as reservoirs require inflow data. Inflow data was obtained using the dataset compiled as part of the Gernaat et al. (2017) paper, which is also used in the GlobalEnergyGIS tool. Weekly inflow profiles for each country are obtained from that database and interpolate for a higher resolution. Further, following the same approach as in the paper, it is assumed that hydropower sites are sized to allow for generation at full capacity for three months in a year. The inflow profile is capped accordingly. Finally, the inflow profiles are scaled for the respective annual generation (or inflow as the case may be) for hydropower plants in the respective country.

2.5.4 Existing generation and storage

As part of the AIKP study, an extensive powerplant database was developed. This database was also used as the starting point for the updated study. The database provides a range of characteristics, including plant names, coordinates, etc. where available.

Figure 2: Snippet of database from AKIP study

country	latitude	longitude	name	category	type	subtype	installed_capacity
algeria	27.8945	-0.29517	Kabertene	Renewable	Wind	Onshore wind power plant	10
algeria			Ahmer Al Ain	Non-renewable	Natural gas	Simple cycle gas turbine	72
algeria	35.8678	6.025637	Ain Djasser I Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	254
algeria	35.8678	6.025637	Ain Djasser II Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	254
algeria	35.8678	6.025637	Ain Djasser III Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	340
algeria			Ain Arnat	Non-renewable	Natural gas	Combined cycle gas turbine	1015
algeria			Alger Port	Non-renewable	Natural gas	Simple cycle gas turbine	71
algeria			Amizour	Non-renewable	Natural gas	Simple cycle gas turbine	136
algeria	36.89237	7.76336	Annaba Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	71
algeria			Arbaa	Non-renewable	Natural gas	Simple cycle gas turbine	560
algeria			Baraki Mobile	Non-renewable	Natural gas	Simple cycle gas turbine	72
algeria			Batna	Renewable	Solar	Solar photovoltaic	20
algeria			Bellara	Non-renewable	Natural gas	Combined cycle gas turbine	1600
algeria			Beni Merad	Non-renewable	Natural gas	Simple cycle gas turbine	34
algeria	35.5658	-0.93858	Bou Tlelis Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	445
algeria	35.5666667	2.9166667	Boufarik Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	100
algeria	35.5666667	2.9166667	Boufarik Mobile Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	48
algeria	35.5666667	2.9166667	Boufarik 2 Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	712
algeria			Darguinah	Renewable	Hydro	Hydro run-of-the-river	65
algeria	35.4393	2.815322	Djelfa CCGT	Non-renewable	Natural gas	Combined cycle gas turbine	1262
algeria			El Oued	Non-renewable	Natural gas	Simple cycle gas turbine	136
algeria			Erraguene	Renewable	Hydro	Hydro reservoir	100
algeria	35.6644444	7.3077778	F'Kirina Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	292
algeria	35.6644444	7.3077778	F'Kirina Mobile Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	144
algeria	36.5767	2.0797	Hadjret En-Nouss Power Plant	Non-renewable	Natural gas	Combined cycle gas turbine	1200
algeria	36.7489	3.08229	Hamma II Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	418
algeria	36.7489	3.08229	Hamma Mobile Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	48
algeria	31.7877	6.0517	Hassi Messaoud Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	993
algeria	31.7877	6.0517	Hassi Messaoud Nord II Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	200
algeria	31.8	6.1333333	Hassi Messaoud Ouest Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	492
algeria	31.8	6.1333333	Hassi Messaoud Ouest Mobile Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	68
algeria	31.8	6.1333333	Hassi Messaoud Ouest Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	660
algeria	32.94748	3.237981	Hassi R'mel Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	88
algeria	32.94748	3.237981	Hassi R'mel Power Plant	Non-renewable	Natural gas	Simple cycle gas turbine	368
algeria	32.94748	3.237981	Hassi R'mel Solar Power Plant	Renewable	Solar	Concentrated solar without storage	30
algeria	36.4556	5.2722	Ighil Emda Power Plant	Renewable	Hydro	Hydro reservoir	24
algeria	36.8139	5.876	Jijel Thermal Power Plant	Non-renewable	Natural gas	Steam thermal power plant	588
algeria	35.80639	-0.2476	Kahrama Power Plant	Non-renewable	Natural gas	Combined cycle gas turbine	345
algeria	35.5503	6.8697	Kais CCGT	Non-renewable	Natural gas	Combined cycle gas turbine	1266

countries | interconnectors | generators | technologies | others | renewables_t | loads_2023_t | loads_2030_t | loads_2030_t_delayed_acc

A high-level validation exercise of installed generation by technology and country was undertaken, comparing it to other reputable sources and powerplant databases. Major deviations that were identified were researched individually, and the powerplant database updated accordingly. Candidate projects listed in the initial powerplant database were research individually and the status was updated accordingly.

Notably, all project that are under construction are considered as committed. Other projects are considered under investment objects for generation and storage.

Further, to reduce simplicity and improve runtime, generators of the same type are aggregated when construction the model. To the same end, generator types with less than five MW of installed capacity in a country are further omitted.

2.5.5 Investable generation and storage

Generation and storage investments potential is largely based on investment objects in the previous AIKP study. However, three additions were made:

- Solar and wind investment potential was updated for each country based on analysis undertaken with the GlobalEnergyGIS tool by Mattsson et al. (2019), and further adjusted to account for potential regulatory or institutional constraints.
- Storage investments potential was adjusted based on existing system size and variable renewable energy potential
- Emergency generator investments were included to capture any potential infeasibility or lack of other generation investments.

Investment costs are applied based on inflation-adjusted AIKP data, supplemented by latest cost data from Lazard, based on review of Multiconsult experts. The applied annualized investment costs are presented in the table below. Annualization of investment costs were made based on an assumed capacity factor of 10 percent, and the economic life of the respective generator type.

Table 15: Annualized investment costs

Type	Sub-type	Economic Life	Annualized investment cost (2023 USD per MW)
Diesel	Simple cycle gas turbine	20	173,274.45
Fueloil	Simple cycle gas turbine	20	173,274.45
Natural gas	Combined cycle gas turbine	20	117,459.62
Methane	Steam thermal power plant	20	317,669.83
Coal	Steam thermal power plant	40	469,115.06
Biomass	Steam thermal power plant	20	433,186.13
Geothermal	Geothermal	25	545,331.96
Nuclear	Nuclear	40	1,053,271.97
Hydro	Hydro run-of-the-river	40	377,128.39
Hydro	Hydro reservoir	40	377,128.39
Solar	Solar photovoltaic	30	84,863.40
Solar	Concentrated solar	35	395,150.02
Wind	Onshore wind power plant	20	158,570.49
Hydro	Hydro pumped storage	40	377,128.39
Wind	Offshore wind power plant	20	358,251.86
Storage	BESS	15	171,441.81

This resulted in the following list of generation and storage investment objects:

Table 16: Investment potential by technology in MW

Country	Battery	Natural Gas	Nuclear	Solar CSP	Geother-mal	Diesel/ Fuel Oil	Hydro RoR	Hydro Res	Solar PV	Biomass	Coal	Methane	On-shore Wind	Off-shore Wind
algeria	7000			2448		1000	130	124	9792	150			7344	686
angola	7000	2000		848		1000	255	3356	3390	27			2543	1695
benin	1380	760		166		1000		160	662	42	200		497	331
botswana	5047			378		1000			1511	15	2695		1133	0
burkina_faso	1438			169		1000	32	154	675	109			506	0
burundi	500			159		1000	140	166	392	11			169	319
cameroon	6368	729		590		1000	3068	2918	2361	63			1771	1181
cape_verde	787			325		1000			1300				975	650
car	500			158		1000		2500	634				475	0
chad	608			158		1000			633	45			475	317
comoros	500			0	40	1000			300				7	230
congo	2658			175		1000			700				525	350
drc	7000			464		1000		39432	2781	54		100	2086	927
djibouti	701			161	50	1000			644				483	322
egypt	7000	10000		5001		1000			20004	799	14000		15003	10002
equ_guinea	631	100		162		1000			647				485	323
eritrea	1474			167		1000		400	256				500	333
eswatini	500			479		1000		15	1916		1000		1437	0
ethiopia	7000			554	4995	1000	22573	12438	2216	594			1662	1108
gabon	2698			173		1000		453	693				520	346
gambia	500			160		1000	42	25	640				480	320
ghana	7000	2317		872		1000		462	3486	73	2400		2615	1743
guinea	4922			188		1000	15	3326	752	43	340		564	376
guinea_bissau	500			158		1000	9	5	632				474	316
ivory_coast	7000	2592		417		1000	242	2377	1668	83	700		1251	834
kenya	7000	358		733	8799	1000	151	90	2932	102	960		2199	1466

Country	Battery	Natural Gas	Nuclear	Solar CSP	Geother-mal	Diesel/ Fuel Oil	Hydro RoR	Hydro Res	Solar PV	Biomass	Coal	Methane	On-shore Wind	Off-shore Wind
lesotho	500			162		1000	110	100	648				486	0
liberia	552			483		1000		200	1933		350		1450	966
libya	7000			931		1000			3725		230		2794	1863
madagascar	2820			184		1000	1921	712	735	127	100		551	368
malawi	1790			168		1000	950	227	673	69	220		505	337
mali	3061			180		1000	54	303	720	107			540	0
mauritania	1140	350		168		1000			673				505	337
mauritius	3103			177		1000	1	17	386	60			136	354
morocco	7000	2400		933		1000	92	233	3734	323	1320		2800	1867
mozambique	7000	4500		222		1000	1500	2575	888	75	5470		666	444
namibia	2867	885		525		1000	220	600	2099	60	300		1574	1049
niger	960			163		1000		278	652	100			489	0
nigeria	7000	2000		1211		1000	3500	1618	4845	854	7980		3634	2422
rwanda	1494			503	310	1000	12	114	1401	92	100	206	237	59
stp	500			43		1000	2	12	111				96	317
senegal	3772	1000		551		1000	141	335	2203	41	960		1652	1101
seychelles	500			26		1000			100				0	320
sierra_leone	549			485		1000	6	749	1941	12			1456	971
somalia	500			161		1000			642				482	321
south_africa	7000	2000	9600	3342		1000		2240	13369	463	11980		10026	6684
south_sudan	500			158		1000	25	2147	634	100			475	0
sudan	7000	900		252		1000		2272	1008	37	534		756	504
tanzania	7000	3945		606	200	1000	522	3163	2422	188	1670		1817	1211
togo	821			489		1000	2	50	1955	30			1466	977
tunisia	7000	1750		606		1000	10	19	2424	81			1818	1212
uganda	5027	50		764	296	1000	154	1928	3054	98			2291	1527
zambia	7000			877		1000	1750	1410	3509	51	600		2632	1755
zimbabwe	7000			693		1000		1100	2771	31	5500		2078	1385

2.6 Reserve margins

In line with the approach in the AIKP study, additional reserve margin requirements were imposed to ensure sufficient grid reliability. There are grouped by spinning (more responsive) and non-spinning reserves (less responsive).

The generator types contributing to spinning and non-spinning reserves respectively are presented in the figure below.

Table 17: Generator types contributing to spinning and non-spinning reserves

Type	Sub-type	Non-spinning reserve	Spinning Reserve
Diesel	Medium speed diesel engine	True	True
Fueloil	Medium speed diesel engine	True	True
Diesel	Low speed diesel engine	True	True
Fueloil	Steam thermal power plant	True	True
Diesel	Steam thermal power plant	True	True
Diesel	Simple cycle gas turbine	True	True
Fueloil	Simple cycle gas turbine	True	True
Diesel	Combined cycle gas turbine	True	True
Natural gas	Steam thermal power plant	True	True
Natural gas	Simple cycle gas turbine	True	True
Natural gas	Combined cycle gas turbine	True	True
Methane	Steam thermal power plant	True	
Coal	Steam thermal power plant		
Biomass	Steam thermal power plant	True	
Geothermal	Geothermal	True	True
Nuclear	Nuclear		
Hydro	Hydro run-of-the-river	True	True
Hydro	Hydro reservoir		
Solar	Solar photovoltaic		
Solar	Concentrated solar		
Wind	Onshore wind power plant		
Hydro	Hydro pumped storage	True	True
Wind	Offshore wind power plant		
Battery	BESS	True	True

Reserve margins are considered for each country separately (not aggregated by region or continent), such that each country can always supply the reserve without relying on trade. The reserve margin requirements have two dimensions – as a share of variable renewable energy generation, and as a share of total demand.

Table 18: Reserve margin requirements

Type	% of VRE generation	% of demand
Spinning	5	3
Non-spinning	5	13

Notably, these reserve requirements are not additive, but rather the minimum requirement of either spinning or non-spinning reserve requirements. The values indicated above are based on assumptions agreed in the previous AIKP study.

2.7 Emissions

The model also considers emissions from fuel combustions in terms of CO2 equivalents. The emission factors considered in the analysis are presented in the table below. They are largely based on the IPCC (2014) report, adjusted to accommodate the structure of technologies applied in this study based on Multiconsult experts.

Table 19: Applied emissions factors by technology

	kgCO2e/GJ	kgCO2e/MWh
diesel	74.00	266.40
fueloil	78.00	280.80
natgas	56.80	204.48
methane	49.28	177.41
coal	95.00	342.00
biomass	0.00	0.00
heat	0.00	0.00
nuclear	0.00	0.00
water	0.00	0.00
sun	0.00	0.00
wind	0.00	0.00

Notably, the emission values in kgCO2equivalent are not considering fuel efficiency of the various generators yet and are adjusted accordingly. The resulting emissions per MWh by technology are accordingly as follows. The full list of fuel efficiency values by generator are listed in the main input sheet to the model.

Table 20: Applied emissions factors by technology sub-type

Type	Sub-type	CO2e emissions in t/MWh
Fuel oil (diesel)	Medium speed diesel engine	0.74000
Fuel oil	Medium speed diesel engine	0.78000
Fuel oil (diesel)	Low speed diesel engine	0.72391
Fuel oil	Steam thermal power plant	0.75080
Fuel oil (diesel)	Steam thermal power plant	0.71230
Fuel oil (diesel)	Simple cycle gas turbine	0.82477
Fuel oil	Simple cycle gas turbine	0.86935
Fuel oil (diesel)	Combined cycle gas turbine	0.53121
Natural gas	Steam thermal power plant	0.54674
Natural gas	Simple cycle gas turbine	0.63307
Natural gas	Combined cycle gas turbine	0.40774
Methane	Steam thermal power plant	0.40047
Coal	Steam thermal power plant	0.87692
Biomass	Steam thermal power plant	0.00000
Geothermal	Geothermal	0.00000
Nuclear	Nuclear	0.00000
Hydro	Hydro run-of-the-river	0.00000
Hydro	Hydro reservoir	0.00000
Solar	Solar photovoltaic	0.00000
Solar	Concentrated solar	0.00000
Wind	Onshore wind power plant	0.00000
Hydro	Hydro pumped storage	0.00000

2.8 Low-carbon scenario

In the base case, no costs were considered for the emission of CO2 from generators, only the respective O&M costs. However, a low-carbon scenario was developed, which considers the emission-related costs as part of the marginal cost of fuel-combusting generators. A fixed social cost of carbon was included for each generators.

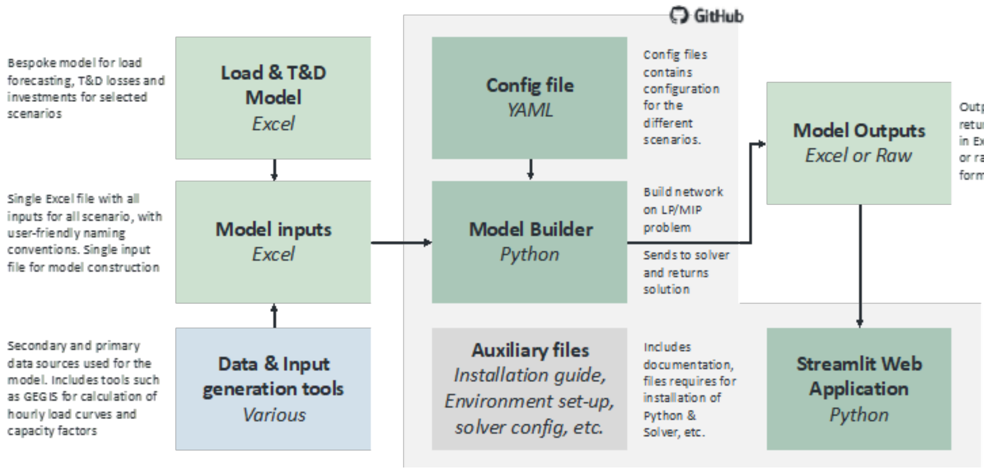
The social cost of CO2 is a monetized measure of the long-term damage done by a ton of emissions. The IPCC in a 2018 report suggested that a carbon price of USD100/ton would cut 2030 global emissions by 50 percent, based on a IPCC (2019) report[32].

[32] https://www.ipcc.ch/site/assets/uploads/sites/2/2019/03/SR15_FGD_Chapter_4.pdf

3 Modelling methodology

3.1 Model infrastructure

The data flow, transformation and model is structures as illustrated below. Documentation on installation and basic functionality is available in the following GitHub repository: https://github.com/Multiconsult-Group/pypsa-africa-invest. Access to the repository can be provided upon reasonable request.



3.2 High-level optimization methodology

Overall, this study employed a two-step optimization process, with the first step consisting of individual generation, storage, and interconnection expansion in each region. The resulting investment decision are than recorded and passed through to a continental optimization problem, with only interconnectors as potential investment objects. This approach was taken to ensure a manageable runtime, while still ensuring incorporation of inter-regional effects in trade. Notably, for the 2023 reference case, only the continental configuration was used, as the runtime was manageable in this case.

Snapshots. Compared to the 2018 AIKP study, the PyPSA based model included the modelling of a full calendar year at an hourly resolution (8760 snapshots). This was chosen for appropriate consideration of seasonal effects on hydropower operations and load, while retaining hourly fluctuation of variable renewable energy.

Optimization. The optimization is based on a Linear Programming (LP) formulation, with the objective function representing the total system cost and the constraints representing characteristics of the energy system that is built. The LP is constructed based on the out-of-the-box formulation by PyPSA, accessible under the following link:

Notably, as the model includes both dispatch and investment objects, the resulting model can be understood as a joint dispatch and investment optimization model.

Custom constraints. A number of customer constraints had to be included to cover the specific neds of the assignment. These were made to accommodate the following

- **Inclusion of reserve margin** for spinning and non-spinning reserves, as well as reserves based on both load and variable renewable energy generation.
- **Correct sizing of interconnector investments.** Interconnectors are modelled as two separate unidirectional links for import and export. A custom constraint was included to ensure that investment in one direction also determines the size of an investment in the other direction.
- **Hydropower reservoir sizing.** The model includes a number of hydropower reservoir investment objects. These reservoirs are modelled as a set of components that need to have correct proportions based on the countries geographical features (e.g. the storage in terms of full load hours is fixed). To ensure that the components are sized appropriately, additional constraints had to be included.

Finally, all files are available in the GitHub repository listed above, and further detailed in the respective code.

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Annex 2 – Tabulated Results by Country

Access expansion

The following table shows total number of on-, mini- and off-grid connections forecasted for each country between 2021 and 2030.

Country	On-grid expansion	Mini-grid expansion	Off-grid expanstion
Algeria	1,079,282	394	495
Angola	2,690,927	4,709,248	6,595,595
Benin	706,361	2,151,694	2,760,361
Botswana	94,125	386,124	127,792
Burkina Faso	1,087,719	6,428,808	9,664,860
Burundi	450,860	5,121,174	7,184,284
Cameroon	1,003,763	3,076,733	3,762,125
Cape Verde	14,529	2,649	2,028
Central African Republic	210,071	929,260	4,105,016
Chad	721,728	7,285,222	15,312,907
Côte d´Ivoire	1,755,138	5,999,908	4,773,326
Comoros	24,904	43,947	32,253
Republic of Congo	566,999	966,149	2,150,468
Djibouti	66,219	86,364	98,905
Democratic Republic of Congo	7,855,903	24,240,462	85,718,518
Egypt	3,432,752	0	0
Eritrea	155,794	365,379	1,029,723
Ethiopia	4,622,677	26,816,109	34,138,622
Equatorial Guinea	90,951	300,638	173,849
Gabon	131,331	181,878	61,570
Gambia	113,795	232,961	247,370
Guinea	398,985	2,668,094	2,877,462
Guinea-Bissau	94,062	384,445	713,915
Ghana	1,694,123	2,689,849	2,478,540
Kenya	2,908,848	10,210,842	9,098,326
Lesotho	166,880	1,108,579	1,412,284
Liberia	416,577	1,352,433	3,351,236
Libya	154,255	816,206	582,854
Madagascar	1,705,205	5,736,699	18,806,658
Malawi	1,007,989	10,965,993	19,561,347
Mali	825,781	3,661,056	4,579,596
Mauritania	235,512	986,215	949,537
Mauritius	386	0	0
Morocco	361,094	0	0
Mozambique	1,627,321	7,125,696	17,082,481
Namibia	136,884	439,069	315,177
Niger	767,324	7,725,446	14,742,027
Nigeria	16,888,499	62,530,660	52,769,742
Rwanda	604,477	6,186,098	4,717,311
Sao Tome and Principe	20,105	9,604	10,631
Senegal	478,705	1,678,157	1,560,048
Seychelles	868	0	0
Sierra Leone	251,292	1,157,999	2,150,031
Somalia	885,243	1,277,581	6,414,987
South Africa	1,045,910	9,315	8,819
South Sudan	296,548	3,783,103	12,923,463
Sudan	2,265,708	6,763,754	9,486,661
Eswatini	48,012	151,711	120,319
Tanzania	3,264,219	12,291,101	18,352,452
Togo	1,049,229	5,944,951	6,504,422
Tunisia	193,955	0	0
Uganda	2,465,878	11,150,168	13,397,129
Zambia	936,738	3,576,162	5,746,574
Zimbabwe	1,198,904	6,865,078	9,956,539

Gross demand in 2030

The following table shows the estimated gross demand applied in the base case. The reported figures include transmission and distribution losses.

Country	Gross Demand (TWh)
Algeria	113.0
Angola	14.4
Benin	3.7
Botswana	7.5
Burkina Faso	10.4
Burundi	1.3
Cameroon	15.0
Cape Verde	0.7
CAR	0.6
Chad	1.6
Comoros	0.2
Congo Rep.	5.0
Djibouti	0.8
DR Congo	30.1
Egypt	365.2
Equ. Guinea	1.3
Eritrea	0.9
Eswatini	2.2
Ethiopia	34.5
Gabon	5.8
Gambia	0.6
Ghana	33.8
Guinea	4.8
Guinea Bissau	0.4
Ivory Coast	16.0
Kenya	25.8
Lesotho	1.7
Liberia	1.4
Libya	57.0
Madagascar	7.7
Malawi	4.0
Mali	7.1
Mauritania	4.8
Mauritius	4.8
Morocco	59.3
Mozambique	45.1
Namibia	6.7
Niger	5.1
Nigeria	64.8
Rwanda	2.5
STP	0.2
Senegal	13.2
Seychelles	0.8
Sierra Leone	0.9
Somalia	2.5
South Africa	278.0
South Sudan	1.3
Sudan	26.6
Tanzania	22.9
Togo	6.2
Tunisia	28.9
Uganda	11.5
Zambia	24.5
Zimbabwe	11.7

Installed capacity and generation in 2030

The following table shows the installed capacity in GW by generation technology as well as the total generation in TWh in the Base Case in year 2030.

Country	Nuclear	Coal	Diesel & Fuel Oil	Natural Gas	Bio & Met.	Geo-thermal	Hydro Res	Hydro Ror	Solar	Wind	Battery	Gen (TWh)
Algeria	0.00	0.00	0.37	24.05	0.00	0.00	0.12	0.36	10.18	7.35	0.00	132.92
Angola	0.00	0.00	1.10	0.96	0.00	0.00	5.02	0.00	0.28	0.00	0.00	27.38
Benin	0.00	0.00	0.09	0.41	0.04	0.00	0.00	0.00	0.69	0.00	0.00	2.75
Botswana	0.00	0.73	0.16	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.02	5.88
Burkina Faso	0.00	0.00	0.29	0.00	0.11	0.00	0.03	0.00	0.71	0.18	0.00	2.90
Burundi	0.00	0.00	0.18	0.00	0.01	0.00	0.22	0.15	0.40	0.17	0.08	3.04
Cameroon	0.00	0.00	0.30	1.00	0.06	0.00	1.46	0.00	2.05	0.00	0.00	15.01
Cape Verde	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.09	0.17	0.00	0.66
CAR	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.00	0.04	0.00	0.01	4.60
Chad	0.00	0.00	0.15	0.00	0.05	0.00	0.00	0.00	0.18	0.30	0.00	1.56
Comoros	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.17
Congo Rep.	0.00	0.00	0.03	0.38	0.00	0.00	0.24	0.02	0.29	0.00	0.00	1.81
Djibouti	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.01	0.20
DR Congo	0.00	0.00	0.87	0.00	0.15	0.00	2.90	0.35	2.78	2.09	0.15	27.17
Egypt	4.80	0.00	2.10	48.66	0.80	0.00	2.83	0.00	21.80	15.85	0.00	366.89
Equ. Guinea	0.00	0.00	0.06	0.18	0.00	0.00	0.32	0.01	0.01	0.00	0.00	1.44
Eritrea	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.20	0.05	0.00	0.57
Eswatini	0.00	0.00	0.00	0.00	0.02	0.00	0.06	0.00	0.53	0.50	0.12	2.44
Ethiopia	0.00	0.00	0.08	0.00	0.11	0.01	11.30	0.57	2.22	0.44	0.00	63.71
Gabon	0.00	0.00	0.05	0.41	0.00	0.00	0.68	0.04	0.43	0.00	0.00	4.21
Gambia	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.14	0.05	0.01	0.33
Ghana	0.00	0.00	1.06	4.21	0.07	0.00	1.48	0.16	3.56	2.84	0.00	40.49
Guinea	0.00	0.00	0.19	0.00	0.04	0.00	0.99	0.26	0.75	0.56	0.00	7.97
Guinea Bissau	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.16
Ivory Coast	0.00	0.00	0.00	1.55	0.13	0.00	1.15	0.01	1.67	1.25	0.00	15.37
Kenya	0.00	0.00	0.37	0.00	0.04	1.24	0.71	0.11	3.06	0.43	0.00	20.75
Lesotho	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.36	0.04	1.92
Liberia	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.32
Libya	0.00	0.00	0.00	10.66	0.00	0.00	0.00	0.00	3.83	2.79	0.00	36.54
Madagascar	0.00	0.27	0.35	0.00	0.13	0.00	0.13	0.24	0.78	0.86	0.21	7.75
Malawi	0.00	0.00	0.00	0.00	0.07	0.00	0.35	0.02	0.49	0.50	0.16	4.32
Mali	0.00	0.00	0.24	0.00	0.11	0.00	0.39	0.07	0.72	0.54	0.00	5.42
Mauritania	0.00	0.00	0.22	0.31	0.00	0.00	0.00	0.00	0.71	0.54	0.00	4.73
Mauritius	0.00	0.12	0.20	0.08	0.07	0.00	0.07	0.01	0.50	0.50	0.19	4.79
Morocco	0.00	2.44	1.27	0.39	0.32	0.00	1.87	0.13	6.15	3.91	0.00	56.96
Mozambique	0.00	0.00	0.09	4.94	0.08	0.00	2.08	0.11	0.95	0.67	0.00	30.73
Namibia	0.00	0.12	0.02	0.89	0.01	0.00	0.35	0.06	0.15	1.57	0.00	7.10
Niger	0.00	0.64	0.18	0.00	0.10	0.00	0.41	0.00	0.70	0.49	0.00	10.50
Nigeria	0.00	0.00	0.00	8.91	0.85	0.00	2.30	0.00	4.85	3.64	0.00	63.50
Rwanda	0.00	0.00	0.04	0.00	0.39	0.00	0.11	0.08	0.01	0.00	0.00	4.06
STP	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.11	0.00	0.06	0.23
Senegal	0.00	0.00	0.69	1.00	0.04	0.00	0.00	0.00	2.33	1.78	0.00	12.56
Seychelles	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.11	0.09	0.04	0.81
Sierra Leone	0.00	0.00	0.06	0.00	0.03	0.00	0.05	0.01	0.00	0.00	0.00	0.43
Somalia	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	1.40
South Africa	1.82	25.18	3.11	2.14	0.50	0.00	5.75	0.06	5.56	12.14	1.78	281.75
South Sudan	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.63	0.00	0.02	1.49
Sudan	0.00	0.11	1.21	0.17	0.00	0.00	1.91	0.00	1.01	0.76	0.00	13.56
Tanzania	0.00	0.00	0.07	4.17	0.00	0.10	0.47	0.10	1.01	0.10	0.00	15.14
Togo	0.00	0.00	0.04	0.10	0.03	0.00	0.21	0.00	1.95	0.20	0.00	5.18
Tunisia	0.00	0.00	0.00	4.73	0.00	0.00	0.05	0.01	2.42	2.09	0.00	31.91
Uganda	0.00	0.00	0.05	0.00	0.05	0.00	1.77	0.22	0.07	0.00	0.00	12.60
Zambia	0.00	0.30	0.12	0.00	0.07	0.00	2.92	0.14	1.81	2.63	0.00	26.56
Zimbabwe	0.00	1.19	0.00	0.00	0.03	0.00	1.05	0.01	0.70	2.08	0.28	20.62

Investments by category and country in millions USD

The following table shows the investments in generation, interconnection, T&D, mini-grid and off-grid solution in the base case. The number references the total investment needs. Please note that in case of cross-border interconnectors, only 50% of the investment costs are attributed to the respective country.

Country	Generation	Interconnection	T&D	Mini-grid	Off-grid
Algeria	20,459	1,443	1,278	-	-
Angola	215	1,767	1,448	511	233
Benin	866	47	770	235	96
Botswana	86	-	507	39	4
Burkina Faso	1,169	105	1,025	707	372
Burundi	2,086	61	674	573	288
Cameroon	4,324	672	866	332	136
Cape Verde	255	-	484	0	0
CAR	3,309	864	576	105	209
Chad	716	346	768	827	693
Comoros	115	-	556	4	1
Congo Rep.	230	510	810	103	76
Djibouti	44	31	504	9	3
DR Congo	8,719	1,098	3,448	2,725	4,021
Egypt	97,535	780	3,092	-	-
Equ. Guinea	738	61	542	32	5
Eritrea	219	52	541	40	44
Eswatini	1,245	-	499	15	3
Ethiopia	27,773	2,201	2,439	2,939	1,290
Gabon	1,885	190	618	18	2
Gambia	193	-	519	25	8
Ghana	9,126	105	1,229	270	75
Guinea	2,628	261	657	292	101
Guinea Bissau	67	-	634	42	27
Ivory Coast	5,388	4	1,143	648	149
Kenya	4,672	1,011	1,816	1,076	286
Lesotho	916	-	517	116	49
Liberia	-	-	699	146	133
Libya	8,152	1,587	702	83	17
Madagascar	4,338	-	1,141	628	858
Malawi	1,471	102	859	1,231	829
Mali	1,700	610	789	407	175
Mauritania	1,528	570	643	107	31
Mauritius	2,764	-	421	-	-
Morocco	10,730	557	759	-	-
Mozambique	6,385	689	1,147	794	762
Namibia	3,064	1,078	529	45	9
Niger	5,831	214	837	909	684
Nigeria	18,802	170	6,281	6,623	1,629
Rwanda	723	137	782	672	147
STP	189	-	521	1	0
Senegal	5,144	279	680	183	51
Seychelles	406	-	416	-	-
Sierra Leone	44	-	675	125	81
Somalia	505	225	936	143	309
South Africa	30,378	327	1,143	0	-
South Sudan	568	672	568	418	634
Sudan	1,997	1,485	1,467	734	364
Tanzania	4,919	1,751	1,766	1,357	729
Togo	2,491	47	1,071	645	227
Tunisia	4,394	151	609	-	-
Uganda	3,504	282	1,429	1,222	482
Zambia	7,885	1,382	891	394	236
Zimbabwe	3,840	92	994	752	394