

**ENERGY ACCESS AND GREEN  
TRANSITION COLLABORATIVELY  
DEMONSTRATED IN URBAN AND  
RURAL AREAS IN AFRICA**

**D8.3**  
Regional climate and  
energy models



## Deliverable Report

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| <b>Participant responsible:</b>   | NTNU                                                                                                                                                                                                             |
| <b>Main authors:</b>              | Haiping Shen (NTNU), Pedro Crespo del Granado (NTNU), Tatiana González Grandón (NTNU), Alessandro Onori (NTNU), Helene Muri (NTNU), Anusha Sathyanadh (NTNU), Homa Esfandiari (NTNU), Abdoulatif Bonkaney (UAM). |
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### Nature of the Deliverable

|       |                                                               |  |
|-------|---------------------------------------------------------------|--|
| R     | Document, report (excluding the periodic and final reports)   |  |
| DEM   | Demonstrator, pilot, prototype, plan designs                  |  |
| DEC   | Websites, patents filing, press & media actions, videos, etc. |  |
| OTHER | Software, technical diagram, etc.                             |  |

### Dissemination Level

|    |                                                                            |  |
|----|----------------------------------------------------------------------------|--|
| PU | Public, fully open, e.g. web                                               |  |
| CO | Confidential, restricted under conditions set out in Model Grant Agreement |  |
| CI | Classified, information as referred to in Commission Decision 2001/844/EC  |  |

### Quality procedure

| Date       | Version            | Reviewers           | Comments            |
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|            |                    |                     |                     |

## I. PROJECT SUMMARY

The Energy Access and Green Transition Collaboratively Demonstrated in Urban and Rural Areas in Africa (ENERGICA) project is an initiative aimed at improving sustainable energy access and green transition across African regions while integrating climate adaptation and mitigation strategies.

The ENERGICA project brings together 11 African-based partners and 17 European organizations with offices or subsidiaries in Africa, aiming to foster close collaborations between the two continents on energy access and sustainable energy development. Its primary goal is to showcase the effective deployment of renewable energy technologies tailored to local needs. The project establishes three demonstration sites, each supported by local Energy Transition Boards responsible for managing community-scale Integrated Community Energy Systems (ICESs). Using innovative technologies and tailored approaches, ENERGICA aims to generate positive social, environmental, technical, and economic impacts through high energy efficiency and low-carbon emission renewable energy technologies. Specifically, the project develops innovative nano grids in rural Madagascar, implement low-tech, efficient biogas systems in peri-urban Sierra Leone, and introduce solar-powered e-mobility solutions in urban Kenya.

## II. OBJECTIVE AND EXECUTIVE SUMMARY

This report is the deliverable of the task 8.3 within Work Package 8 for the ENERGICA project, which has been funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 101037428.

The task aims at establishing and implementing in-depth regional-scale climate adaptation and mitigation integrated models, leveraging advanced climate-energy modelling to optimize renewable energy deployment and strengthen climate resilience in the face of changing climatic conditions. It explores regional energy system transitions through the application of high-resolution climate models to assess projected changes in temperature, wind speed, precipitation, and other critical climate parameters up to 2050. The integration of climate projections facilitates the development of regional climate-energy models that inform policy and investment decisions for sustainable energy transitions. These models incorporate climate adaptation strategies to mitigate greenhouse gas (GHG) emissions while enhancing energy sustainability and security across African regions.

This derivable includes regional case studies in Kenya, Sierra Leone and Madagascar, focusing on the key climate variables and local applications of renewable energy technologies as the adaptation of the regional future energy system design in response to climate change towards 2050. Different methodologies and research questions are applied and tailored to different demonstrate sites based on the local climate characteristics and energy conditions, as well as the data availabilities. NTNU as the first step applied the Norwegian Earth System Model (NorESM2). However, there are difficulties using NorESM2 for integrating climate with the energy system modelling. Therefore, other climate models, such as EC-earth3 Earth System Model, MRI-ESM2.0 Earth System Model and Machine Learning (ML) algorithms, have been applied due to their higher resolutions, tailored to Africa. The report assesses the feasibility of integrating renewable energy sources such as solar, wind, hydro and bioenergy to strengthen energy resilience while reducing carbon emissions. Furthermore, Multi-Criteria Decision Analysis (MCDA) tools are employed to support the development of robust policy frameworks that enable climate-smart energy planning.

For Kenya, a climate-informed energy-system pathway is explored by embedding future climate projections directly into capacity expansion decisions for the regional power system across three integrated climate-energy scenarios, with the aim of formulating climate-aware future energy profiles and assessing how climate warming could influence the design of Kenya's future power system. The three scenarios include: (1) a green-path scenario reflecting a high share of renewables in line with ENERGICA technologies; (2) a baseline scenario; and (3) an intermediate scenario to examine how climate adaptation may differ across potential futures. The PyPSA-Earth model is used to calculate capacity expansion decisions for Kenya's power system. The EC-Earth3-Veg Earth System Model provides projected climate variables such as wind speed. Cooling demand under warming is estimated from Cooling Degree Days (CDDs) derived from a Multi-Climate Model ensemble. The integrated climate and energy models apply projected climate variables, CO<sub>2</sub> emission limits, and energy demand projections in 2050, to model future energy system optimization under predicted climate conditions. Capacity-expansion results indicate that energy demand and CO<sub>2</sub> emission limits significantly shape Kenya's future energy system profile. Temperature increases raise cooling

demand by about 11.5%–18.5% of total energy demand. Wind-speed changes are complexed: onshore wind declines while offshore wind rises, boosting offshore-wind share to roughly 9.1%–19.0% of total capacity. A life cycle assessment of the optimized systems shows that decarbonization strategies focusing only on the operation phase may mislead the effectiveness of climate-change mitigation. Geothermal energy is expected to remain a critical role in Kenya's energy strategy, and offshore wind is forecasted to become an increasingly important renewable source as the energy system adapts to climate change. However, substantial climate projection uncertainty persists, and improvements in climate-model resolution and accuracy are needed for robust integration into energy system optimization.

For Sierra Leone, the study assesses how climate variability and drought risk could reshape Sierra Leone's least-cost electricity pathway to 2050. By combining basin-level hydro-climate projections with a national energy system model, it evaluates the resilience of hydro-centric expansion plans and the costs, reliability, and emissions implications of substituting lost hydropower under different climate futures.

Sierra Leone's grid is small (~177 MW), hydro-dependent, and financially fragile, with costly thermal contracts such as the Karpowership lease (~USD 53 m/yr). National strategies emphasise new hydropower projects (Bumbuna II, Bekongor, Betmai, Singimi) alongside utility-scale PV and CLSG imports. While this portfolio promises low operating costs, it tightly links system adequacy to rainfall—already erratic and projected to grow more variable with climate change. The framework integrates climate projections with OSeMOSYS capacity expansion. Climate inputs combine the CMIP6 MRI-ESM2.0 model (SSP1-2.6 and SSP5-8.5) with Random Forest downscaling of ERA5-Land (1960–2023), refined through the Standardised Precipitation–Evapotranspiration Index (SPEI-6). These are translated into monthly hydropower capacity factors for run-of-river and storage plants. The resulting profiles inform least-cost investment and dispatch optimisation for 2025–2050, calibrated to Sierra Leone's techno-economic context.

Results show heterogeneous rainfall responses: SSP1-2.6 yields widespread drying, while SSP5-8.5 produces more volatile, basin-specific patterns with up to 9% interannual variability. Hydropower availability declines accordingly: Bumbuna II remains firm ( $CF \approx 0.98$ ), but Bekongor drops to ~0.65, Bumbuna I and Betmai lose ~20–25%, and Singimi effectively halves. Stress tests confirm the implications: under historical hydrology, hydro suffices with minimal emissions (~0.13 MtCO<sub>2</sub>). Under SSP1-2.6, ~165 MW of oil capacity is added as backup, raising costs and emissions (~0.66 MtCO<sub>2</sub>). Under SSP5-8.5, ~273 MW of biomass and LFO is required, doubling or tripling costs and pushing emissions near 0.95 MtCO<sub>2</sub>. The analysis underscores that Sierra Leone's power future is inseparable from its climate future. Hydropower remains central but not climate-proof. A resilient pathway demands integrating climate-conditioned hydrology into planning, diversifying with solar PV and storage, reinforcing interconnections, and adopting adaptive reservoir management to safeguard affordable, sustainable electricity.

For Madagascar, this study uses an integrated climate–energy modelling approach to examine how large-scale carbon dioxide removal (CDR) strategies could influence future climate conditions over the country. Madagascar is highly vulnerable to warming, rainfall

variability, and climate-related health and infrastructure risks. Using the Norwegian Earth System Model (NorESM2-LM), researchers simulated not only climate processes but also the effects of different energy- and industry-based mitigation pathways from 2030 to 2100. These included a reference mitigation pathway, bioenergy expansion without carbon capture, Bioenergy with Carbon Capture and Storage (BECCS), Ocean Alkalinity Enhancement (OAE), and a combined BECCS-OAE scenario. Because BECCS and OAE represent future energy production and industrial carbon removal systems, the experiments link global energy transition choices to changes in atmospheric CO<sub>2</sub> and regional surface temperatures over Madagascar.

The results show that while Madagascar continues to warm until mid-century in all scenarios, pathways that include active carbon removal lead to a gradual decline in atmospheric CO<sub>2</sub> later in the century and modest regional cooling. By 2100, BECCS and the combined BECCS-OAE scenario reduce average surface temperatures over Madagascar by roughly 0.1–0.2 °C compared with the reference pathway, while OAE alone produces a smaller and slower response. The cooling is uneven across the island but generally slightly stronger in northern and coastal areas. Although these temperature reductions are limited, they demonstrate how global energy-system interventions aimed at achieving net-negative emissions can slightly ease long-term heat stress in Madagascar, while emphasizing that carbon removal can only complement, not replace, rapid emissions reductions and local adaptation efforts.

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## V. ABBREVIATIONS AND ACRONYMS

| Acronym  | Description                                                                                        |
|----------|----------------------------------------------------------------------------------------------------|
| ENERGICA | Energy Access and Green Transition Collaboratively Demonstrated in Urban and Rural Areas in Africa |
| ESMs     | Earth System Models                                                                                |
| GHG      | Greenhouse Gas                                                                                     |
| IPCC     | Intergovernmental Panel on Climate Change                                                          |
| KCERT    | Kenya Carbon Emission Reduction Tool                                                               |
| LCA      | Life Cycle Assessment                                                                              |
| AFOLU    | Agriculture, Forestry and other Land Use                                                           |
| LULUCF   | Land Use, Land-Use Change, and Forestry                                                            |
| MCDA     | Multi-Criteria Decision Analysis                                                                   |
| BAU      | Business-as-usual                                                                                  |
| SSPs     | Shared Socioeconomic Pathways                                                                      |
| RCPs     | Representative Concentration Pathways                                                              |
| CCS      | Carbon Capture and Storage                                                                         |
| LCD      | Low Carbon Development                                                                             |
| KPLC     | Kenya Power and Lighting Company                                                                   |
| LV       | Low Voltage                                                                                        |
| MV       | Medium Voltage                                                                                     |
| CDDs     | Cooling Degree Days                                                                                |
| PV       | Photovoltaic                                                                                       |
| ETIP     | Energy Transition and Investment Plan                                                              |
| CMIP6    | Coupled Model Intercomparison Project Phase 6                                                      |
| CORDEX   | Coordinated Regional Downscaling Experiment                                                        |
| TUB      | Technical University of Berlin                                                                     |
| CSPOUT   | Concentrated Solar Power Output                                                                    |
| EACREEE  | East African Centre of Excellence for Renewable Energy and Efficiency                              |

|         |                                                          |
|---------|----------------------------------------------------------|
| ECREEE  | ECOWAS Centre for Renewable Energy and Energy Efficiency |
| ICESs   | Integrated Community Energy Systems                      |
| IOD     | Indian Ocean Dipole                                      |
| ML      | Machine Learning                                         |
| NorESM2 | Norwegian Earth System Mode                              |
| NZE     | Net-Zero Energy                                          |
| PVP     | Photovoltaic Power Potential                             |
| RCMs    | Regional Climate Models                                  |
| UNEP    | United Nations Environment Programme                     |
| WAM     | West African Monsoon                                     |
| WCRP    | World Climate Research Program                           |
| WMO     | World Meteorological Organization                        |
| CDR     | Carbon Dioxide Removal                                   |
| BECCS   | Bio-Energy for Carbon Capture and Storage                |
| OAE     | Ocean Alkalinity Enhancement                             |
| SSP     | Shared Socio-Economic Pathway                            |

## 1. INTRODUCTION

This deliverable addresses the intersection of climate change and energy transitions in Africa, recognizing the urgent need for climate-resilient and sustainable energy solutions. Africa's energy systems are particularly vulnerable to climate variability, with increasing temperatures, shifting precipitation patterns, changing wind speed and extreme weather events posing significant risks to energy security and infrastructure (ENERGICA, 2025).

To mitigate these challenges, we integrate high-resolution climate modelling with energy system analysis to assess the impact of climate change on energy security and sustainability. By leveraging advanced climate models such as EC-Earth3 Earth System Model, MRI-ESM2.0 Earth System Model and Machine Learning (ML) algorithms, the deliverable provides detailed insights into future climate trends, including temperature, wind speed, irradiation and precipitation changes, which directly influence energy demand and supply dynamics (Rahman & Pekkat, 2024; Seland et al., 2020; Vimmerstedt et al., 2025).

The deliverable has developed various data-driven solutions that enable African countries to understand the transition challenges toward low-carbon, renewable energy sources while ensuring energy accessibility and resilience. It applied a comprehensive methodology combining climate modeling, scenario-based energy system analysis, and regional policy evaluation to address the impacts of climate change on Africa's future energy systems. Through regional modelling, this report supports policymakers and interested stakeholders in designing robust strategies for energy system adaptation. Furthermore, by conducting demonstrations in Kenya, Madagascar, and Sierra Leone, the report showcases that its findings are applicable and scalable, facilitating long-term sustainable development across diverse African regions (ENERGICA, 2025; Løken, 2007; Vimmerstedt et al., 2025).

The deliverable objectives are driven to understand the climate mitigation and adaptation in green transition pathway, the resilience and sustainability of Africa's energy systems in response to climate change. These objectives include:

- Developing regional climate and energy models to project future changes in temperature, wind speed, precipitation, and energy demand across different African regions towards 2050. These models will provide valuable insights into the long-term impact of climate change on energy systems.
- Assessing the feasibility of integrating renewable energy solutions such as solar, wind, hydro, geothermal, and bioenergy to enhance energy system resilience and reduce greenhouse gas emissions, connecting with climate projections. This assessment will identify sustainable pathways for energy transitions.
- Utilizing Multi-Criteria Decision Analysis (MCDA) tools to support the development of robust policy frameworks that facilitate climate-smart energy planning. MCDA will help evaluate various factors influencing energy policy decisions.
- Conducting regional case studies in Kenya, Madagascar, and Sierra Leone to test and validate the effectiveness of climate-energy models through applying different methodologies based on the local climate characteristics and energy conditions, as well as the data availabilities. These case studies will offer practical insights into the

applicability of proposed energy solutions under climate change conditions in diverse African settings.

- By leveraging the findings from demonstration sites, this deliverable aims to provide a blueprint for broader energy transformation efforts.

For the climate modeling component, NTNU initially employed the Norwegian Earth System Model (NorESM2). Although NorESM2 offered robust global climate simulations, it presented limitations when it came to the integration of detailed energy system modeling, particularly in terms of resolution and regional adaptability. To overcome these challenges, it has been transitioned to the EC-Earth3 Earth System Model, MRI-ESM2.0 Earth System Model and Machine Learning (ML) algorithms, providing a higher spatial resolution and greater flexibility, making it better suited for capturing the complex climatic conditions specific to the African continent. These models allowed to generate more precise projections of critical climate variables, such as temperature changes, precipitation patterns, and wind dynamics, essential for informing energy planning.

In parallel, a scenario-based energy system analysis was developed to explore possible future pathways for Africa's energy transitions under climate change. Several distinct climate-energy scenarios were defined to capture a wide range of possible developments. The Green Path Scenario envisioned a future characterized by high renewable energy adoption, closely aligned with sustainability goals of this project. The Baseline Scenario represented a continuation of the current energy trajectory without significant intervention or policy changes. The Intermediate Scenario depicted a mixed development pathway, combining both fossil fuel use and renewable energy integration. To model and optimize the energy systems under these scenarios, the Power-Earth model and OSeMOSYS were employed for Kenya and Serro Leone respectively. These models allowed to simulate energy system evolution by factoring in constraints such as CO<sub>2</sub> emission limits, projected changes in climate variables, and future energy demand trends up to 2050.

Complementing the technical modeling work, the task also conducted a detailed regional sensitivity and policy analysis to tailor its strategies to the specific needs of African regions. The project collaborated closely with the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) for West Africa, the East African Centre of Excellence for Renewable Energy and Efficiency (EACREEE) for East Africa, and the Southern African Centre for Renewable Energy and Energy Efficiency (SACREEE) for Southern Africa. These partnerships provided critical regional insights into the adaptation requirements of local energy systems in the face of climate change. Additionally, UAM conducted Multi-Criteria Decision Analysis (MCDA) tools, integrated into the policy development process. MCDA enabled the systematic evaluation of competing factors — including environmental, economic, technical, and social considerations — ensuring that the resulting policy recommendations were robust, transparent, and adaptable to different regional contexts.

Through these multi-faceted approaches, the deliverable established a strong methodological foundation for supporting climate-resilient and sustainable energy transitions across Africa. It highlights the profound implications of climate change for Africa's energy systems and highlights the critical role of adaptive, data-driven strategies to ensure future energy resilience.

Climate change projections generated through high-resolution modeling reveal significant temperature increases across the African continent. These projections indicate not only a general rise in mean surface temperatures but also a pattern of shifting precipitation regimes. Some regions are expected to experience more intense and frequent droughts, while others may encounter heightened risks of extreme rainfall and flooding. These evolving climatic conditions pose severe challenges to the stability, reliability, and sustainability of existing energy infrastructures, which are often vulnerable to environmental extremes. The use of high-resolution climate models has proven crucial for enabling more accurate forecasting and supporting effective policy planning. The detailed climate simulations generated by these models provide policymakers and energy planners with the granular information needed to design adaptive energy systems that account for localized climate risks, future energy demand fluctuations, and emission reduction targets.

In light of these projections, the integration of renewable energy sources emerges as a key strategy for mitigating the adverse impacts of climate change while simultaneously enhancing energy security. Renewable technologies such as solar, wind, hydro, and bioenergy offer climate-resilient alternatives to traditional fossil-fuel-based systems, reducing dependency on vulnerable supply chains and contributing to the decarbonization of national energy portfolios.

The case studies of the demonstration sites provided invaluable insights into how different renewable energy strategies perform under varied climatic and socio-economic conditions. They confirmed the scalability and effectiveness of the proposed models and solutions, reinforcing the potential for widespread adoption across diverse African contexts. The deliverable delivers critical insights into the profound impact of climate change on energy transitions across Africa. Through its integration of high-resolution climate modelling and comprehensive energy system analysis, the deliverable demonstrates how future climatic shifts, including rising temperatures, shifting precipitation patterns, and changing wind speed, can substantially affect energy demand, supply stability, and infrastructure resilience. These findings underscore the urgent need for forward-looking, adaptive strategies that align energy planning with the realities of a changing climate.

The models and case studies developed and validated through the deliverable serve as practical examples of how sustainable energy transitions can be implemented on the ground. The scalability and adaptability of these solutions pave the way for their large-scale replication across diverse African contexts, ensuring that lessons learned can be leveraged to drive widespread, long-term sustainable development across the continent.

## 2. Climate change challenges in Africa

### 2.1 Climate change mitigation and adaptation pathways

The Shared Socioeconomic Pathways (SSPs) framework provides a range of plausible global development pathways influencing climate change mitigation and adaptation strategies. Developed as part of the IPCC's scenario framework, SSPs define potential future socioeconomic trends, including population growth, economic development, and technological advancements, without considering climate policies (IPCC, 2023; O'Neill et al., 2014). The five SSPs—SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-fuelled Development)—each present distinct socioeconomic pathways that interact with climate forcing pathways (RCPs) to explore different climate change scenarios (Riahi et al., 2017).

Economic growth (GDP) and population size are two primary drivers influencing climate change scenarios. SSPs incorporate varied assumptions regarding economic and demographic trends. For instance, SSP1 envisions rapid technological progress, low population growth, and a transition to sustainable economic models, while SSP5 assumes fossil-fuel-driven high economic growth with high energy demands (Fricko et al., 2017). The implications of these trends are significant, with high-growth scenarios like SSP5 leading to greater greenhouse gas emissions and climate change impacts (Meinshausen et al., 2020). Moreover, population growth assumptions vary across SSPs, with SSP3 predicting high population growth in developing countries and constrained economic development, leading to increased vulnerability to climate change (Jiang, 2014).

SSP1-2.6 represents a sustainable development pathway with strong mitigation policies, resulting in limited warming of approximately 1.5–2°C by 2100. In contrast, SSP5-8.5 is a fossil-fuel-intensive scenario, leading to a projected temperature increase of 4.6–5.2°C by 2100 (Nazarenko et al., 2022).

Figure 1 shows historical and projected global temperature anomalies relative to the 1880–1899 baseline, based on GISS CMIP6 simulations. Historically, temperatures fluctuated until around 1950, after which a clear warming trend emerged, surpassing 1°C by the early 21st century. Future projections vary depending on emissions scenarios, with outcomes ranging from moderate warming to severe climate consequences. In a low-emissions future (SSP1-2.6), strong mitigation efforts could limit warming to around 2°C (3.6°F) by 2100. A moderate-emissions pathway (SSP2-4.5) would push temperatures beyond 2°C and closer to 3°C, while higher-emissions scenarios (SSP3-7.0 and SSP5-8.5) could drive warming to 3.5–5°C (6.3–9°F) (NASA Goddard Institute for Space Studies, 2021).

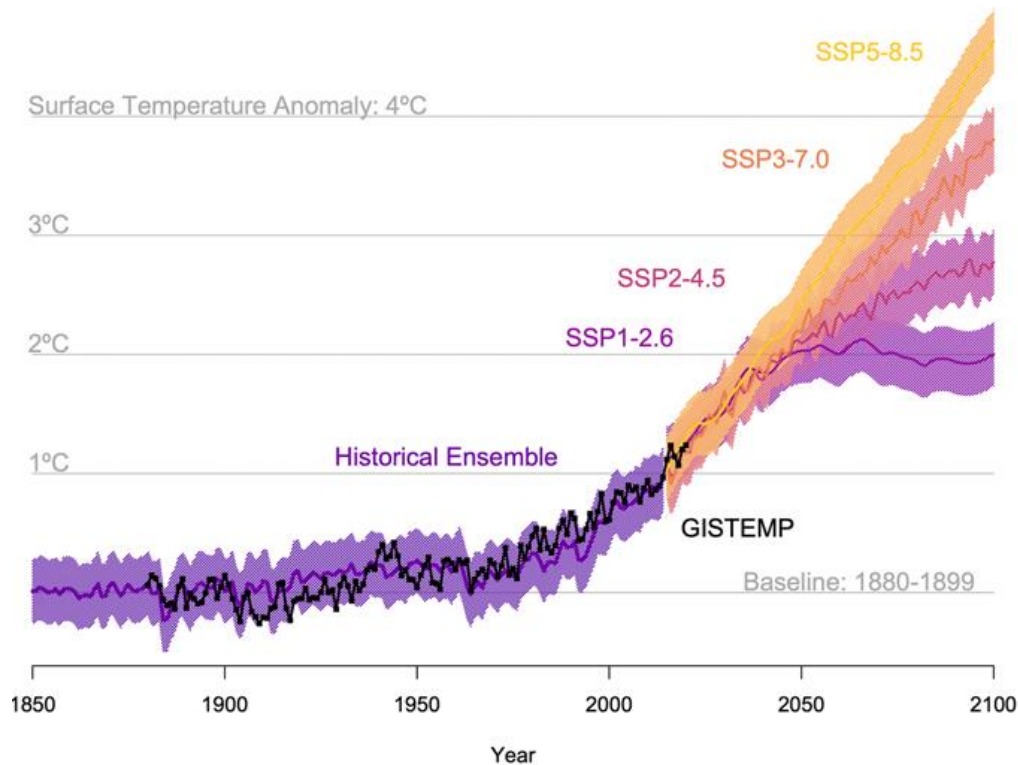


Figure 1. Global mean surface temperature anomalies from GISS model simulations for 1850–2014 driven by observed emissions and greenhouse gas concentrations and for 2015–2100 driven by four Shared Socioeconomic Pathways (SSPs). Source: (NASA Goddard Institute for Space Studies, 2021).

Meanwhile, the difference in greenhouse gas (GHG) emissions between SSP1-2.6 and SSP5-8.5 is substantial. In SSP1-2.6, emissions decline significantly after peaking in the mid-21st century due to widespread adoption of renewable energy and sustainable practices. Conversely, SSP5-8.5 assumes continuous reliance on fossil fuels, leading to CO<sub>2</sub> concentrations exceeding 1135 ppm by 2100 (Meinshausen et al., 2020). The projected emissions from SSP5-8.5 could lead to severe environmental consequences, including intensified climate extremes and higher rates of sea-level rise.

It is essential to emphasize that SSP1-2.6 focuses on energy efficiency, renewable energy expansion, and reduced reliance on fossil fuels. In contrast, SSP5-8.5 is characterized by rapid economic growth fueled by coal and oil, leading to increased energy demand and carbon emissions (Riahi et al., 2017). Studies indicate that in SSP5-8.5, coal consumption remains high, while SSP1-2.6 transitions towards carbon neutrality with large-scale investments in clean energy (Chen et al., 2017).

## 2.2 Climate change trends in Africa

Africa faces significant challenges from climate change, arguably more than any other continent, due to its inherent vulnerabilities, lower adaptive capacity, and heavy reliance on rain-fed agriculture (Parkes et al., 2019). The region is expected to experience more frequent heatwaves, prolonged droughts, and shifting precipitation patterns, with profound implications for agriculture, water resources, and public health (Weber et al., 2018). Given Africa's dependence on climate-sensitive sectors such as agriculture and energy, it is crucial

to assess the impacts of climate change on key variables, including temperature, wind speed, solar radiation, precipitation, water inflow, and land use (Agence Française de Développement, 2023; Trisos et al., 2022). This literature review examines future climate projections, focusing on temperature variations at both continental and national scales, with specific attention to Kenya, Madagascar, and Sierra Leone.

### 1. Change in Temperature

The Global Carbon Budget report, released at the U.N.'s COP29 climate summit in Azerbaijan, projected global CO<sub>2</sub> emissions to reach 41.6 billion metric tons in 2024, an increase from 40.6 billion tons in 2023 (Abnett, 2024). This increase is largely driven by the energy sector, which remains the dominant contributor to climate change, accounting for approximately 75% of global greenhouse gas emissions, primarily from the combustion of fossil fuels such as coal, oil, and gas (IEA, 2024).

The IPCC's SSPs provide projections for future climate scenarios based on different greenhouse gas emission trajectories. Figure 2 illustrates the contribution of various emissions to global surface temperature increase from 2081 to 2100 relative to 1850–1900, highlighting the dominant role of CO<sub>2</sub> emissions. Across all SSPs, CO<sub>2</sub> remains the primary driver of global warming, with its contribution increasing significantly in high-emission scenarios. In SSP1-1.9 and SSP1-2.6, where strong mitigation efforts are implemented, temperature rise is limited to 1.0–1.8°C and 1.3–2.4°C, respectively. SSP2-4.5 projects a moderate increase of 2.1–3.5°C, while SSP3-7.0 and SSP5-8.5, characterized by high fossil fuel use, indicate extreme warming of 2.8–4.6°C and 3.3–5.7°C, respectively (IPCC, 2021).

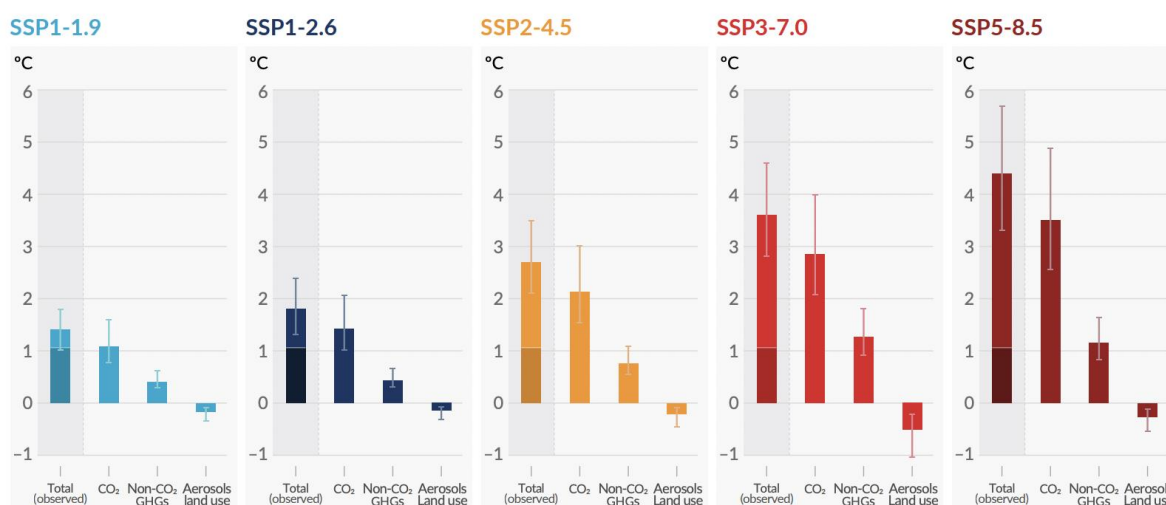


Figure 2. Contribution to global surface temperature increase from different emissions, with a dominant role of CO<sub>2</sub>.

Source: IPCC, 2021.

Africa's warming trend has intensified, exceeding the global average. As can be seen from the Figure 3, in 2022, the mean near-surface air temperature was 0.16°C above the 1991–2020 average and 0.88°C above the 1961–1990 average. The warming rate has accelerated to +0.3°C per decade (1991–2022) from +0.2°C (1961–1990). Rising temperatures exacerbate droughts in East Africa, heatwaves in North Africa, and coastal vulnerabilities, worsening food insecurity, displacement, and economic losses, underscoring the need for urgent adaptation (IPCC, 2021; WMO, 2023).

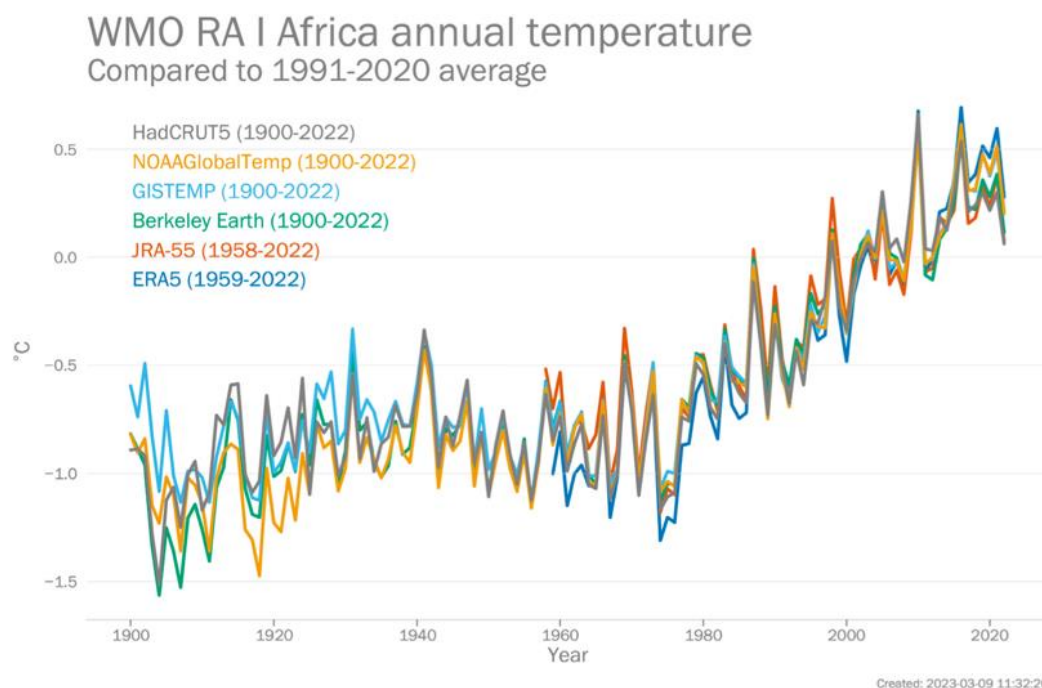


Figure 3. Temperature difference in °C with respect to the 1991–2020 climatological period for Africa (WMO Regional Association I) from 1900 to 2022.

This plot is based on six data sets, including observational data sets (HadCRUT5 [black], NOAAGlobal Temp [yellow], GISTEMP [light blue], and Berkeley Earth [green]) and reanalyses (JRA-55 [orange] and ERA5 [dark blue]).

Source: WMO, 2023.

The Figure 4 illustrates projected temperature changes in Africa under different emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) for two future periods: 2030–2059 and 2070–2099, relative to pre-industrial levels. It highlights the increasing intensity of warming as emissions rise and time progresses. In the low-emission scenario (SSP1-2.6), temperature increases remain relatively moderate, with most of Africa experiencing less than 2°C warming by the end of the century. This scenario reflects a future where strong climate policies limit global temperature rise. Meanwhile, under SSP2-4.5 (moderate emissions), the warming becomes more pronounced, particularly in North Africa and parts of Southern Africa, where temperatures rise by over 3°C by 2100. This pathway represents a world with some mitigation efforts but continued reliance on fossil fuels. The high-emission scenario (SSP5-8.5) paints a stark picture. By the late 21st century, much of Africa faces extreme warming, with the Sahara and Sahel regions surpassing 5.5°C above pre-industrial levels. Southern Africa also experiences severe temperature increases, making heatwaves and droughts more likely (Almazroui et al., 2020).

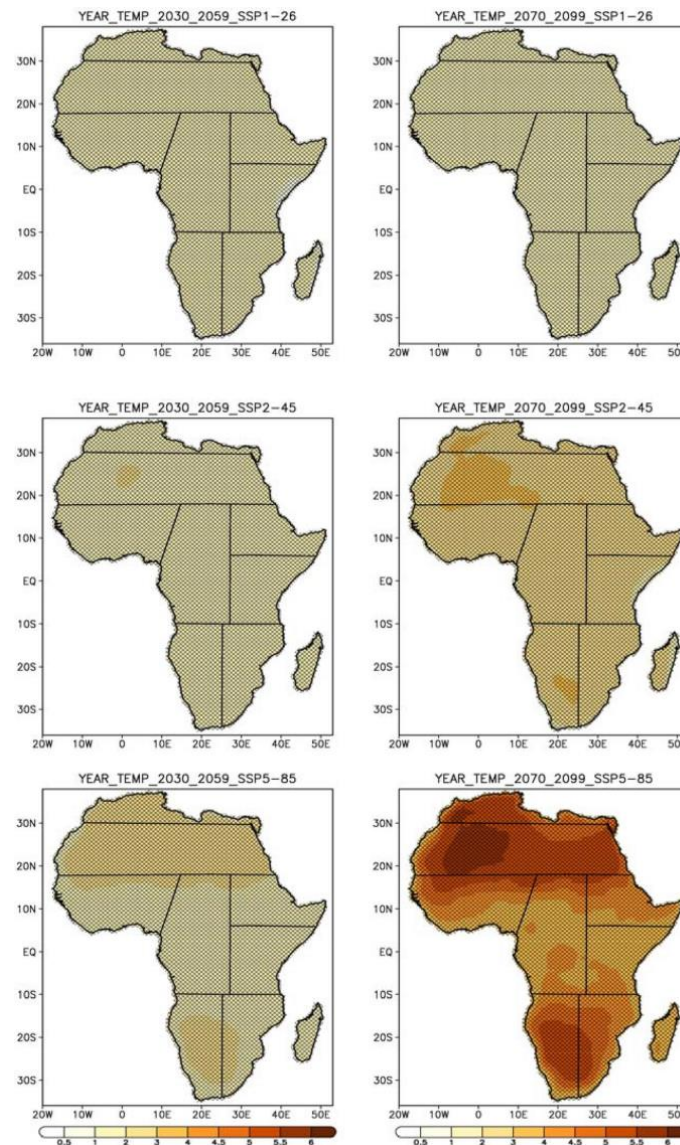


Figure 4. Future changes in mean annual temperature (°C) over Africa under three scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) for the two time periods (2030–2059 and 2070–2099) as compared with the reference period (1981–2010).

The backslash and forward slash represent the grid boxes having significant and robust change, respectively, while hatching represents the grid boxes having both significant and robust change.

Source: Almazroui et al., 2020.

For Kenya, according to the Figure 5, mean surface temperature is projected to rise across all emission scenarios by 2050, with the extent of warming depending on climate policies and mitigation efforts. In low-emission scenarios (SSP1-1.9 and SSP1-2.6), which assume strong climate action and a shift to a low-carbon economy, the median temperatures are expected to reach 26.29°C and 26.47°C, respectively. These values represent an increase of 0.59°C and 0.77°C above the historical average temperature of 25.70°C (1995–2014), indicating moderate warming due to significant emissions reductions. Under SSP2-4.5, a moderate-emission scenario, Kenya's temperature is projected to reach 26.60°C by 2050, marking a 0.90°C increase from the historical baseline. This scenario reflects partial mitigation efforts, leading to noticeable but still controlled warming. In contrast, high-emission scenarios (SSP3-

7.0 and SSP5-8.5) project more significant temperature increases. Under SSP3-7.0, the median temperature is expected to reach 26.90°C by 2050, which is 1.20°C above the historical average, while SSP5-8.5, the worst-case scenario, pushes temperatures to 27.00°C, 1.30°C higher than the historical period. These pathways assume continued fossil fuel use and limited climate mitigation, driving more substantial warming (World Bank, 2021).

Looking further ahead to 2100, the warming trend intensifies. In low-emission scenarios, where aggressive climate policies are implemented, temperatures are projected to rise more slowly, reaching 26.20°C under SSP1-1.9 and 26.51°C under SSP1-2.6, which are 0.50°C and 0.81°C higher than the historical average, respectively. These scenarios suggest a stabilized climate with effective mitigation. In SSP2-4.5, a scenario with moderate climate policies, the temperature is projected to rise to 27.42°C by 2100, a 1.72°C increase above the historical baseline, signaling continued but controlled warming. However, in high-emission scenarios, the effects of climate change become far more severe. SSP3-7.0 projects a temperature of 28.68°C by 2100, which is 2.98°C higher than the historical period, while SSP5-8.5, the most extreme scenario, leads to a dramatic increase to 29.57°C—3.87°C above historical levels. These projections indicate a future where unchecked emissions cause significant temperature rises, leading to harsher climate conditions in Kenya. Overall, the data highlights the critical role of mitigation efforts in limiting temperature increases. While low-emission scenarios keep warming below 1°C by 2100, high-emission pathways could push Kenya's temperatures nearly 4°C higher, with severe consequences for ecosystems, agriculture, and human well-being (World Bank, 2021).

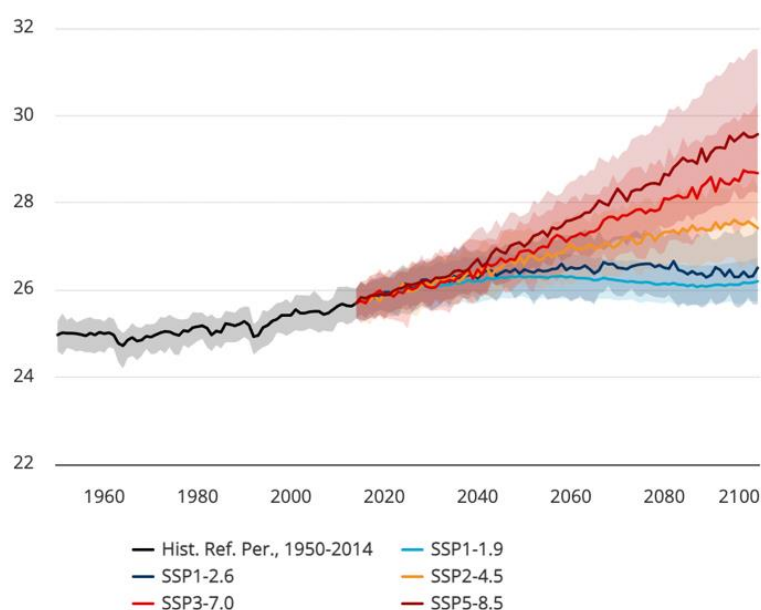


Figure 5. Projected Mean Surface Air Temperature in Kenya (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

Meanwhile, according to Figure 6, Madagascar's mean surface temperature is expected to rise under all emission scenarios by 2050, with the degree of warming largely influenced by climate policies and the effectiveness of mitigation strategies. In low-emission pathways (SSP1-1.9 and SSP1-2.6), which assume strong climate action and a transition toward

sustainability, the projected median temperatures are 23.76°C and 23.98°C, respectively. These figures represent an increase of 0.64°C and 0.86°C compared to the historical average of 23.12°C (1991–2014), indicating moderate warming controlled by stringent emission reductions. For SSP2-4.5, a mid-range emissions scenario, Madagascar's temperature is expected to reach 24.13°C by 2050, an increase of 1.01°C above the historical reference. This scenario suggests partial mitigation efforts, resulting in a measurable but still manageable rise in temperature. Conversely, in high-emission scenarios (SSP3-7.0 and SSP5-8.5), the temperature increase is more significant. SSP3-7.0 is projected to bring the median temperature to 24.25°C by 2050, which is 1.13°C above the historical period, while SSP5-8.5, the most extreme scenario, pushes the temperature up to 24.55°C—1.43°C warmer than the historical average. These projections align with continued fossil fuel dependency and minimal climate action, resulting in accelerated warming (World Bank, 2021).

Looking ahead to 2100, the warming trajectory becomes more pronounced. In low-emission scenarios, where aggressive climate policies are enacted, temperatures are expected to rise more gradually, reaching 23.67°C under SSP1-1.9 and 23.88°C under SSP1-2.6—0.55°C and 0.76°C higher than the 1991–2014 average, respectively. These pathways suggest that sustained climate mitigation efforts could help limit temperature increases. For SSP2-4.5, which assumes moderate climate policies, the projected temperature in 2100 is 24.93°C, an increase of 1.81°C above the historical average, signalling a steady but controlled warming trend. However, in high-emission scenarios, the impacts of global warming become much more severe. SSP3-7.0 anticipates a temperature of 26.34°C by 2100, exceeding the historical period by 3.22°C, while SSP5-8.5—the most extreme scenario—projects a dramatic rise to 27.32°C, which is 4.20°C higher than the historical baseline. These outcomes indicate that a lack of emission reductions would result in significant climate changes, leading to higher temperatures, increased heat stress, and broader environmental consequences for Madagascar. Overall, these projections emphasize the importance of strong mitigation efforts in limiting global temperature increases. While low-emission scenarios suggest a manageable warming of less than 1°C by 2100, high-emission pathways could elevate Madagascar's temperatures by over 4°C, posing serious threats to biodiversity, agriculture, and human livelihoods (World Bank, 2021).

For Sierra Leone, as shown in Figure 7, temperatures are projected to rise under all emission pathways by 2050, with the level of warming influenced by climate policies and mitigation strategies. In low-emission scenarios (SSP1-1.9 and SSP1-2.6), which assume ambitious climate measures and a shift toward a sustainable future, the median temperatures are expected to reach 27.35°C and 27.67°C, respectively. These values indicate an increase of 0.65°C and 0.97°C above the historical average of 26.70°C (1991–2014), suggesting moderate warming driven by effective emissions reductions. Under SSP2-4.5, a mid-range emissions scenario, Sierra Leone's median temperature is projected to rise to 27.69°C by 2050, representing a 0.99°C increase compared to the historical baseline. This scenario reflects partial climate action, which slows warming but does not entirely prevent it. By contrast, high-emission scenarios (SSP3-7.0 and SSP5-8.5) lead to substantially greater temperature increases. SSP3-7.0 forecasts a median temperature of 27.82°C, which is 1.12°C higher than the historical period, while SSP5-8.5, the most extreme pathway, pushes temperatures to 28.16°C, an increase of 1.46°C from historical levels. These scenarios assume a continued

dependence on fossil fuels and minimal climate intervention, resulting in intensified warming (World Bank, 2021).

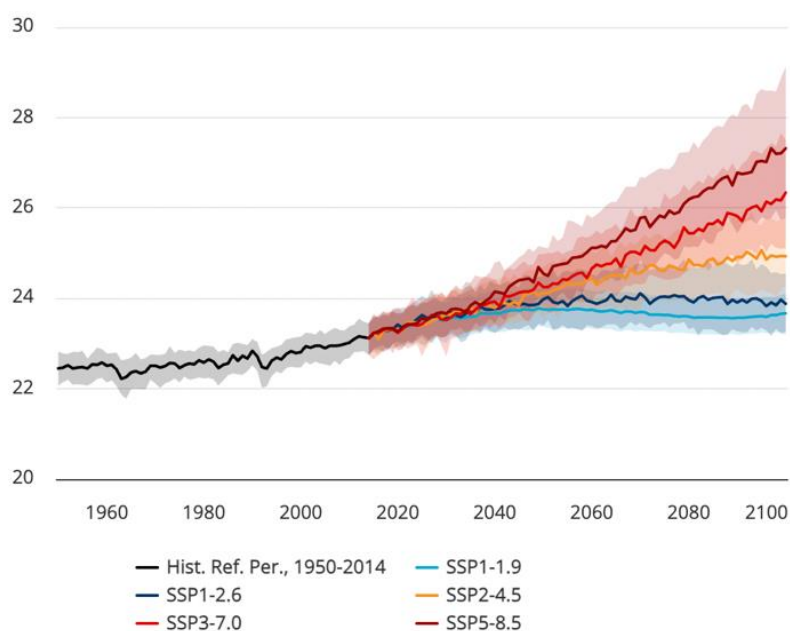


Figure 6. Projected Mean Surface Air Temperature in Madagascar (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

By 2100, the warming trend becomes even more pronounced. Under low-emission scenarios, where strong climate policies are adopted, temperatures increase more gradually, reaching 27.26°C in SSP1-1.9 and 27.50°C in SSP1-2.6, which are 0.56°C and 0.80°C above historical averages, respectively. These projections indicate that sustained mitigation efforts could help curb rising temperatures. In SSP2-4.5, which represents moderate climate action, the median temperature by 2100 is projected to be 28.73°C, an increase of 2.03°C from the historical period, signaling significant but somewhat controlled warming. However, in high-emission scenarios, the consequences become more severe. SSP3-7.0 anticipates a median temperature of 30.03°C by 2100, which is 3.33°C higher than the historical average, while SSP5-8.5, the worst-case scenario, projects an extreme rise to 31.02°C—4.32°C above historical levels. This makes Sierra Leone's temperature increase one of the highest among the three African nations examined, underscoring the urgent necessity for climate mitigation to prevent excessive warming (World Bank, 2021).

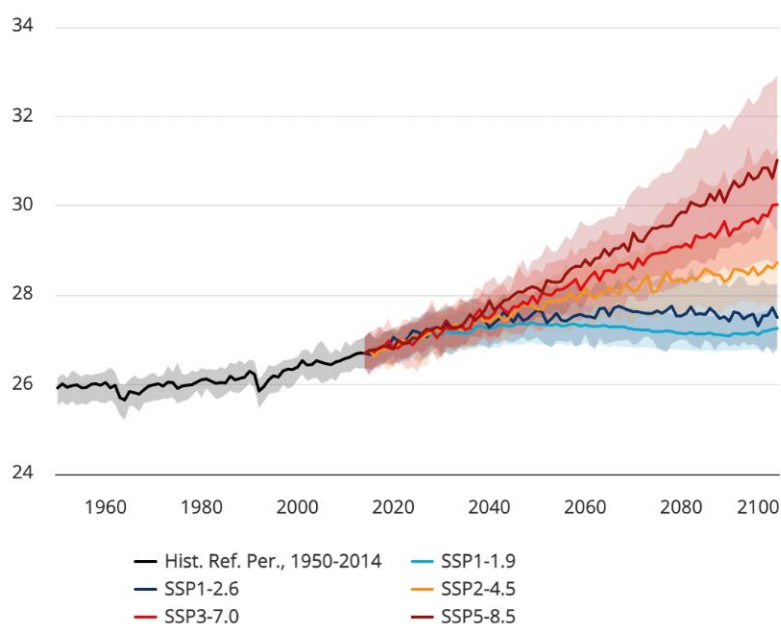


Figure 7. Projected Mean Surface Air Temperature in Sierra Leone (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

## 2. Change in Wind speed

Global wind speeds are shifting due to climate change, with wind power density declining by over 30% in mid-latitude regions like North America, Europe, and China while increasing by 20-30% in tropical and polar areas. By 2100, North America could see a 15-40% reduction, especially in Quebec and the US Great Plains, while Brazil and Southeast Asia may experience over 30% growth. This shift also increases wind power variability by 50%, making energy generation less predictable. Strategic planning in wind farm placement and grid integration will be crucial to sustaining renewable energy contributions (Martinez & Iglesias, 2024; Meehl et al., 2007).

Wind speed across Africa has exhibited significant regional variations due to climate change, with notable declines in intensity observed in parts of West and North Africa. Meanwhile, regions such as the Sahel and coastal zones are experiencing fluctuating wind patterns that influence weather dynamics, soil erosion, and the feasibility of renewable energy projects. The Sahelian belt, particularly around Dakar and the Western Sahel, has historically recorded the highest wind speeds in West and Central Africa. Analyzing ten downscaled and bias-adjusted CMIP6 models, researchers project a future increase in wind speeds, especially in coastal areas, potentially boosting wind power potential by 12–50% across most countries and by 25–100% in coastal nations (Obahoundje et al., 2024).

It is essential to mention that study by Samson and Aweda (2024) investigated wind speed variations across five major African cities—Yaoundé (Cameroon), Pretoria (South Africa), Nairobi (Kenya), Cairo (Egypt), and Abuja (Nigeria)—using Machine Learning (ML) algorithms, such as Linear regression and Random Forest. Wind data were gathered from the Solar Radiation Data Archive over the period spanning January 1, 2000, to December 31, 2022. According to the study, wind speed across major African cities exhibits significant variability, with Nairobi and Cairo emerging as the windiest locations. Nairobi recorded the highest mean

wind speed at 3.81 m/s, closely followed by Cairo at 3.61 m/s. In contrast, Yaoundé experienced the lowest mean wind speed, averaging just 1.09 m/s, indicating less favorable conditions for wind power. When analyzing maximum wind speeds, Cairo stood out with the highest recorded value of 9.73 m/s, reinforcing its potential for harnessing wind energy. On the other end of the spectrum, Yaoundé had the lowest maximum wind speed, reaching only 2.69 m/s (Samson & Aweda, 2024).

For Kenya, the IPCC Interactive Atlas, utilizing data from the Coupled Model Intercomparison Project Phase 6 (CMIP6), projects that under the SSP1-2.6 scenario, median wind speeds will remain stable at 3.9 m/s, with slight fluctuations between 3.6 and 4.3 m/s. Under the SSP5-8.5 scenario, median wind speeds are expected to decline from 4.0 m/s to 3.9 m/s by 2100, representing a 2.5% reduction (Masson-Delmotte et al., 2021).

In Kenya, offshore wind speeds are projected to increase, aligning with literature on offshore wind potential scenarios. A technological advancement scenario—which includes innovations such as floating platforms enabling access to deeper waters—greatly enhances wind resource availability. Conversely, the unimproved technology scenario remains constrained by existing shallow-water technology, limiting offshore wind utilization (Elsner, 2019). Meanwhile, onshore wind speeds in Kenya are expected to decline due to local factors. These include the weakening of the Turkana jet, driven by a reduction in thermal contrasts between the East African interior and the Indian Ocean, as well as increased surface roughness and land-use changes. In contrast, offshore wind speeds are projected to rise significantly due to intensified large-scale pressure gradients over the western Indian Ocean. These gradients amplify southeasterly winds that fuel the Turkana jet. Additionally, climate change-induced shifts in global circulation patterns may further strengthen these winds, particularly during the boreal summer, when the thermal gradient over the Indian Ocean reaches its peak (Bloomfield et al., 2022).

For Madagascar, climate projections indicate that by 2050, the region may experience an increase in the intensity of tropical cyclones, leading to higher maximum wind speeds. This is attributed to warmer sea surface temperatures, which fuel more powerful storms. Studies suggest a rise in the proportion of intense tropical cyclones (categories 4–5) with higher peak wind speeds (Muis et al., 2023).

Sierra Leone experiences a monsoon-type climate influenced by the West African monsoon system (Wadsworth et al., 2019). Changes in wind speed are closely linked to shifts in monsoon patterns, which affect rainfall and temperature. According to the study by Akinsanola et al. (2021), wind speeds in Sierra Leone are set to rise, particularly towards the latter half of the century. By mid-century (2040–2069), wind speeds in Sierra Leone are expected to increase by 0.2 to 0.6 m/s, and by late-century (2070–2099), this rise could reach 0.6 to 1.2 m/s. These projections indicate stronger and more consistent wind flows, which could have significant implications for both weather patterns and renewable energy generation in the country (Akinsanola et al., 2021).

### 3. Change in Solar radiation

Solar radiation is the primary driver of Earth's climate system, influencing weather patterns, temperatures, and ecological processes (Schmutz, 2021; Wild et al., 2005). However, climate

change is altering the way solar radiation interacts with the Earth's atmosphere and surface. As greenhouse gas emissions continue to rise, the planet experiences shift in cloud cover, atmospheric composition, and surface reflectivity, which in turn affect the distribution and intensity of solar radiation globally (IPCC, 2013).

A study by Soares et al. (2019) indicates that high levels of solar irradiance will persist across Africa. In some areas, reductions in solar irradiance are projected, particularly in northern and central-eastern Africa, where declines may reach up to  $-10 \text{ W/m}^2$  under the RCP8.5 scenario. Conversely, localized increases of up to  $+12 \text{ W/m}^2$  are expected in parts of northwestern and southern Africa. Seasonally, future changes suggest an intensified annual signal during the austral summer. A distinct dipole pattern emerges, with significant increases in solar irradiance over southern Africa, particularly in Angola ( $>+15 \text{ W/m}^2$ ;  $>+5\%$ ), while reductions are anticipated in Kenya and Tanzania, reaching approximately  $-15 \text{ W/m}^2$  ( $-10\%$ ) (Soares et al., 2019).

These variations in solar radiation across different regions are influenced by several atmospheric and environmental factors beyond temperature changes. One major factor is cloud cover and precipitation patterns. Increased cloud cover in regions like Kenya and Tanzania leads to a reduction in solar radiation, particularly during the rainy seasons. More clouds result in higher albedo (reflection of sunlight) and greater absorption of solar energy by atmospheric water droplets before reaching the surface (Soares et al., 2019). Conversely, arid regions with minimal cloud cover, such as northwestern and southern Africa, receive higher solar radiation due to clearer skies and reduced atmospheric water vapor (Kariuki & Sato, 2018).

Another important factor is atmospheric aerosols and air pollution. Aerosols, such as dust, smoke, and industrial pollutants, can scatter and absorb solar radiation. In central-eastern and northern Africa, increased dust storms (e.g., from the Sahara) and human-induced pollution reduce surface solar radiation by reflecting and absorbing sunlight before it reaches the ground. In contrast, regions with lower aerosol concentrations, such as southern Africa, allow more sunlight to reach the surface, leading to localized increases in solar radiation (IPCC, 2013).

Additionally, surface reflectivity (albedo) changes due to land cover modifications significantly influence solar radiation distribution. Deforestation and desertification, common in parts of Sahel and East Africa, increase surface albedo, reducing the absorption of solar energy and leading to localized decreases in solar radiation. Conversely, regions experiencing increased vegetation cover absorb more solar energy, leading to localized increases in solar irradiance (IPCC, 2013).

Shifts in atmospheric circulation also play a critical role in solar radiation distribution. Large-scale climate patterns such as the Intertropical Convergence Zone (ITCZ) affect cloud formation and precipitation, impacting solar radiation levels differently across regions. For example, Angola experiences increased solar radiation due to shifts in circulation patterns that reduce cloud cover, while Kenya and Tanzania experience reductions due to increased convective activity (Soares et al., 2019).

Finally, elevation and topography influence how solar radiation is received. Higher-altitude regions receive more direct solar radiation because the atmosphere is thinner and absorbs less energy. This explains why some highland areas may still experience increased solar radiation despite surrounding climate trends (Kariuki & Sato, 2018).

#### 4. Change in Precipitation

Climate change alters precipitation patterns by intensifying the Earth's water cycle. Higher temperatures increase evaporation, leading to stronger and more frequent storms that bring heavier rainfall and a greater risk of flooding. Conversely, areas far from storm tracks may receive less precipitation, increasing the likelihood of droughts (NASA Global Precipitation Measurement, n.d.).

This variability is especially evident in Africa, where climate change is driving significant regional differences in precipitation patterns. In West Africa, coastal regions are projected to see increased rainfall, while inland areas, including parts of the Sahel, are expected to experience longer dry spells and heightened drought risks (Ndehedehe et al., 2021). Central Africa has witnessed a decrease in wet-season precipitation and a slight increase in dry-season rainfall, particularly in coastal areas (Tokpa et al., 2023). In East Africa, precipitation trends vary widely. Some regions, particularly near the equator and the Somali coast, are projected to experience more rainfall, while Ethiopia and the Sudan region are likely to see a decline (Souverijns & Thiery, 2016). Southern Africa is experiencing more frequent droughts, especially in winter, with an overall decline in precipitation projected over time (Banze et al., 2018). Meanwhile, North Africa is seeing a general drying trend, with desertification worsening due to reduced rainfall (Meyer et al., 2013).

For Kenya, as illustrated in Figure 8, precipitation levels are expected to increase across all emission scenarios by 2050, with variations depending on emission levels and climate policies. In low-emission scenarios (SSP1-1.9 and SSP1-2.6), which assume strong mitigation efforts and a transition toward sustainability, projected median precipitation levels are 777.97 mm and 793.53 mm, respectively. These values indicate an increase compared to the historical period (1991–2014), suggesting moderate wetting trends under these pathways. Under SSP2-4.5, a mid-range emissions scenario, the median precipitation is projected to be 764.26 mm by 2050, showing a slight deviation from historical levels. This scenario reflects partial mitigation, resulting in relatively stable precipitation patterns. In contrast, high-emission scenarios (SSP3-7.0 and SSP5-8.5) project more significant changes. SSP3-7.0 estimates median precipitation at 761.61 mm, while SSP5-8.5 forecasts the highest increase, with 855.00 mm by 2050. These figures suggest that higher emissions may lead to increased rainfall variability, with more extreme wet and dry periods (World Bank, 2021).

By 2100, precipitation trends continue to evolve. Under SSP1-2.6, precipitation is expected to reach 770.59 mm, reflecting a minor increase of 1.44 mm compared to the historical period (769.15 mm, 1991–2014), indicating a relatively stable climate with only slight variations. Under SSP2-4.5, precipitation is projected to increase to 854.78 mm by 2100, which is 85.63 mm above the historical average, highlighting a noticeable shift toward wetter conditions. In high-emission scenarios, precipitation changes become more pronounced. SSP3-7.0 projects a median precipitation of 886.71 mm by 2100, which is 117.56 mm higher than the historical average, while SSP5-8.5, the most extreme scenario, anticipates an increase to 1001.52 mm—

232.37 mm above historical levels. These pathways indicate that under continued high emissions, Kenya could experience more intense rainfall events, increasing the risk of floods and seasonal variability (World Bank, 2021).

Overall, these projections underscore the significant role of emissions pathways in shaping precipitation trends. While low-emission scenarios suggest relatively stable rainfall levels, high-emission scenarios could lead to more extreme precipitation changes, with potential consequences for water resources, agriculture, and flood risks (World Bank, 2021).

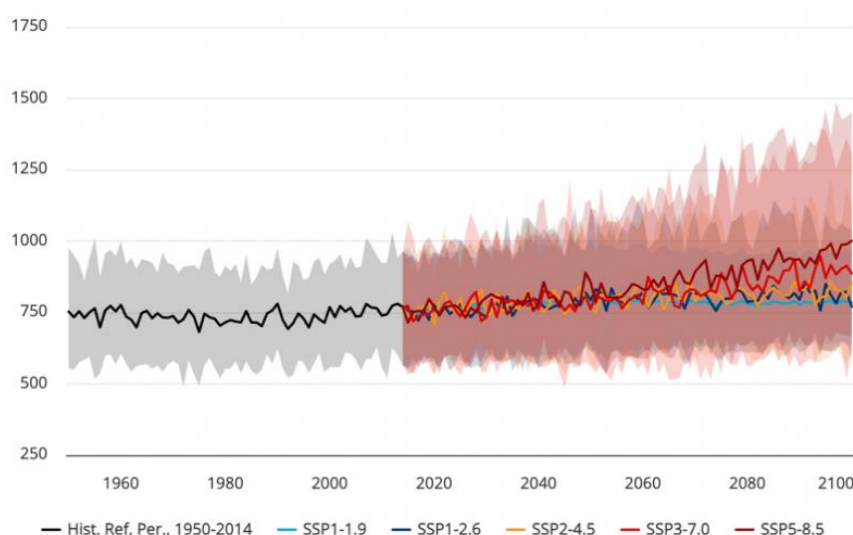


Figure 8. Projected Precipitation in Kenya (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

For Madagascar, as shown in Figure 9, precipitation levels are expected to fluctuate across different emission pathways by 2050, with the extent of change influenced by climate policies and greenhouse gas levels. In low-emission scenarios (SSP1-1.9 and SSP1-2.6), which assume strong climate action and substantial mitigation measures, median precipitation is projected to be 1,395.73 mm and 1,360.86 mm, respectively. These values indicate relatively minor variations from the historical period (1991–2014), suggesting that rainfall patterns will remain fairly stable under these pathways. For SSP2-4.5, a moderate-emission scenario, the projected median precipitation is 1,377.40 mm by 2050, representing a slight reduction compared to the historical baseline. This scenario reflects partial climate mitigation, resulting in minor changes to rainfall distribution. On the other hand, high-emission scenarios (SSP3-7.0 and SSP5-8.5) indicate more substantial shifts in precipitation. SSP3-7.0 projects a median precipitation of 1,429.28 mm, while SSP5-8.5 forecasts 1,416.33 mm by 2050. These figures suggest that higher emissions could lead to increased rainfall variability, with the potential for both wetter and drier periods (World Bank, 2021).

Looking ahead to 2100, precipitation trends show further changes. Under SSP1-2.6, rainfall is projected to decrease slightly to 1,374.54 mm, which is 18.23 mm lower than the historical period (1,392.77 mm, 1991–2014), indicating a relatively steady climate with minimal long-term changes. Under SSP2-4.5, precipitation is expected to decline further, reaching 1,312.85 mm by 2100, a 79.92 mm reduction from the historical average, pointing to a noticeable

drying trend under moderate emissions scenarios. In high-emission pathways, precipitation trends are less predictable. SSP3-7.0 projects a median precipitation of 1,386.79 mm by 2100, reflecting a minor decline of approximately 6 mm from historical levels, while SSP5-8.5 anticipates an increase to 1,396.71 mm—about 4 mm above the historical baseline. These findings suggest that under continued high emissions, rainfall patterns could become more erratic, potentially disrupting water resources and agricultural activities (World Bank, 2021).

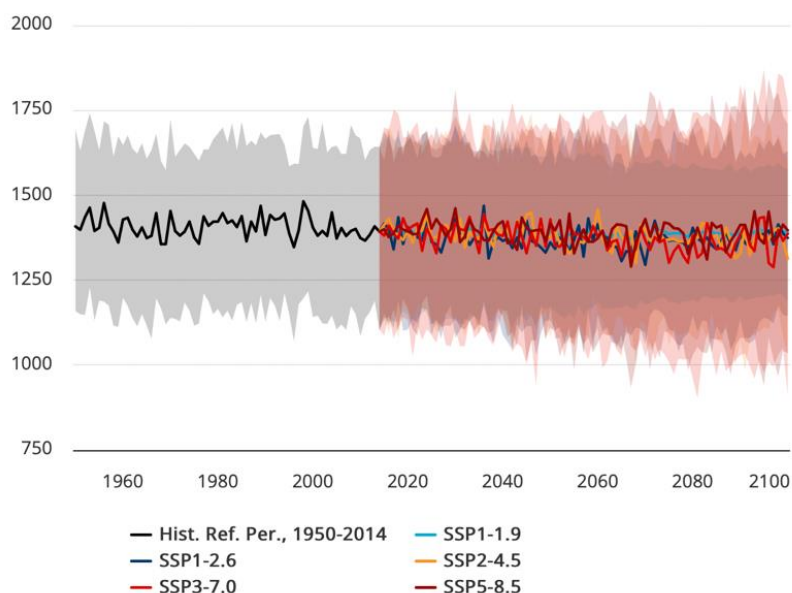


Figure 9. Projected Precipitation in Madagascar (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

The contrasting trends in Madagascar's precipitation under different SSPs arise from the complex interplay of ocean-atmosphere interactions. Lower-emission scenarios are associated with drying trends due to weakened moisture transport, whereas extreme warming in high-emission scenarios enhances monsoonal rainfall and tropical cyclone intensity, leading to localized precipitation increases (Arivelo & Lin, 2016; Lim Kam Sian et al., 2021; Tiger et al., 2023).

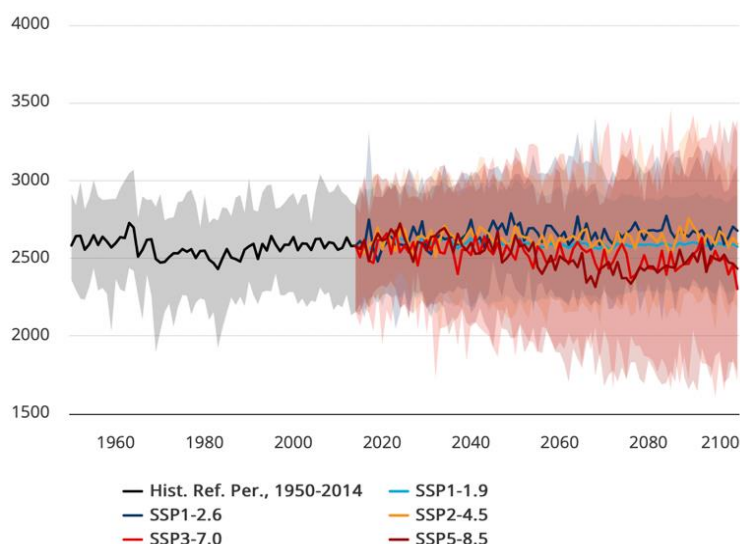


Figure 10. Projected Precipitation in Sierra Leone (1995–2014 Baseline) based on Multi-Model Ensemble.

Source: World Bank, 2021.

For Sierra Leone, as shown in Figure 10, precipitation patterns are projected to shift across different emissions scenarios by 2050, with variations depending on climate policies and greenhouse gas concentrations. In low-emission scenarios (SSP1-1.9 and SSP1-2.6), which assume ambitious mitigation strategies and sustainable development, median precipitation is expected to reach 2,621.84 mm and 2,701.42 mm, respectively. These values suggest a slight increase compared to the historical period (1991–2014), indicating that rainfall amounts may remain relatively steady under effective climate policies. For SSP2-4.5, a mid-range emissions scenario, precipitation levels are projected to reach 2,707.66 mm by 2050, reflecting a small rise compared to the historical average. This scenario indicates moderate mitigation efforts, resulting in only slight fluctuations in precipitation. In contrast, high-emission scenarios (SSP3-7.0 and SSP5-8.5) present more significant variations. SSP3-7.0 projects a median precipitation of 2,492.06 mm, whereas SSP5-8.5 anticipates 2,647.85 mm by 2050. These projections suggest that higher emissions could contribute to increased rainfall variability, affecting seasonal wet and dry periods (World Bank, 2021).

By 2100, precipitation patterns are expected to shift further. Under SSP1-2.6, rainfall is estimated to rise to 2,677.65 mm, marking an increase of 96.97 mm from the historical average (2,580.68 mm, 1991–2014), signifying a moderate increase in precipitation under a low-emission pathway. For SSP2-4.5, precipitation is expected to experience a minor increase, reaching 2,591.60 mm by 2100, a 10.92 mm rise compared to historical levels, indicating relatively stable rainfall trends. However, in high-emission scenarios, precipitation levels are projected to decline. SSP3-7.0 forecasts median precipitation of 2,303.41 mm by 2100, indicating a notable reduction of 277.27 mm from historical records, while SSP5-8.5 estimates 2,433.91 mm, representing a decrease of 146.77 mm relative to historical averages. These projections suggest that continued high emissions could lead to drier conditions, potentially disrupting water availability and agricultural productivity (World Bank, 2021).

The reason behind Sierra Leone's shifting precipitation trends lies in the complex interactions between rising temperatures, atmospheric moisture, and monsoonal patterns. Under lower-

emission scenarios (SSP1-2.6 and SSP2-4.5), increased evaporation and shifts in the West African Monsoon contribute to slight rainfall increases. In contrast, higher-emission scenarios (SSP3-7.0 and SSP5-8.5) are expected to disrupt atmospheric circulation, reducing moisture convergence and leading to long-term drying. Additionally, while greenhouse gases intensify the hydrological cycle, aerosols from human activities can suppress rainfall (Taylor et al., 2014; Wadsworth et al., 2019).

#### 5. Change in Inflow (Rainfall)

Since the 1980s, Africa has experienced persistent arid conditions, with notable shifts in rainfall patterns. The 1990s remained drier than the long-term average, particularly in the Sahel and equatorial regions. While some areas, like the western Sahel, saw partial recovery in the 2000s, drought conditions continued across much of the continent. In East Africa, the October–December "short rains" have shown increasing variability, influenced by large-scale climate drivers such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). A strong positive IOD often brings wetter conditions, while a negative phase is linked to drier years. However, extreme rainfall events, such as in 1997 and 2019, highlight the unpredictable nature of these patterns. The Indian Ocean remains the dominant moisture source, though the Congo Basin also plays a role, particularly in western East Africa. Despite occasional wet years, such as 2010 and 2012, long-term drying trends persist, especially in the March–May season. Forecasting localized rainfall remains a challenge due to the complex interplay of climatic drivers, topography, and atmospheric circulation. While climate models can predict broad trends, geographical rainfall variability remains difficult to anticipate, affecting agriculture and water resources across the continent (Kolstad et al., 2024; Nicholson et al., 2018).

Specifically for Kenya, Regional Climate Models (RCMs) predict an increase in extreme rainfall events during the March–April–May (MAM) wet season, whereas a decrease is projected for the October–November–December (OND) season (Ouédraogo et al., 2019). Additionally, increased streamflow in Kenya's river basins is expected, driven by intensified rainfall extremes (Odworí, 2022). However, long-term trends indicate a risk of increased dry spells, which will require enhanced water management strategies (Langat et al., 2017).

Meanwhile, rainfall in Madagascar has been declining over the past few decades, particularly in southern regions, leading to drought conditions (Lim Kam Sian et al., 2021). Under future climate change scenarios, Madagascar is projected to experience more frequent dry years, especially under high-emission pathways (Bobde et al., 2024). The Mozambique Channel Trough has also been linked to changes in Madagascar's precipitation, affecting seasonal rainfall patterns (Barimalala et al., 2018).

Sierra Leone, located in West Africa, experiences a monsoon climate heavily influenced by the West African Monsoon (WAM). Studies indicate a decreasing trend in rainfall, particularly in the northwest, which could impact agricultural productivity (Wadsworth et al., 2019). Despite the general decline, El Niño events have contributed to extreme rainfall variability, increasing the frequency of flood events in certain areas (Bobde et al., 2024).

## 6. Change in land use

Climate change has significantly influenced land use patterns in Africa, driving changes in agricultural practices, urbanization trends, and deforestation rates. Rising temperatures, changing precipitation patterns, and extreme weather events have intensified land degradation and altered traditional land-use systems. Large-scale land acquisitions by foreign investors, combined with climate-induced pressures, have further transformed land tenure systems, affecting local livelihoods and food security (Haller et al., 2019). Additionally, climate change has exacerbated soil degradation and desertification, leading to unsustainable land use practices (Bullock et al., 2021).

Kenya has witnessed severe impacts of climate change on land use, with increased drought frequency and erratic rainfall patterns driving shifts in agricultural practices. In the Mt. Kenya region, reduced rainfall has led to a decline in traditional farming areas, while expanding cropland has resulted in deforestation and soil erosion (Willkomm et al., 2016). Furthermore, climate-induced variability has intensified pastoral conflicts over dwindling grazing lands, particularly in dryland regions like Baringo, where bush encroachment and land degradation threaten livelihoods (Greiner et al., 2021).

Madagascar's land use has been heavily affected by climate change, particularly in the form of increasing droughts and deforestation. The rising temperatures and declining rainfall have accelerated desertification in the southern region, leading to reduced agricultural productivity and forced migration (Tiandraza et al., 2023). Climate-induced changes have also contributed to the loss of biodiversity, with deforestation driven by shifting cultivation and illegal logging worsening the situation (Bobde et al., 2024).

Sierra Leone has experienced notable land use changes due to climate change, particularly in coastal and urban regions. Rising sea levels and increased flooding events have displaced communities, leading to urban expansion into previously undeveloped areas. Additionally, extreme weather events have contributed to soil erosion and agricultural land degradation, impacting food security and rural livelihoods. Poor environmental governance has further exacerbated the vulnerability of land resources, making adaptation strategies more challenging (Gbanie et al., 2015).

## 7. Change in extreme events

Africa has experienced increasing extreme weather events, particularly in regions prone to droughts and flooding. East Africa has seen a notable rise in temperature extremes and erratic rainfall patterns, affecting water resources and food security (Gebrechorkos et al., 2018). Future projections indicate an increase in extreme rainfall and longer drought periods, contributing to more frequent and severe climate-related disasters (Ayugi et al., 2022).

As mentioned above, Kenya has witnessed significant changes in climate extremes, particularly in increased incidences of droughts and floods. Studies show that prolonged droughts are more frequent in Kenya's arid and semi-arid lands, affecting agricultural productivity and water availability (Marthews et al., 2019). Additionally, rising temperatures and unpredictable rainfall patterns have exacerbated food insecurity, requiring urgent adaptation measures (Haile et al., 2020).

Meanwhile, Madagascar is highly vulnerable to tropical storms and cyclones, with climate change intensifying their frequency and intensity. The southeastern coast is particularly prone to economic losses due to these events, necessitating robust adaptation strategies (Molua et al., 2020). Additionally, recent studies indicate that Madagascar has experienced prolonged dry spells, leading to increased food and water insecurity (Humphries et al., 2020).

Sierra Leone has seen increased flooding due to erratic rainfall patterns, exacerbated by climate change. Data from the past few decades indicate that extreme rainfall events have become more common, leading to displacement and infrastructure damage (Wadsworth et al., 2019). Furthermore, increased storm surges threaten coastal communities, with rising sea levels further amplifying flood risks (Pietroiusti et al., 2024).

## 2.3 Renewable resources potential in Africa

### 1. Current energy potential for Africa

Africa's energy mix is still predominantly reliant on fossil fuels, with coal, oil, and natural gas accounting for approximately two-thirds of the continent's electricity generation. However, renewable energy adoption is increasing, driven by investments in hydro, solar, wind, and geothermal power (Kazimierczuk, 2019).

Africa's total energy supply in 2023 was approximately 33,330 PJ (International Energy Agency, 2023). According to the Figure 10, Africa's energy supply remains heavily reliant on biofuels and waste (39.3%), primarily used for cooking and heating, though it raises concerns about deforestation and air pollution.

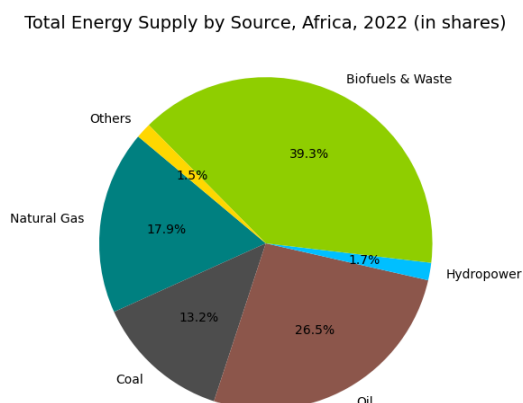


Figure 11. Total energy supply in Africa, 2022.

Source: International Energy Agency, 2023.

Oil (26.5%) dominates transport and industry, while natural gas (17.9%) is expanding, especially for electricity generation. Coal (13.2%), mainly used in South Africa, continues to be a key power source despite environmental concerns. Renewables play a minor role, with hydropower (1.7%) contributing to electricity but affected by climate variability. Other sources (1.5%), including solar, wind, and geothermal, remain underdeveloped despite Africa's vast potential (International Energy Agency, 2023).

The total electricity generation capacity in Africa reached 246 GW in 2023, reflecting a 4% increase from the previous year (BloombergNEF, 2024). Renewable energy capacity, including hydro, solar, and wind, accounted for 72 GW, marking substantial progress in the sector. Despite these improvements, renewable energy investment in Africa accounted for only 2.3% of the global total in 2023, although it more than doubled compared to the previous year (BloombergNEF, 2024). In 2022, Africa generated 905,136 GWh of electricity (International Energy Agency, 2023).

According to Figure 12, by 2023, natural gas holds the largest share in both installed capacity (42.5%, as shown in Figure 12a) and actual electricity generation (39.4%, as shown in Figure 12b) in Africa. Coal, while making up 20.8% of capacity, contributes a higher share of generation at 28.3%, indicating greater utilization. Hydropower also plays a key role, accounting for 16.0% of capacity and 20.2% of actual generation (BloombergNEF, 2024).

Electricity Generation Capacities, Africa, 2023 (in shares) Electricity Generation Sources, Africa, 2023 (in shares)

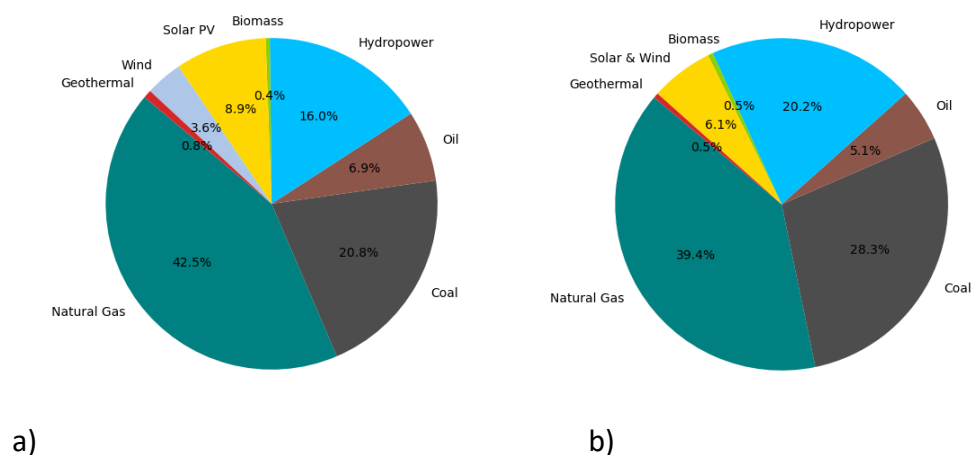


Figure 12. Electricity Generation Capacities (a) and Actual Generation Sources (b) in Africa, 2023.

Source: BloombergNEF, 2024.

Renewable sources, including solar and wind, represent 8.9% of installed capacity but only 6.1% of actual generation, suggesting lower efficiency or intermittency challenges. Oil, geothermal, and biomass have smaller shares in both capacity and generation. Overall, the figure highlights Africa's continued reliance on fossil fuels, despite increasing renewable energy capacity (BloombergNEF, 2024).

## 2. Current energy potential for Kenya

Kenya's total energy supply in 2023 was approximately 1,257 PJ (International Energy Agency, 2023). According to the Figure 13, Kenya's energy supply is dominated by biofuels and waste (61.4%), reflecting heavy reliance on biomass for household use, despite environmental concerns. Renewables (18.0%), led by geothermal, solar, and wind, play a growing role, showcasing Kenya's clean energy transition. Oil (16.8%) remains essential for transport and industry, while coal (3.0%) has a minimal presence (International Energy Agency, 2023).

As of 2023, Kenya's installed electricity capacity reached 3,321 MW, nearly doubling from 1,800 MW in 2014. Despite this growth, it remains insufficient for a population exceeding 50

million (International Trade Administration, 2024). It is essential to emphasize that in 2023, Kenya generated 12,703 GWh of electricity (International Energy Agency, 2023).

According to the Figure 14a, Kenya's electricity generation capacity in 2023 was dominated by hydropower (39%) and geothermal energy (23%), highlighting the country's reliance on renewable sources. Solar PV (13%) and wind (9%) have also emerged as significant contributors, showcasing the growing adoption of clean energy technologies. Fossil fuels, including oil and gas (12%), still play a role but are considerably lower compared to renewables. Biomass makes up a small fraction (4%) of the total capacity (BloombergNEF, 2024).

Total Energy Supply by Source, Kenya, 2023 (in shares)

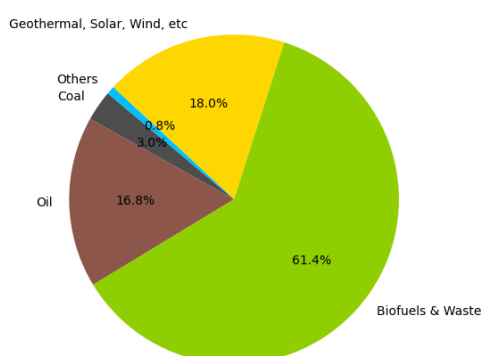
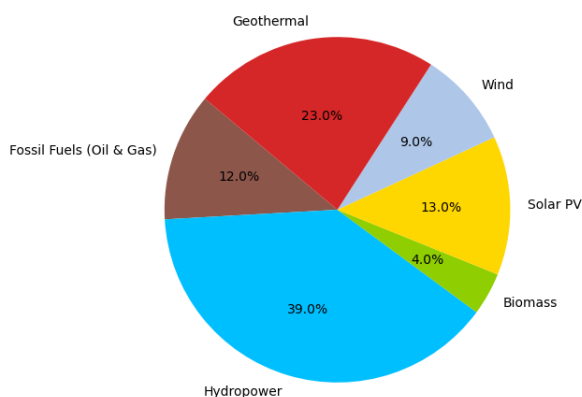


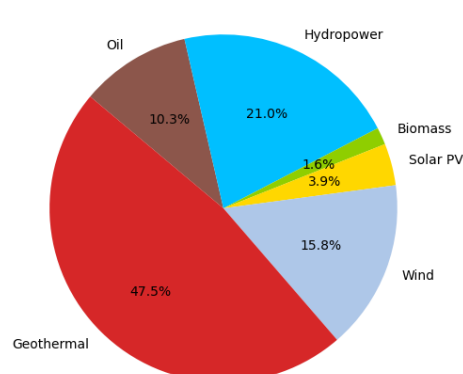
Figure 13. Total Energy Supply, Kenya, 2023.  
Source: International Energy Agency, 2023.

According to the Figure 14b, Kenya's electricity generation is predominantly powered by renewable energy sources, with geothermal contributing the largest share at 47.5%. Hydropower follows at 21.0%, while wind energy accounts for 15.8%. Fossil fuels, represented by oil, make up 10.3% of the generation mix, indicating some reliance on non-renewable energy. Additionally, solar PV (3.9%) and biofuels (1.6%) contribute smaller portions to the overall electricity generation (International Energy Agency, 2023).

Electricity Generation Capacities, Kenya, 2023 (in shares) Electricity Generation Sources, Kenya, 2023 (in shares)



a)



b)

Figure 14. Electricity Generation Capacities (a) and Actual Generation Sources (b) in Kenya, 2023.

Source: BloombergNEF, 2024; International Energy Agency, 2023.

### 3. Current energy potential for Madagascar

Total energy supply in Madagascar for 2022 was 393,354 TJ. According to the Figure 15, biofuels and waste dominated the energy mix, accounting for 85.2%, highlighting the country's heavy reliance on traditional biomass like firewood and charcoal. Oil (11.5%) played a key role in transportation and industry, while coal (2.5%) contributed a smaller share. Hydropower (0.8%) remained underutilized despite Madagascar's renewable energy potential. This energy profile underscores a strong dependence on traditional fuels, emphasizing the need for a transition toward more sustainable sources such as hydro, solar, and wind.

As of 2023, Madagascar's installed electricity capacity is approximately 759 megawatts (MW), with 244 MW (about 35%) derived from renewable sources such as hydroelectric and solar power (countryeconomy.com, 2024). However, another source estimates that renewables account for about 32% of the total capacity in 2023 (TheGlobalEconomy.com, 2025).

Total Energy Supply by Source, Madagascar, 2022 (in shares)

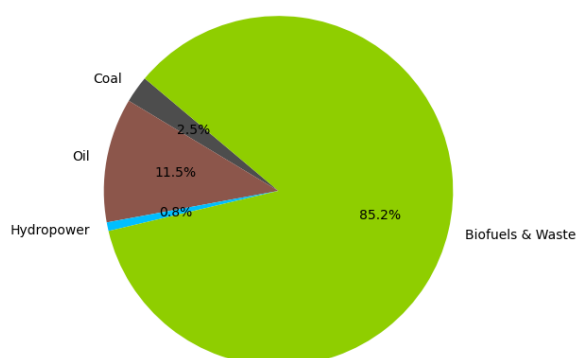


Figure 15. Total Energy Supply, Madagascar, 2022.

Source: International Energy Agency, 2022.

The Figure 16a illustrates Madagascar's electricity generation capacities by energy source in 2023. Fossil fuels (oil & gas) dominate with 68.4% of total capacity, equating to 520 MW. Hydropower accounts for 25% (190 MW), while solar PV contributes 6.6% (50 MW). This breakdown highlights the country's heavy reliance on fossil fuels, with renewables making up just under one-third of total capacity (TheGlobalEconomy.com, 2025).

Meanwhile, according to the Figure 16b, Madagascar's total electricity generation reached 2,611 GWh in 2022, with a mix of fossil fuels and renewables. According to Figure 16b, oil was the dominant source, contributing 46.1% (1,203 GWh), followed by hydropower at 31.5% (822 GWh), playing a crucial role in renewable energy production. Coal accounted for 19.5% (509 GWh), while solar PV made up a modest 2.0% (53 GWh). Other sources, including biofuels, contributed just 0.9% (24 GWh) (International Energy Agency, 2022).

Electricity Generation Capacities, Madagascar, 2023 (in shares) Electricity Generation Sources, Madagascar, 2022 (in shares)

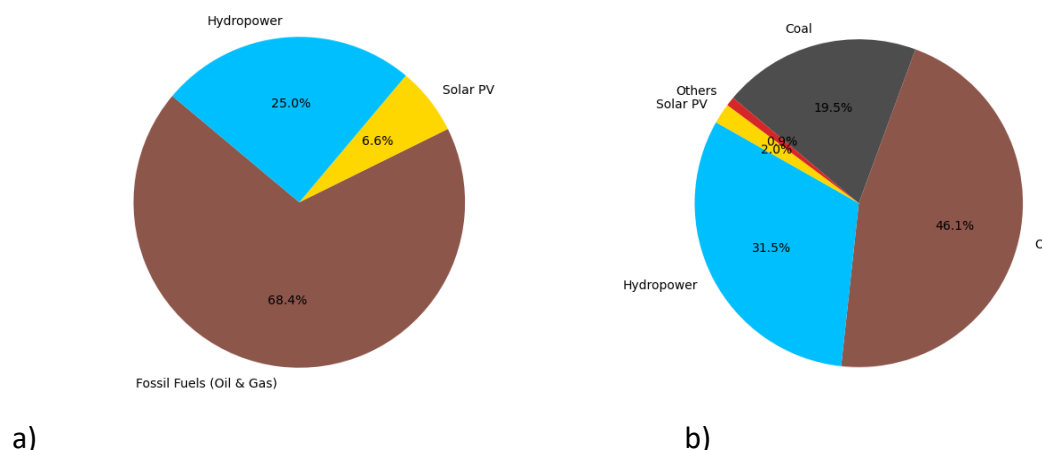


Figure 16. Electricity Generation Capacities (a), 2023 and Actual Generation Sources (b) in Madagascar, 2022.

Source: TheGlobalEconomy.com, 2025; International Energy Agency, 2022.

#### 4. Current energy potential for Sierra Leone

As of 2021, according to the Figure 17, Sierra Leone's total energy supply is approximately 74,663 TJ, with renewable sources contributing about 76% of this supply, which is 56 690 TJ (IRENA, 2024).

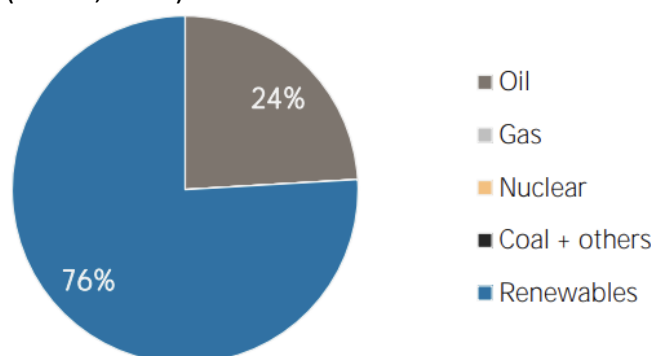


Figure 17. Total Energy Supply, Sierra Leone, 2021.

Source: IRENA, 2024.

According to the Figure 18a, Sierra Leone's electricity generation capacity in 2023 is primarily dominated by Oil & Diesel, which accounts for 56.2% (113 MW) of the total 201.1 MW capacity. Hydropower follows as the largest renewable source, contributing 30.9% (62.1 MW). Biomass makes up 7.5% (15 MW), while solar PV represents the smallest share at 5.5% (11 MW). This distribution indicates that while renewables constitute about 44% of the total capacity, the country remains heavily reliant on fossil fuels for electricity generation (BloombergNEF, 2024).

Meanwhile, the Figure 18b illustrates Sierra Leone's electricity generation mix for 2023 in shares and gigawatt-hours (GWh). Oil & Diesel dominates with 51.0% (237 GWh), reflecting the country's strong dependence on fossil fuels. Hydropower follows closely, contributing 44.7% (208 GWh), making it the primary renewable energy source. Solar PV accounts for 3.4% (16 GWh), while Biomass represents the smallest share at 0.9% (4 GWh). Despite

hydropower's substantial role, fossil fuels remain the leading source of electricity generation (BloombergNEF, 2024; Kiley et al., 2024).

Electricity Generation Capacities, Sierra Leone, 2023 (in shares) Electricity Generation Sources, Sierra Leone, 2023 (in shares)

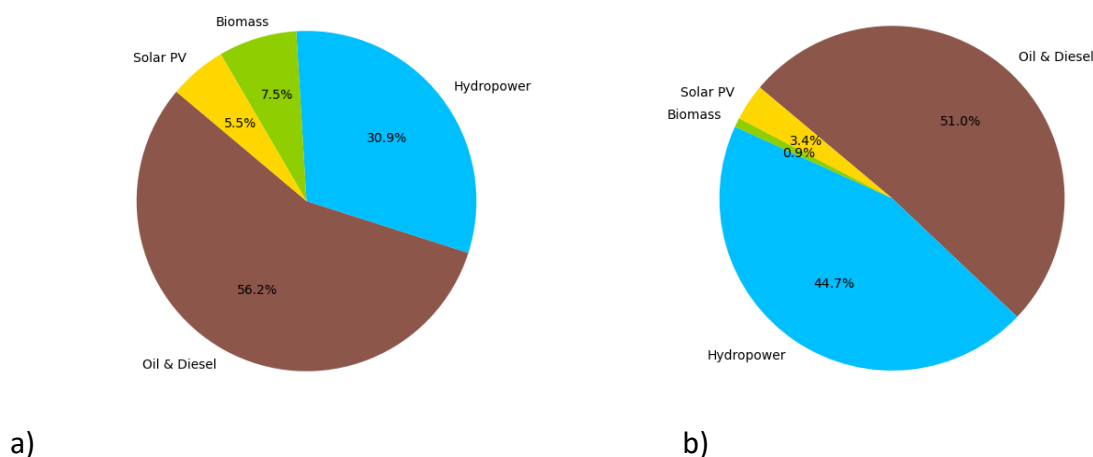


Figure 18. Electricity Generation Capacities (a) and Actual Generation Sources (b) in Sierra Leone, 2023.

Source: BloombergNEF, 2024.

A key contributor to Sierra Leone's non-renewable electricity generation is the Karadeniz Powership Doğan Bey, a floating power plant operated by Karpowership. The powership has an installed capacity of 126 MW, but its actual power supply varies due to contractual agreements and operational constraints (Karpowership, 2023). In Sierra Leone, its effective operational output has been reported at 66 MW in 2022, with actual electricity generation fluctuating based on fuel availability and financial conditions (Kiley et al., 2024).

The powership has played a critical role in stabilizing the country's electricity supply, particularly during the dry season when hydropower production declines. It historically generated 246,712 MWh (246.7 GWh) annually, increasing to 261,177 MWh (261 GWh) in 2022, before declining to 232,246 MWh (232 GWh) in 2023 due to financial constraints. However, unpaid arrears have at times forced the powership to reduce its supply, prioritizing electricity for essential services while non-essential consumers, including industries and households, faced power cuts (Kiley et al., 2024).

The powership operates at an average efficiency of 35%, meaning that only 35% of the fuel energy input is converted into usable electricity. This is significantly lower than renewable energy sources, highlighting the economic and environmental challenges associated with fossil fuel-based generation. Moreover, the reliance on imported Heavy Fuel Oil (HFO) increases the cost burden on Sierra Leone's energy sector, making long-term sustainability a concern (Kiley et al., 2024).

The reliance on the Karadeniz Powership Doğan Bey demonstrates the necessity of diversifying energy sources to ensure stability and sustainability in electricity generation. While Sierra Leone has vast renewable energy potential, including solar, bioenergy, and hydropower expansion projects, the country still depends on imported fossil fuel-based electricity during seasonal fluctuations. Strategic investments in energy storage, grid

infrastructure, and additional renewable capacity will be critical in reducing reliance on temporary thermal power solutions and achieving a more resilient and self-sufficient energy system (IRENA, 2024; Kiley et al., 2024). However, according to Kiley et al. (2024), the Karadeniz Powership Doğan Bey, which has been supplying 66 MW to Sierra Leone by 2023, will have zero capacity allocated to the country by 2026. This loss will significantly impact Sierra Leone's electricity mix, given that fossil fuel-based generation currently constitutes over 50% of total installed capacity (Kiley et al., 2024).

## 5. Projected renewable energy potential

### 1. Projected renewable energy potential for Africa

Africa receives some of the highest levels of solar radiation globally, averaging between 3 and 7 kWh/m<sup>2</sup>/day. Studies using high-resolution climate models indicate that solar power potential remains consistently high across the continent, though climate change may lead to a slight decrease of up to 4% in solar radiation in some regions (Bichet et al., 2019). However, the decrease is not expected to significantly impact the viability of large-scale solar projects. Another study suggests that photovoltaic power potential (PVP) might decline by approximately 2%, while concentrated solar power output (CSPOUT) could increase by the same percentage, particularly under scenarios with lower carbon emissions (Sawadogo et al., 2021).

As shown in Figure 19, Africa holds a huge theoretical potential for renewable energy, but its renewable energy landscape presents a noticeable contrast between theoretical potential and relatively modest installed capacity. Solar photovoltaics (PV) stand out as the continent's most promising renewable energy resource, with an estimated theoretical potential of 1,449,742 terawatt-hours per year (TWh/y) as of 2020 (IRENA, GIZ, and KfW Development Bank, 2021). This extraordinary figure is supported by Africa's favorable solar radiation levels, averaging between 3 and 7 kWh/m<sup>2</sup>/day. High-resolution climate studies confirm that solar potential remains consistently strong across the continent, with only minor projected reductions of up to 4% in some regions due to climate change—insufficient to threaten the viability of large-scale solar projects (Bichet et al., 2019; Sawadogo et al., 2021). Nevertheless, by 2019, the installed solar capacity was only 7,234 megawatts (MW), translating to around 63.4 TWh/y in theoretical output—merely a fraction of the continent's vast solar promise (IRENA, GIZ, and KfW Development Bank, 2021).

Wind energy similarly shows enormous theoretical potential, estimated at 978,066 TWh/y. However, installed capacity in 2019 amounted to just 5,753 MW, corresponding to approximately 50.4 TWh/y in theoretical generation. This highlights a significant underutilization of wind resources, especially considering favorable wind corridors along North and East Africa's coasts and parts of West Africa (IRENA, GIZ, and KfW Development Bank, 2021; Ndiaye et al., 2022). Encouragingly, climate models predict up to a 20% increase in wind power density in some areas, which could further bolster future opportunities (Sawadogo et al., 2021).

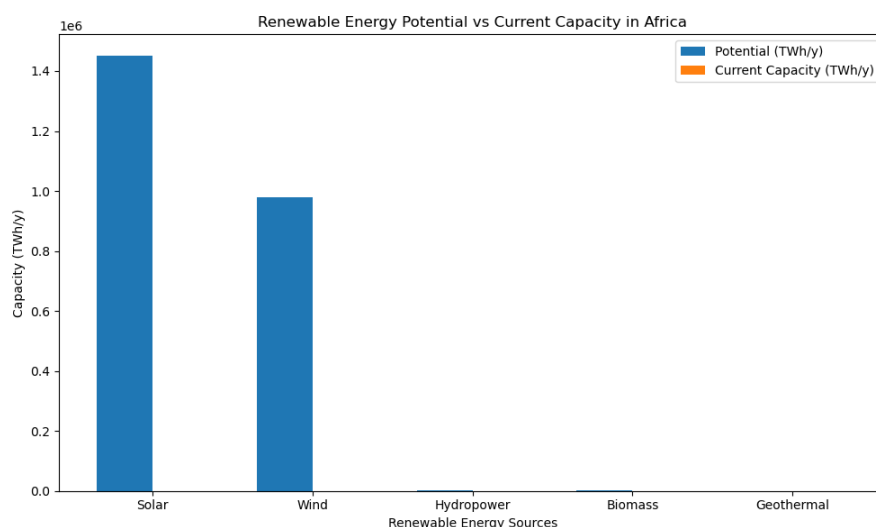


Figure 19. Renewable Resource Potential vs Current Capacity in Africa.

Source: IRENA, GIZ, and KfW Development Bank, 2021.

Hydropower, long recognized as a key element in Africa's renewable energy mix, offers a theoretical potential of about 1,478 TWh/y. By 2019, installed capacity reached 35,754 MW, theoretically capable of generating around 313.2 TWh/y. Although hydropower is relatively better developed than other renewables, nearly 90% of its potential remains untapped (IRENA, GIZ, and KfW Development Bank, 2021). Future hydropower expansion is critical, with projections indicating the need for an additional 40 GW of capacity by 2030 to meet growing energy demands (International Hydropower Association, 2022). However, climate change—by altering water availability and river flows—poses a major challenge, risking the viability of 32% to 60% of proposed hydropower projects (Carlino et al., 2023). Experts increasingly advocate for hybrid systems combining hydropower with solar and wind to mitigate these risks.

Biomass energy offers a theoretical potential of 2,374 TWh/y. In contrast, installed bioenergy capacity in 2019 was just 1,626 MW, with a theoretical output of around 14.2 TWh/y. While biomass contributes a smaller share compared to solar and wind, it plays a vital role in decentralized and off-grid systems, particularly in rural areas where agricultural and organic waste is abundant (IRENA, GIZ, and KfW Development Bank, 2021).

Finally, geothermal energy, with the smallest theoretical potential of 105 TWh/y, had 830 MW of installed capacity in 2019—equivalent to about 7.3 TWh/y in theoretical output. Although modest in scale, geothermal energy offers critical baseload power, especially in East Africa's Rift Valley region, where geological conditions are favorable (IRENA, GIZ, and KfW Development Bank, 2021).

## 2. Projected renewable energy potential for Kenya

Kenya is renowned as one of Africa's frontrunners in renewable energy, owing to its favorable geography and substantial policy initiatives. However, while the country's ambitions are high, there remains a significant disparity between its renewable energy potential and its actual installed capacities (Rotich et al., 2024).

As shown in Figure 20, Kenya's geothermal potential is significant estimated at 10,000 MW, largely due to the tectonic activity of the Rift Valley. By 2021, the country had installed approximately 950 MW, mostly in the Olkaria and Menengai fields—representing just 9.5% of its potential (Rotich et al., 2024). As of 2023, geothermal capacity had risen to 984 MW (IRENA, 2024). Geothermal now supplies about 45% of Kenya's electricity, highlighting its central role in the energy mix. However, over 90% of the resource remains untapped, underscoring the need for further investment and development (Rotich et al., 2024).

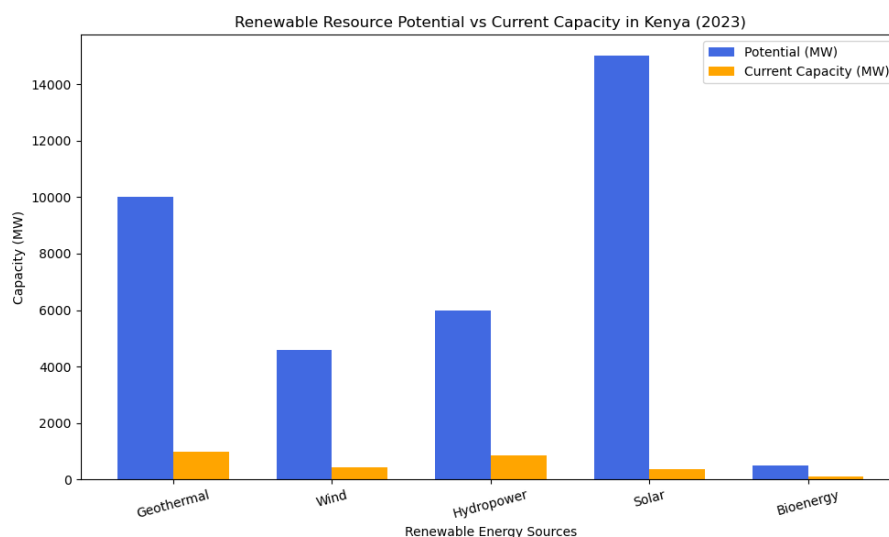


Figure 20. Renewable Resource Potential vs Current Capacity in Kenya.

Kenya has an estimated wind energy potential of 4,600 MW, particularly in its arid and semi-arid regions where average wind speeds exceed 6 m/s (Rotich et al., 2024). By 2023, installed wind capacity reached 436 MW, supplying about 10% of the country's electricity (IRENA, 2024). While this reflects meaningful progress, it also means that over 90% of the wind potential remains untapped, pointing to substantial opportunities for future growth (Rotich et al., 2024).

Hydropower has historically been essential for Kenya's power supply, with an estimated potential of 6,000 MW distributed across the country's major river systems, including the Tana, Athi, and Lake Victoria basins. Despite this substantial resource, by 2021, only about 818 MW of hydropower capacity had been connected to the national grid, representing just under 14% of the total potential. This illustrates the significant opportunity for expansion, as well as the challenges—such as environmental degradation and climate variability—that often hinder the full utilization of hydropower infrastructure (Rotich et al., 2024). According to IRENA (2024), installed hydropower capacity had increased slightly to 859 MW by 2023, but the vast majority of Kenya's hydropower potential remains untapped (IRENA, 2024).

Kenya possesses one of the highest solar energy potentials globally, with global horizontal irradiation (GHI) averaging about 2,400 kWh/m<sup>2</sup>/year. The country enjoys 5 to 7 peak sunshine hours per day, particularly in the northern and northeastern regions (Rotich et al., 2024). The estimated solar potential stands at approximately 15,000 MW (Ministry of Energy

Kenya, 2022). Despite this vast resource, development remains modest. By 2021, Kenya had only about 174 MW of grid-connected solar capacity, representing less than 5% of its practical potential. While many households and businesses have embraced off-grid solar systems, deployment of large-scale solar farms has been limited, reflecting a considerable underutilization of the resource (Rotich et al., 2024). According to IRENA (2024), Kenya's total installed solar capacity increased to 358 MW by 2023, signalling recent growth but still far below the country's potential (IRENA, 2024).

In the biomass sector, the Kenyan government has identified considerable potential for electricity generation, especially through cogeneration using agro-industrial residues like sugarcane bagasse. Current estimates indicate that bagasse-based cogeneration could deliver up to 193 MW, with Mumias Sugar Company alone generating 35 MW, of which 26 MW is fed into the national grid. In addition, studies suggest that another 300 MW could be harnessed from other sugar factories that remain undeveloped. This brings Kenya's total biomass cogeneration potential to approximately 493 MW (Ministry of Energy, Kenya, 2025). As of 2023, however, only 99 MW of biomass-based capacity had been installed, highlighting a substantial gap between available potential and actual deployment (IRENA, 2024).

### 3. Projected renewable energy potential for Madagascar

Madagascar possesses an abundance of renewable energy resources, but its exploitation remains significantly underdeveloped (Nematchoua, 2021).

For instance, as can be seen in Figure 21, Madagascar has about 7,800 MW of hydroelectric potential, mainly in the central, northern, and eastern regions. Yet as of 2016, only around 140 MW—just 1.3% of the total—had been developed. The largest plant, in Andekaleka, generates 58 MW, leaving much of the country's capacity untapped (Nematchoua, 2021). By 2023, installed hydropower capacity had grown to 193 MW (IRENA, 2024).

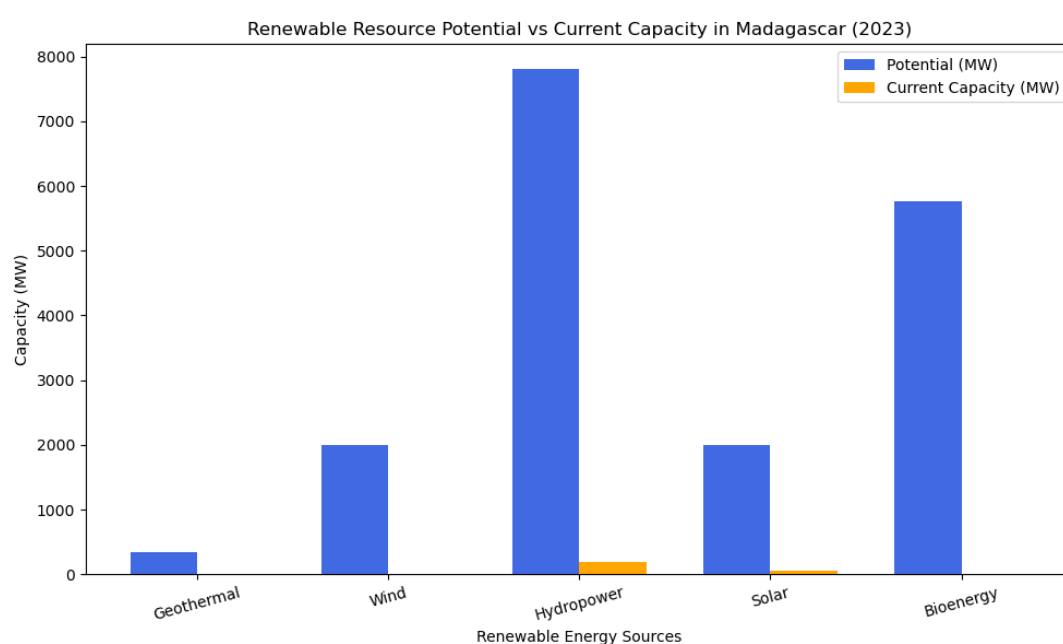


Figure 21. Renewable Resource Potential vs Current Capacity in Madagascar (2023).

Madagascar is one of the world's most solar-rich countries, with average solar irradiation of 2000 kWh/m<sup>2</sup> per year and more than 2800 hours of sunshine annually in many regions (Nematchoua, 2021). The African Development Bank (2023) estimates the country's total solar potential at over 2,000 MW (African Development Bank, 2023). Since the 1990s, over 1,000 solar photovoltaic systems have been installed, mainly in rural, off-grid areas—tapping into less than 3% of the available potential (Nematchoua, 2021). By 2023, total installed solar capacity reached 59 MW (IRENA, 2024).

Madagascar also has significant wind energy potential, especially in the northern and southern regions, where average wind speeds range from 6 to 9 m/s at 50 meters height. The country's wind energy capacity is estimated to exceed 2,000 MW, yet by 2018, wind accounted for just 0.1% of national energy consumption (African Development Bank, 2023; Nematchoua, 2021). According to IRENA (2024), there was still no installed wind capacity as of 2023, largely due to infrastructure challenges and a lack of investment (IRENA, 2024).

Moreover, Madagascar holds significant geothermal energy potential, offering an untapped opportunity to diversify its energy mix. Three key geothermal zones have been identified: the northern region (Ramena, Sambirano, Ankaizina), the Itasy geothermal zone, and the Antsirabe zone in the central highlands. Subsurface temperatures range from 130°C to 265°C across these areas, indicating moderate to high potential for power generation. The country's estimated geothermal generation potential is about 350 MW, driven by medium-temperature resources in volcanic regions and moderate potential in fault and sedimentary zones (Andriamifidisoa & Andrianaivo, 2024). These resources are mainly located along tectonic and volcanic formations, with about 117 identified thermal springs spread across 12 geothermal sites. Despite this promising resource base, Madagascar has yet to harness any of its geothermal potential for electricity production (Andriamifidisoa & Andrianaivo, 2024). As of 2023, no geothermal power plants have been built, and geothermal energy contributes 0 MW to the national grid (IRENA, 2024). Development remains at the exploratory stage, with ongoing geological, geochemical, and geophysical studies aiming to define viable prospects. Key challenges include high upfront costs, limited investment, and gaps in policy support (Andriamifidisoa & Andrianaivo, 2024; Rajaobelison et al., 2020).

It is essential to highlight that agricultural biomass holds immense potential as a sustainable energy source in Madagascar, where the agricultural sector dominates both the economy and waste generation (Nematchoua, 2021). Madagascar generates approximately 27.78 million tons of agricultural residue per year by 2024, comprising both crop residues and livestock manure. This biomass has the capacity to yield 181.91 petajoules (PJ) of energy annually, of which 128.75 PJ comes from crop residues and 53.16 PJ from animal manure (Anicaelle et al., 2024). When converted to electrical power terms, this total energy potential equates to approximately 5,770 megawatts (MW) of continuous output, assuming standard conversion rates (1 PJ = 277.78 GWh and 1 MW = 8.76 GWh/year) (Anicaelle et al., 2024). Despite this vast potential, there is no reported grid-connected biomass electricity generation capacity in Madagascar (IRENA, 2024). The study highlights that current biomass use remains mostly traditional—mainly firewood and charcoal—rather than being converted through modern technologies such as anaerobic digestion or thermochemical conversion (Anicaelle et al., 2024).

#### 4. Projected renewable energy potential for Sierra Leone

Sierra Leone has significant renewable energy potential across multiple sources, including hydropower, solar, wind, and bioenergy. Studies highlight the country's capacity to expand its electricity generation through these resources while reducing dependence on fossil fuels and improving electrification rates (Conteh et al., 2023; Fields et al., 2024). However, by 2023, Sierra Leone's total installed renewable energy capacity stood at 104 MW, placing it among the countries with the lowest renewable energy capacity globally (IRENA, 2024).

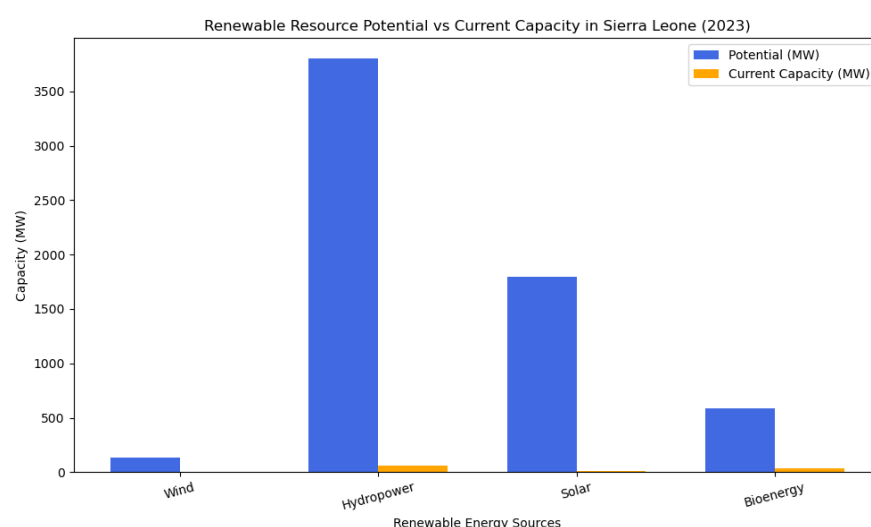


Figure 22. Renewable Resource Potential vs Current Capacity in Sierra Leone (2023).

As shown in Figure 22, hydropower is currently the most developed renewable energy source in Sierra Leone, providing a significant portion of the country's electricity. The Bumbuna Hydropower Plant is a key contributor to the national grid, and several expansion projects—including Bumbuna II, Betmai, Bekongor, and Singimi—have been proposed to boost generation capacity (Conteh et al., 2023). According to the Government of Sierra Leone (2024), the country's hydropower potential is estimated at 3,800 MW (Government of Sierra Leone, 2024), yet as of 2023, only 61 MW had been installed (IRENA, 2024), highlighting a vast untapped opportunity for growth in this sector.

Due to its geographic location, Sierra Leone receives abundant solar radiation, making solar photovoltaic (PV) systems a practical solution for energy generation. With an estimated solar PV potential of 1,800 MW, solar energy is especially well-suited for remote and off-grid communities (Government of Sierra Leone, 2024; Sankoh et al., 2022). However, as of 2023, the installed solar capacity remains limited at just 9 MW, underscoring the vast gap between potential and actual deployment (IRENA, 2024).

According to meteorological data from 2012, average wind speeds in Sierra Leone range between 3 and 5 meters per second, with higher velocities—up to 8 m/s—observed in mountainous areas. In certain locations, wind speeds may even reach 12 m/s, indicating that wind energy could be viable in select regions with consistent and strong wind flow. Despite this potential, wind energy development in Sierra Leone remains minimal. The country

currently has just one small wind system—a 5 kW (0.005 MW) installation in Bonthe District, along the southern coastline (UKRI, 2023). According to the Government of Sierra Leone (2024), the nation's onshore wind energy potential is estimated at 131 MW. This underscores a significant gap between available wind resources and actual installed capacity, suggesting that with proper investment and infrastructure, wind power could play a much larger role in Sierra Leone's renewable energy mix (Government of Sierra Leone, 2024).

As of 2017, Sierra Leone had 33 MW of installed biomass capacity, with an estimated energy generation potential of 2.706 GWh (UKRI, 2023). By 2023, this capacity had increased slightly to 34 MW (IRENA, 2024). According to the 2015 Population and Housing Census, 97% of the population relies on firewood or charcoal for cooking, while only 3% use alternatives such as gas, kerosene, or electricity. Nationally, 65% of households use firewood and 32% rely on charcoal, highlighting the country's strong dependence on traditional biomass for daily energy needs (UKRI, 2023). However, according to the Government of Sierra Leone (2024), the total biomass energy potential is estimated at 587 MW, pointing to a major opportunity for scaling up modern biomass energy solutions (Government of Sierra Leone, 2024).

Sierra Leone currently has no installed geothermal energy capacity, and this is primarily due to its geological and tectonic characteristics. The country sits on the stable West African Craton, an ancient and inactive piece of continental crust. Unlike regions with geothermal power, Sierra Leone lacks the volcanic activity, tectonic rifting, and recent magmatic intrusions that are typically needed to generate the high subsurface temperatures required for geothermal energy development. In addition, measured heat flow and geothermal gradients in the region are relatively low, meaning that even at considerable depths, temperatures are unlikely to be high enough for efficient energy production (IRENA, 2024; Mazarovich et al., 2001).

## 2.4 Energy transition targets in Africa

Achieving energy transition targets in Africa requires a significant expansion of electricity access. The Figure 23 and Table 1 highlight the progress and disparities in electrification across these three countries, illustrating the challenges and opportunities in scaling up energy access—a key pillar of the continent's transition to sustainable energy (World Bank, 2023).

As can be seen in Figure 23 and Table 1, Kenya demonstrates the most significant progress, with electrification rising from 10.9% in 1993 to 76% in 2022. The sharp increase after 2013 suggests successful government initiatives and investment in grid expansion and renewable energy. Meanwhile, Madagascar shows a more gradual rise, from 10.1% in 1993 to 36.1% in 2022, with some fluctuations indicating infrastructural or policy challenges. Sierra Leone, with data available from 2000, grows from 7.7% to 29.4% by 2022, reflecting post-conflict rebuilding efforts and energy sector reforms (World Bank, 2023).

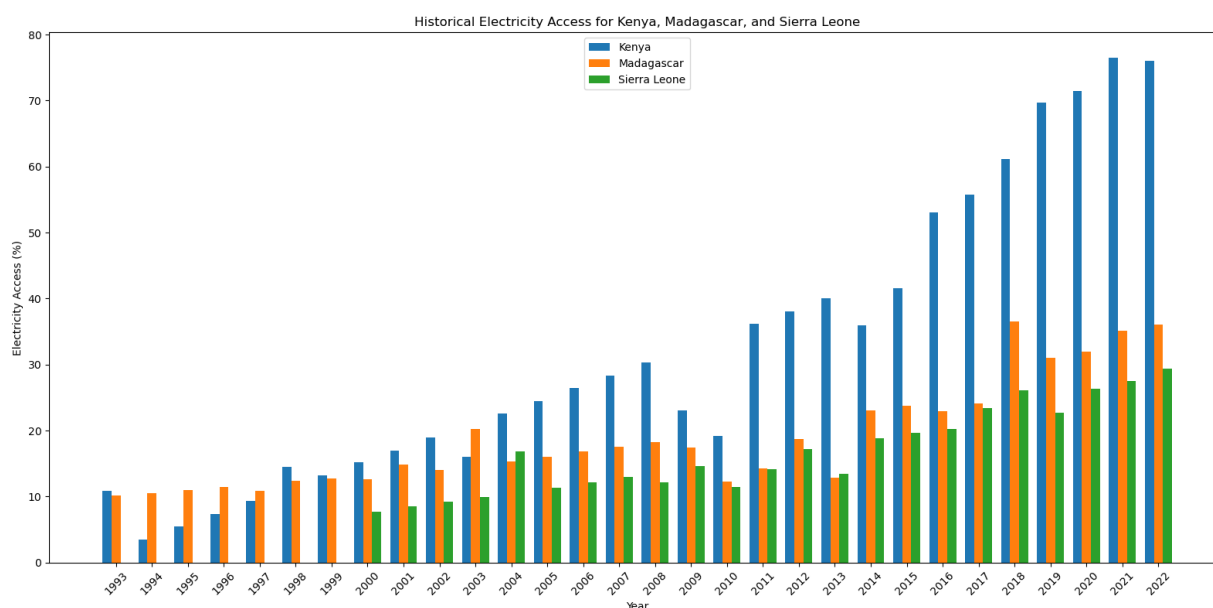


Figure 23. Historical Electricity Access for Kenya, Madagascar, and Sierra Leone.

The electricity access projections for Kenya, Madagascar, and Sierra Leone in 2030 and 2050, which are shown in the Figure 23, are based on available targets, ongoing projects, and expected investment trends.

Kenya has made significant progress in expanding its electricity infrastructure and aims to continue this trajectory through 2030 and beyond. Vision 2030 outlines several national priorities to increase access to reliable, affordable, and sustainable electricity. By 2030, Kenya aims to achieve universal electricity access, which is depicted in Figure 24. This includes connecting more households through programs like the Last Mile Connectivity Project and extending grid and off-grid infrastructure to underserved areas. As of FY 2020/21, over 8.2 million customers had already been connected, exceeding annual targets, and renewable energy accounted for 75% of the 2,984 MW generation capacity. Beyond 2030, its strategic direction and investments in long-term projects such as high-voltage transmission lines, nuclear readiness, and regional power trade infrastructure suggest continued progress. These are expected to support a resilient, high-capacity electricity network that can meet projected national and regional demand well into 2050 (Climate Investment Funds, 2024; Pappis et al., 2019; Vision 2030 Delivery Secretariat, 2022).

Meanwhile, the Government of Madagascar targets 70% electricity access across the country by 2030, as stated in recent World Bank and government strategy documents. This is a major scale-up from older projections that had set rural access much lower and reflects increased investment in both grid and off-grid solutions (International Energy Agency, 2023; Ministry of Energy and Hydrocarbons, 2022). According to the Nogueira et al. (2020), Madagascar's power sector is expected to rely on 100% renewable energy by 2030, and the country could achieve full electrification by 2050. Electrification would be especially driven by household demand, with 67% of power consumption in 2050 coming from the residential sector. This transition includes expanded deployment of decentralized solar and wind power, biomass-based electricity, and electrification of cooking and household energy services (Nogueira et al., 2020).

By 2030, Sierra Leone aims to achieve universal electricity access, as outlined in its Electricity Sector Reform Roadmap 2017–2030, which identifies a mix of grid, mini-grid, and off-grid systems as the path to nationwide electrification. However, given current infrastructure, financing, and implementation challenges, a more realistic target would be to reach about 60% access by that time (Ministry of Energy, Republic of Sierra Leone, 2017). This vision is expanded in the Energy Transition and Green Growth Plan, which projects 100% electrification across residential, social, and agricultural sectors by 2040. Key initiatives for 2020–2030 include:

- Expanding and densifying the national grid to serve currently underserved areas.
- Deploying 132 MW of solar mini-grids and 13 MW of solar home systems where grid expansion is not feasible.
- Scaling off-grid and rural electrification solutions in line with sustainable development goals.

With these measures in place, electricity access is expected to remain at or near 100% by 2050, with continued emphasis on improving supply quality, affordability, and resilience (Government of Sierra Leone, 2024).

Table 1 - Electricity Access Data for Kenya, Madagascar, and Sierra Leone.

| Year | Kenya (%) | Madagascar (%) | Sierra Leone (%) |
|------|-----------|----------------|------------------|
| 1993 | 10.90     | 10.11          | N/A              |
| 1994 | 3.47      | 10.56          | N/A              |
| 1995 | 5.43      | 11.02          | N/A              |
| 1996 | 7.38      | 11.47          | N/A              |
| 1997 | 9.33      | 10.90          | N/A              |
| 1998 | 14.50     | 12.36          | N/A              |
| 1999 | 13.21     | 12.80          | N/A              |
| 2000 | 15.20     | 12.60          | 7.70             |
| 2001 | 17.00     | 14.80          | 8.50             |
| 2002 | 18.90     | 14.00          | 9.20             |
| 2003 | 16.00     | 20.30          | 9.90             |
| 2004 | 22.60     | 15.30          | 16.80            |
| 2005 | 24.50     | 16.00          | 11.30            |
| 2006 | 26.40     | 16.80          | 12.20            |
| 2007 | 28.30     | 17.50          | 13.00            |
| 2008 | 30.30     | 18.30          | 12.10            |
| 2009 | 23.00     | 17.40          | 14.60            |
| 2010 | 19.20     | 12.30          | 11.50            |
| 2011 | 36.20     | 14.30          | 14.20            |
| 2012 | 38.10     | 18.70          | 17.20            |
| 2013 | 40.10     | 12.90          | 13.50            |
| 2014 | 36.00     | 23.00          | 18.80            |
| 2015 | 41.60     | 23.80          | 19.70            |
| 2016 | 53.10     | 22.90          | 20.30            |
| 2017 | 55.80     | 24.10          | 23.40            |
| 2018 | 61.20     | 36.50          | 26.10            |

|      |       |       |       |
|------|-------|-------|-------|
| 2019 | 69.70 | 31.00 | 22.70 |
| 2020 | 71.50 | 32.00 | 26.30 |
| 2021 | 76.50 | 35.10 | 27.50 |
| 2022 | 76.00 | 36.10 | 29.40 |

Source: World Bank, 2023.

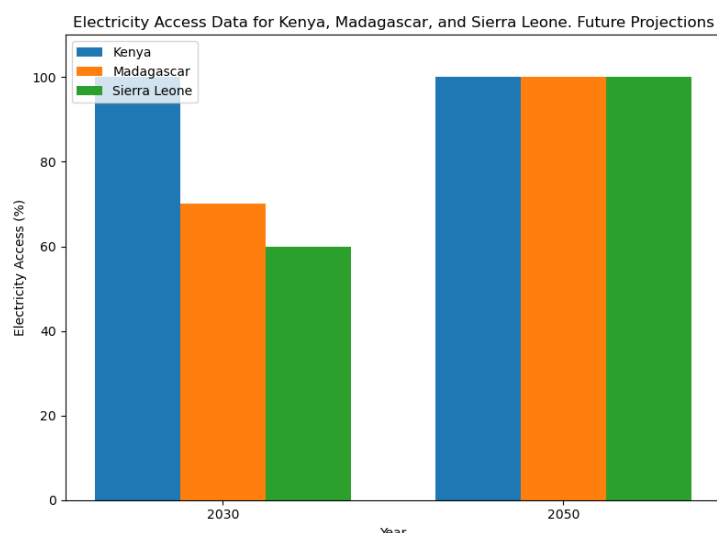


Figure 24. Electricity Access Data for Kenya, Madagascar, and Sierra Leone. Future Projections.

Overall, Kenya is leading the way with clear targets and strong investments in renewable energy, while Madagascar and Sierra Leone are making steady progress through large-scale projects and international support. Though neither of these two countries has official long-term targets, continued investments suggest significant improvements in electricity access over the next few decades (International Energy Agency, 2023)

In Africa, the majority of CO<sub>2</sub> emissions from the energy sector stem from burning fossil fuels—coal, oil, and natural gas—to generate electricity and power vehicles and machinery (International Energy Agency, 2023). In 2019, the energy sector was the continent’s largest source of emissions, excluding land use, land-use change, and forestry (LULUCF), accounting for approximately 55% of total emissions (Attard et al., 2022). However, Africa has the lowest per capita energy-related CO<sub>2</sub> emissions of any continent, reflecting its relatively limited industrial activity and energy consumption (International Energy Agency, 2023).

Despite its vast renewable energy potential, Africa remains one of the least electrified regions in the world. In 2023, clean energy sources contributed only 25% of the continent’s electricity generation—far below the global average of 39% (Ember, 2024). Meanwhile, electricity and heat production accounted for 39% of Africa’s total CO<sub>2</sub> emissions in 2022, amounting to 496.461 Mt CO<sub>2</sub>eq (International Energy Agency, 2023).

The Figure 25 shows total energy-related CO<sub>2</sub> emissions from Kenya, Madagascar, and Sierra Leone between 2000 and 2021, highlighting both absolute values and growth trends across the three countries. Kenya consistently recorded the highest emissions, rising from 8.06 Mt CO<sub>2</sub>eq in 2000 to 17.44 Mt in 2021, reflecting its larger economy and growing energy demand,

especially in transport and industry. Meanwhile, Madagascar's emissions, while much lower in absolute terms, more than doubled over the same period—from 1.63 Mt to 3.98 Mt CO<sub>2</sub>eq—driven by increased reliance on fossil fuels for electricity generation and rising vehicle use. Sierra Leone, starting from a very low baseline of 0.26 Mt CO<sub>2</sub>eq in 2000, saw a steady increase to 1.3 Mt in 2021, a fivefold growth that reflects its gradual economic development and energy sector expansion (World Resources Institute, 2025). The core difference across these countries lies in the scale and structure of energy use. Kenya's emissions are shaped by a more diversified energy economy and rapid urbanization, while Madagascar and Sierra Leone are experiencing fast relative growth as they work to expand energy access amid rising fossil fuel use (International Energy Agency, 2023).

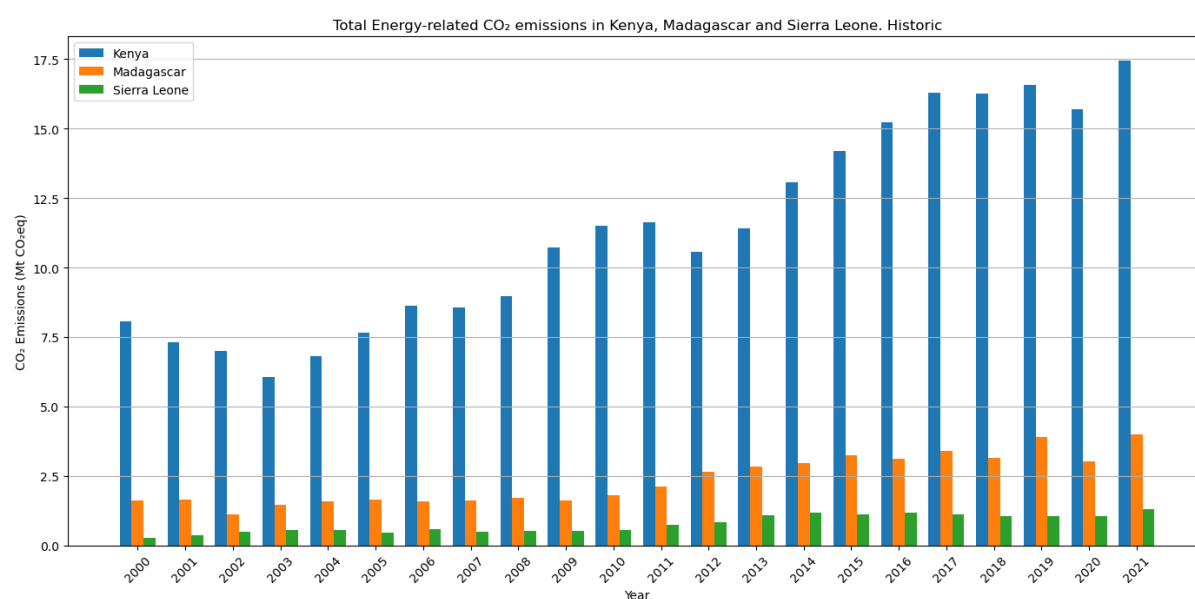


Figure 25. Total energy-related CO<sub>2</sub> emissions in Kenya, Madagascar and Sierra Leone. Historic.

Looking deeper into sector-specific emissions, the Figure 26, Figure 27, and Figure 28 reveals significant differences in the structure and sources of energy-related CO<sub>2</sub> emissions across Kenya, Madagascar, and Sierra Leone. In Kenya, as can be seen in Figure 26, emissions are well-distributed across multiple sectors. The transport sector is the dominant emitter, reaching 10.82 Mt CO<sub>2</sub>eq in 2021, followed by industry (3.21 Mt) and electricity and heat production (1.18 Mt). Kenya's diversified emissions profile reflects its relatively advanced infrastructure, greater fuel consumption in road transport, and a broader industrial base. Additionally, emissions from the residential sector (1.09 Mt in 2021) and commercial and public services (0.84 Mt) show the energy demand linked to urbanization and public infrastructure (International Energy Agency, 2023).

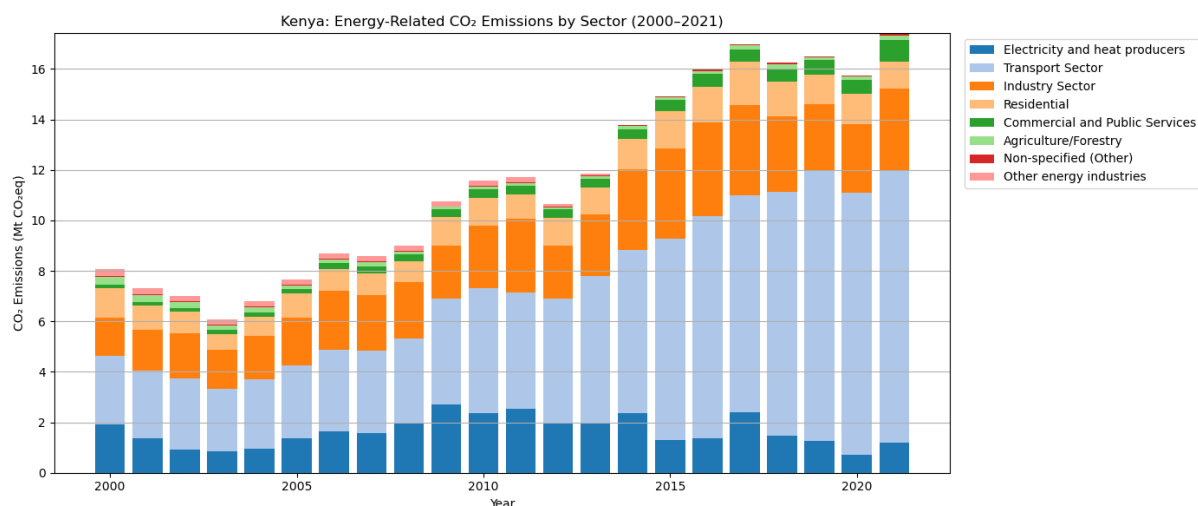


Figure 26. Kenya: energy-related CO<sub>2</sub> emissions by sector (2000–2021).

In contrast, as shown in Figure 27, Madagascar's emissions are concentrated more narrowly, with the electricity and heat production sector taking the lead at 1.67 Mt CO<sub>2</sub>eq in 2021, up from just 0.35 Mt in 2000. This reflects the country's growing reliance on fossil fuels for power generation. The transport sector follows at 1.37 Mt, while emissions from industry and residential use remain below 1 Mt each. Notably, sectors like commercial services and agriculture do not contribute significantly, highlighting Madagascar's more limited and less industrialized energy landscape (International Energy Agency, 2023).

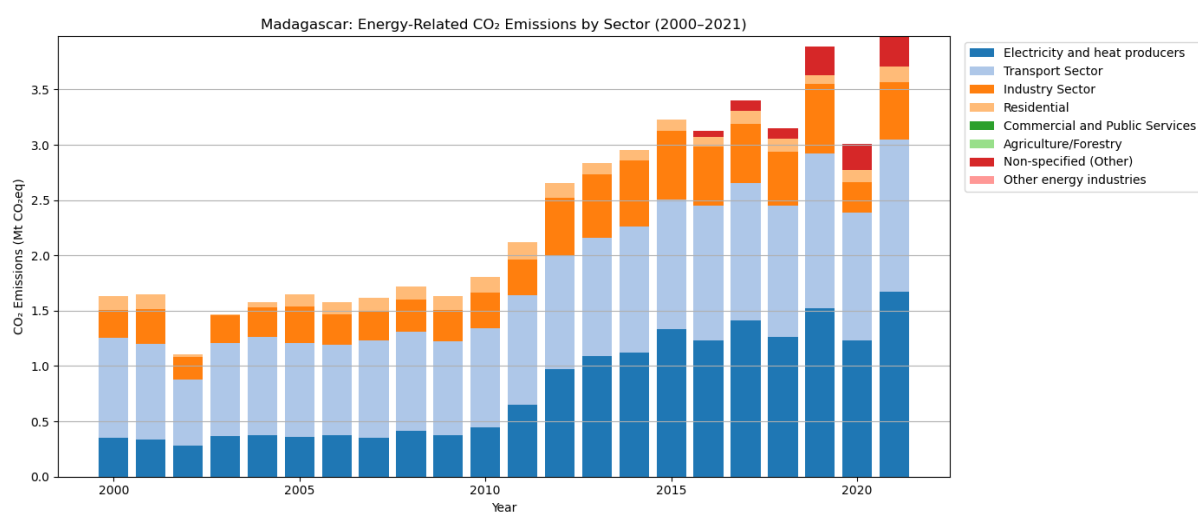


Figure 27. Madagascar: energy-related CO<sub>2</sub> emissions by sector (2000–2021).

Sierra Leone, meanwhile, exhibits a much smaller and less diversified emissions footprint, as shown in Figure 28. As of 2021, transport (0.81 Mt) and non-specified energy uses (0.48 Mt) are the primary contributors, with electricity and heat production remaining extremely low at just 0.01 Mt CO<sub>2</sub>eq. Sierra Leone reports zero emissions from industry, residential, and commercial sectors, likely reflecting significant gaps in infrastructure, industrialization, and energy access (International Energy Agency, 2023; World Resources Institute, 2025).

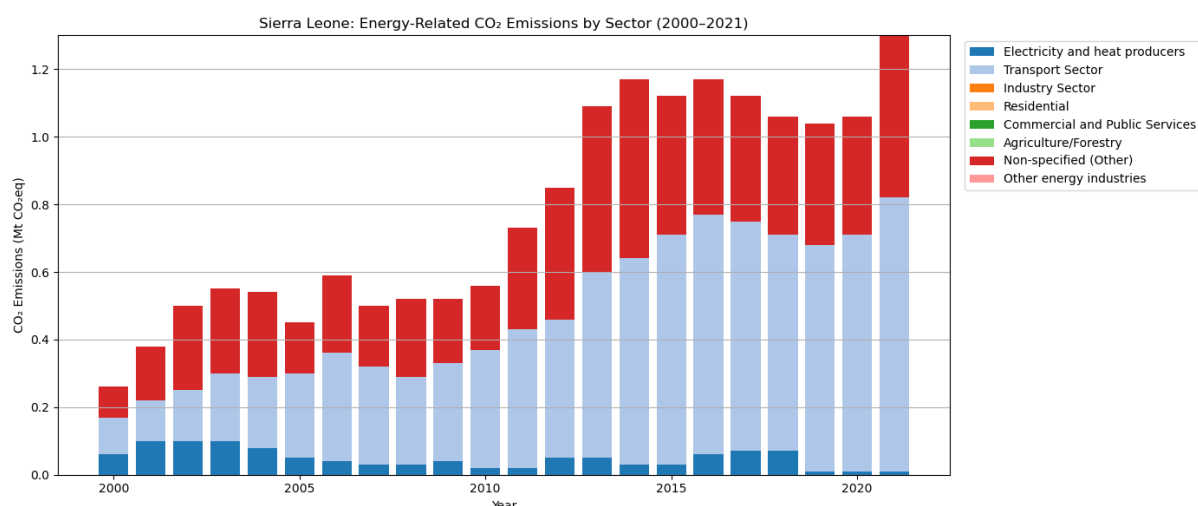


Figure 28. Sierra Leone: energy-related CO<sub>2</sub> emissions by sector (2000–2021).

The Africa Energy Outlook 2022 outlines two possible futures for the Africa’s energy-related CO<sub>2</sub> emissions. If current policies continue as they are—what the report calls the Stated Policies Scenario—emissions are projected to reach around 1.3 gigatonnes by 2030. However, under the Sustainable Africa Scenario, which assumes stronger climate action and full implementation of African climate pledges, emissions would rise only slightly to just over 1.2 gigatonnes. This modest increase, just 3% above 2020 levels, would be driven by major improvements in energy efficiency and a rapid expansion of renewable energy across the continent (International Energy Agency, 2022).

The CO<sub>2</sub> emissions projections chart on Figure 29 illustrates the impact of climate policies versus a business-as-usual (BAU) scenario for Kenya, Madagascar, and Sierra Leone in 2030 and 2050. It provides insights into how emissions will evolve under different policy approaches.

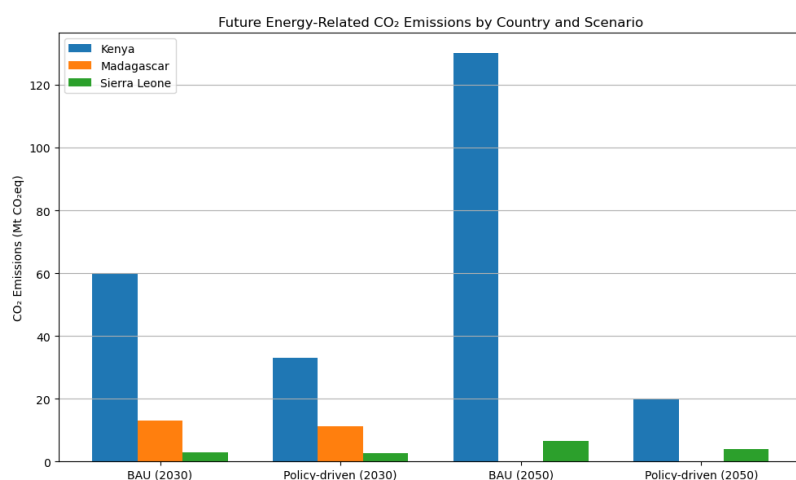


Figure 29. Future energy-related CO<sub>2</sub> emissions by country and scenario.

In its first updated NDC (2020), Kenya committed to reducing total greenhouse gas emissions by 32% by 2030, compared to a business-as-usual (BAU) projection of 143 Mt CO<sub>2</sub>eq. This translates to an absolute emissions target of 97.24 Mt CO<sub>2</sub>eq by 2030, including land use, land-use change, and forestry (LULUCF). This target represents Kenya’s core pledge under the

Paris Agreement for the pre-2030 period (Climate Action Tracker, 2024; World Resources Institute, 2025). In the energy sector, emissions are expected to fall to 19.3 Mt CO<sub>2</sub>eq by 2030 and to 8.13 Mt CO<sub>2</sub>eq by 2050 under the net-zero pathway (Climate Analytics, 2024). According to the Kenya's Energy Transition and Investment Plan (ETIP 2023), under the BAU scenario, energy-related CO<sub>2</sub> emissions in Kenya are expected to reach approximately 60 Mt CO<sub>2</sub>eq by 2030. In contrast, under the Net-Zero Energy (NZE) scenario, emissions are projected to be 33 Mt CO<sub>2</sub>eq by 2030. This nearly 50% reduction is enabled by major interventions across the power, transport, and buildings sectors, including increased electrification, renewable energy deployment, clean cooking technologies, and efficiency measures. By 2050, the BAU pathway sees emissions growing significantly to about 130 Mt CO<sub>2</sub>eq. This increase is largely due to expanded transport demand and industrial output, without substantial shifts toward low-carbon technologies. Under the NZE scenario, energy-related emissions are reduced to approximately 20 Mt CO<sub>2</sub>eq by 2050. These remaining emissions are expected to be offset by land use and forestry measures (LULUCF), allowing Kenya to reach net-zero emissions overall. This scenario assumes wide-scale adoption of renewables, electrification of transport and cooking, clean hydrogen, and emerging carbon capture technologies (Ministry of Energy, Kenya, & Sustainable Energy for All, 2023).

Without additional climate action, Madagascar's total greenhouse gas emissions are projected to reach 87 Mt CO<sub>2</sub>eq by 2030 and rise further to 180 Mt CO<sub>2</sub>eq by 2050, nearly tripling 2010 levels. This Business-as-Usual (BAU) pathway reflects continued reliance on traditional energy and unsustainable land use. Under its Nationally Determined Contribution (NDC), Madagascar targets a 14% emissions reduction by 2030, mainly through land-based carbon removal (AFOLU), with gross emissions remaining close to BAU levels. In the more ambitious NDC+ scenario, higher land-use mitigation costs shift reductions toward the energy sector, resulting in early signs of decarbonization—especially in residential energy use. By 2050, the NDC+ pathway brings gross emissions down to 167 Mt CO<sub>2</sub>eq, compared to 180 Mt CO<sub>2</sub>eq under BAU. This modest reduction is driven by electrification and a transition to renewables, showing the importance of energy system transformation for long-term climate goals (Nogueira et al., 2020).

Meanwhile, in Madagascar's energy sector, the 2030 BAU scenario projects emissions at 13.0 Mt CO<sub>2</sub>eq (Ministère de l'Environnement et du Développement Durable, 2022; Republic of Madagascar, 2015). Under the mitigation (policy-driven) scenario, emissions are reduced to 11.3 Mt CO<sub>2</sub>eq, achieving a modest reduction of 1.7 Mt CO<sub>2</sub>eq. This reduction is enabled by actions such as increased renewable energy use, network rehabilitation, improved power plant efficiency, and reduced kerosene consumption (Republic of Madagascar, 2015). No emissions scenario is publicly available for 2050, as national planning documents for Madagascar currently focus only on short- to medium-term horizons up to 2030 (Ministère de l'Environnement et du Développement Durable, 2022).

For Sierra Leone, energy-related CO<sub>2</sub> emissions are projected to reach 3.0 Mt CO<sub>2</sub>eq by 2030 under the BAU scenario, compared to 2.7 Mt CO<sub>2</sub>eq under the policy-driven Low Carbon Development (LCD) scenario. By 2050, this divergence becomes more pronounced, with emissions climbing to 6.6 Mt CO<sub>2</sub>eq in BAU but limited to 3.9 Mt CO<sub>2</sub>eq in LCD—a 41% reduction. The BAU pathway assumes continued reliance on fossil fuels, delayed electrification of key sectors, and no binding emissions targets, with emissions peaking only

by 2046. In contrast, the LCD scenario includes early policy interventions such as nationwide grid expansion, clean cooking adoption, and widespread deployment of solar and hydropower (Government of Sierra Leone, 2024).

Key renewable energy sources—including solar, wind, hydro, and geothermal—are being increasingly integrated into national energy policies. However, Africa’s energy transition faces significant hurdles across social, political, economic, technological, and cultural domains. Political instability, insufficient financial resources, and outdated infrastructure continue to impede progress. Additionally, energy poverty remains a pressing issue, with many rural communities lacking access to modern energy services (Munro et al., 2020).

While these challenges are widespread, progress varies significantly across countries. Some nations are moving faster than others in shifting to low-carbon energy systems. Kenya stands out as one of the continent’s front-runners in this transition. In 2021, its carbon intensity was just 0.22 kg CO<sub>2</sub> per kWh—reflecting one of the cleanest energy mixes in Africa (Ritchie & Roser, n.d.). Despite this, the country’s electricity and heat production still emitted 1.2 Mt CO<sub>2</sub>eq in the same year (International Energy Agency, 2023). Kenya has set bold targets: 100% clean energy by 2030 and net-zero emissions by 2050. Already, nearly 90% of its electricity is sourced from renewables (International Energy Agency, 2023). To support these goals, the government launched the Kenya Carbon Emission Reduction Tool (Ministry of Energy Kenya, 2022), an interactive model that helps guide energy policy and emissions planning (British High Commission Nairobi, 2022).

Madagascar, by contrast, is in the earlier stages of its energy transition. In 2022, its energy-related CO<sub>2</sub> emissions were approximately 4 million tonnes—accounting for just 0.01% of global emissions but marking a 161% increase since 2000. The energy sector contributes about 18.7% of the country’s total GHG emissions, with the buildings sector being the largest contributor at 1.81 million tonnes. Fossil fuels still dominate electricity generation, resulting in a carbon intensity of 436.19 gCO<sub>2</sub>eq per kWh—substantially higher than Kenya’s (Boyle, 2024; International Energy Agency, 2023).

To address these challenges, Madagascar has set ambitious energy transition targets. The government aims to achieve a 70% electricity access rate by 2030 (International Energy Agency, 2023). Efforts include scaling up renewable energy projects, such as mini grids, which are expected to provide electricity to over 50,000 people, support 1,800 businesses, and reduce CO<sub>2</sub> emissions by approximately 1,455 tonnes annually (SEforALL, 2024). Despite these initiatives, as of 2023, 0% of Madagascar’s greenhouse gas emissions are subject to a positive Net Effective Carbon Rate, indicating the absence of explicit carbon pricing mechanisms (OECD, 2024).

In 2021, Sierra Leone’s energy sector contributed approximately 1.1 million tonnes of CO<sub>2</sub>eq, accounting for 16% of the nation’s total emissions (Boyle, 2024). The majority of these emissions stemmed from transportation (706,000 tonnes), other fuel combustion activities (364,000 tonnes), and manufacturing/construction (31,600 tonnes) (Boyle, 2024). Meanwhile, the electricity and heat generation sector alone emitted around 200,000 tonnes of CO<sub>2</sub> in 2022, reflecting the country’s ongoing reliance on fossil fuels for power generation (IRENA, 2023).

To address its growing carbon footprint, Sierra Leone has established ambitious energy transition targets. The country aims to reduce emissions by 5% by 2025, 10% by 2030, and 25% by 2050, relative to a business-as-usual scenario from 2015 levels (BloombergNEF, 2022). A core component of this strategy is the expansion of renewable energy sources, including hydropower, solar, and bioenergy, to gradually replace fossil fuel dependence. The government has also committed to achieving 85% renewable energy capacity by 2030, alongside significant investments in off-grid solar solutions and rural electrification projects (SEforALL, 2023).

Despite these goals, financial and infrastructural constraints continue to hinder rapid decarbonization. Limited private sector investment and the high cost of renewable energy deployment have slowed progress, particularly in rural electrification efforts (Sam et al., 2018). However, with ongoing international support and policy reforms, Sierra Leone is positioning itself for a low-carbon energy future while striving to balance economic growth with environmental sustainability.

## 2.5 Climate change impact on Energy system

### 1. Cooling demand

Africa, which includes many developing countries, is especially susceptible to heat stress and an increased need for cooling. Climate change is expected to increase the severity of heat stress incidents and introduce new heat stress events in Africa, leading to a rise in energy-intensive cooling needs (Parkes et al., 2019).

According to the Figure 30, the plot illustrates a clear trend of rapidly increasing demand for residential cooling in Africa over the next two decades, emphasizing the impact of rising temperatures and socio-economic developments on energy needs. For instance, the year 2018 represents the baseline cooling demand, showing a relatively small amount of total energy usage devoted to residential cooling. Meanwhile, Stated Policies scenario in 2040 projects the cooling demand based on current and announced energy policies (International Energy Agency, 2019).

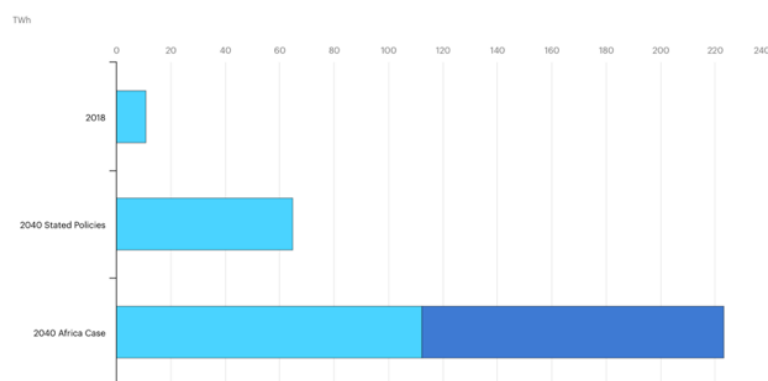


Figure 30. Residential cooling demand in Africa by scenario, 2018-2040.

Source: International Energy Agency, 2019.

There is a significant increase in cooling demand compared to 2018, indicating an expectation of higher energy use for cooling as policies and infrastructure evolve. Africa Case scenario in

2040 shows an even higher projection than the stated policies scenario, which might represent a situation where economic growth and increasing access to cooling technology drive much higher usage of residential cooling systems (International Energy Agency, 2019). Central Africa exhibits the widest variation in cooling needs due to the differences in monsoon patterns affecting the region's meteorology. Cooling requirements, when considering future climate change, are assessed for scenarios at +2°C and +4°C, with linear interpolation used to establish demand trajectories. For instance, in 2005, space cooling represented 0.4% of Africa's total final energy demand; under baseline conditions, this figure falls to 0.2% by 2100. However, with climate change considerations, it is projected to increase to 1.2% by the end of the century (Parkes et al., 2019).

Figure 31 illustrates the projected additional cooling demand, measured in petajoules (PJ), for various African countries under two climate warming scenarios, such as +2°C and +4°C increase. This additional demand is a response to heat stress mitigation needs as modeled under the RCP 8.5 climate scenario, which assumes high greenhouse gas emissions throughout the century (Parkes et al., 2019).

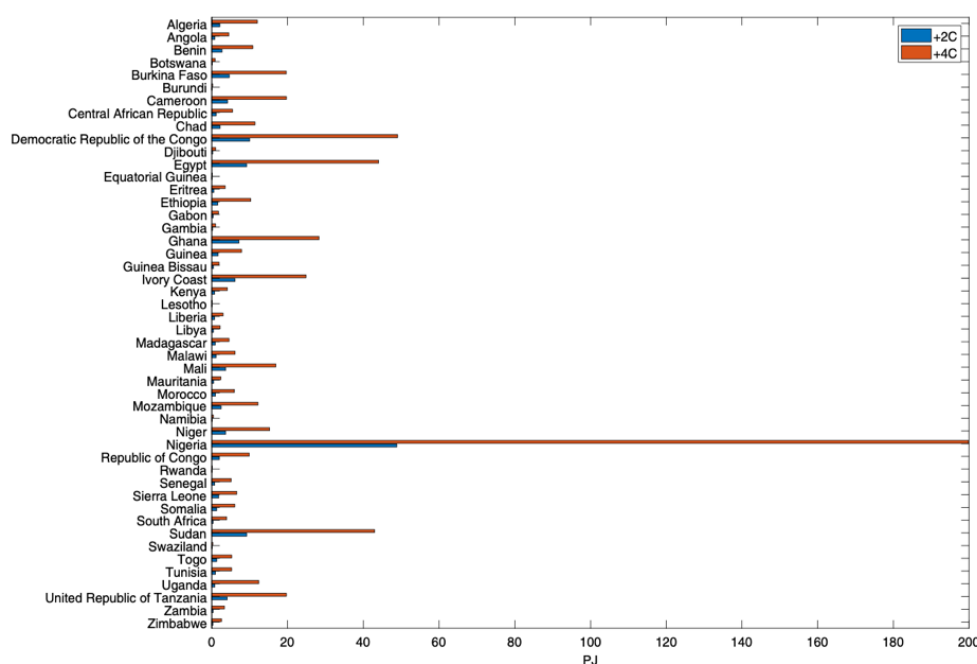


Figure 31. Country-level additional cooling demand due to heat stress mitigation under RCP8.5 for two timeslices.

Source: Parkes et al., 2019.

In the Africa Case, greater availability of cooling is achieved through universal electricity access and higher household incomes, driving demand to exceed 110 TWh by 2040, which is nearly double the demand projected in the Stated Policies Scenario. Additionally, the implementation of stricter efficiency policies for cooling equipment and the use of passive cooling methods—such as improved building design and increased vegetation—prevent an extra 110 TWh of demand (International Energy Agency, 2019; International Energy Agency, 2023).

There are various methods to evaluate the influence of climate change on cooling demand. Traditionally, this is done through the calculation of Cooling Degree Days (CDDs), a technique commonly employed by electric utilities to forecast upcoming cooling loads based on climate predictions. CDDs show the extent to which daily average temperatures surpass a baseline temperature over a specific period (International Energy Agency, 2019).

To predict cooling demand data for Africa, it is crucial to consider the relationship between the yearly CDDs and the cooling demand. According to the article by Ding et al. from Beijing Meteorological Bureau, there is a moderately strong connection between CDDs and an energy demand for cooling, with a correlation coefficient of 0.56. This means that as CDD increases, the demand for electricity also tends to increase (Ding et al., 2007).

## 2. Wind power

The Figure 32 shows projected wind power variations across regions for early (present–2030), mid (2040–2060), and long (2070–2100) terms. As a result of climate change, Africa exhibits increasing uncertainty over time, with early-term changes remaining moderate but expanding significantly in the mid and long terms. The projections suggest both positive and negative variations, highlighting regional variability. This growing uncertainty underscores the need for adaptive energy planning in Africa (Russo et al., 2022).

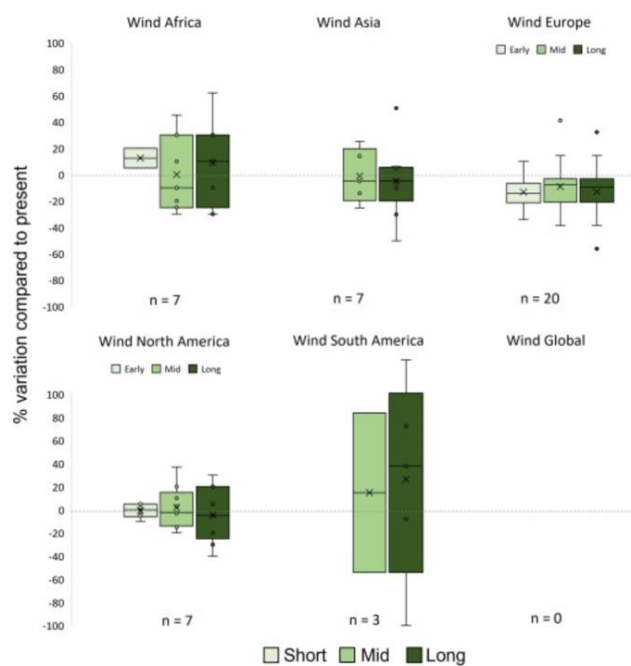


Figure 32. Percent variation estimated by the selected research articles in potential energy production from wind RES-E caused by climate change.

Source: Russo et al., 2022.

The study by Bloomfield et al. (2022) explores the meteorological factors influencing wind power generation across different African regions, with a particular emphasis on Senegal and Kenya. In Senegal, wind power peaks in boreal spring, while in Kenya, it reaches its highest levels in boreal autumn. Kenya also experiences greater year-to-year fluctuations, posing challenges for grid stability. While overall wind energy resources in Africa are expected to remain stable, some regions could see shifts in diurnal wind cycles, influencing efficiency. Additionally, El Niño and La Niña events impact wind power. During El Niño years, Kenya sees

higher wind power from July to September, followed by a decline in October to December. In contrast, La Niña years bring lower wind speeds, which can reduce energy reliability (Bloomfield et al., 2022).

Beyond these seasonal and inter-annual variations, climate change introduces additional complexities to wind power generation in Kenya. Rising temperatures and shifting climate patterns may both enhance and hinder wind energy production, while also increasing the risk of wind-related damage to turbines and infrastructure. A key factor in this variability is the Turkana Jet, a crucial wind system that significantly influences the country's wind energy potential. Changes in the jet's strength directly impact wind speeds, affecting the reliability of wind energy production. A weaker jet may reduce output, while a stronger jet could create unstable conditions, compromising turbine efficiency and infrastructure resilience (Future Climate for Africa, 2020; Munene, 2021).

In Madagascar, climate change affects wind power generation by altering wind patterns, increasing cyclone activity, and influencing diurnal wind cycles. The island has substantial wind energy potential, as mentioned above, particularly in the north and far south, where wind speeds range from 6 m/s to 9 m/s at 50m height. Shifts in trade winds and changing atmospheric circulation may cause reductions in wind speeds in some areas while intensifying them in others, affecting generation consistency. Additionally, frequent and intense cyclones, which are becoming more common due to climate change, threaten wind infrastructure, potentially leading to turbine damage and energy supply disruptions (Nematchoua, 2021).

In West Africa, including Sierra Leone, projections under Representative Concentration Pathways (RCP4.5 and RCP8.5)—which represent moderate and high greenhouse gas emission scenarios—indicate a potential decrease in energy production of up to 12% in the near term (2021–2050). However, in the distant future (2071–2100), wind power generation could increase by approximately 24–30% across most areas (Kara & Şahin, 2023).

### 3. Solar power

The Figure 33 illustrates the regional variation in solar power potential as projected across selected studies, considering changes over the early (present to 2030), mid (2040 to 2060), and long (2070 to 2100) terms. Data is categorized by region, showing how climate change might influence solar power generation. Like wind power, the impact of climate change on solar energy production is generally modest, with variations typically within 10% regionally and up to 20% globally. Focusing on Africa, the Figure suggests that solar power generation remains relatively stable in the short term but experiences some variations over longer periods (Russo et al., 2022).

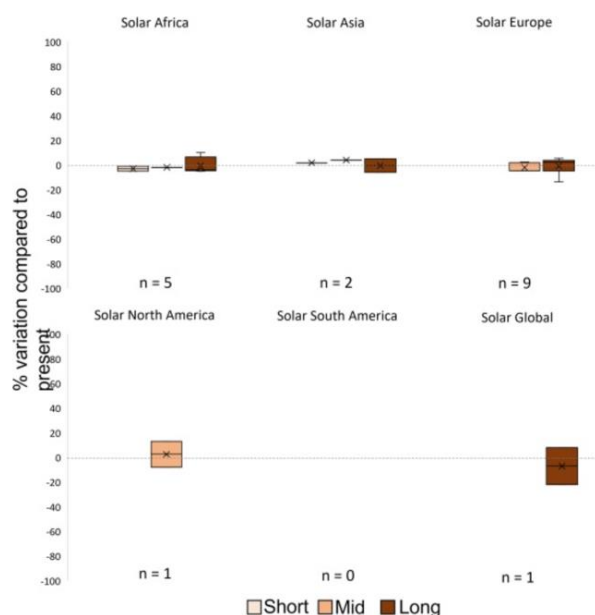


Figure 33. Percent variation estimated by the selected research articles in potential energy production from solar RES-E caused by climate change.

Source: Russo et al., 2022.

Weather patterns, cloud formations, humidity levels, fires, and the duration of daylight all represent key climate-related factors that influence the availability of solar radiation in this region. It is crucial to mention that Photovoltaic (PV) panels operate most efficiently at temperatures below 25°C. Above this threshold, their performance declines by about 0.3–0.5% for every additional degree, largely due to material degradation and heightened electrical resistance. With African regions projected to experience increasingly frequent heatwaves, this degradation can be exacerbated, potentially reducing solar power output over time (PreventionWeb, 2024). It is also crucial to emphasize that Gaetani et al. used the ECHAM5 global climate model to assess near-future changes in PV productivity in Africa and found that reductions in aerosol emissions contribute to increased global warming. This warming leads to significant variations in surface solar radiation, which, in turn, affects PV energy productivity. Specifically, the study observed a statistically significant reduction in PV productivity of up to 7% in northern Africa by 2045 (Bazyomo et al., 2016).

In Kenya, as was mentioned above, climate change influences solar radiation variability, reducing solar energy output during the rainy seasons due to increased cloud cover and atmospheric aerosols. Conversely, arid regions like northern Kenya, with minimal cloud cover, retain strong solar energy potential. However, significant uncertainty in solar irradiation persists due to the limitations of current climate models (Kariuki & Sato, 2018).

In Madagascar, increasing climatic instability results in more unpredictable weather patterns, affecting PV performance. With over 2800 hours of sunshine per year and irradiation around 2000 kWh/m<sup>2</sup>, solar potential is high, but rising temperatures (22°C–40°C) reduce solar panel efficiency. Cyclones frequently damage infrastructure, while high humidity accelerates degradation, especially in coastal areas. Seasonal shifts and cloud cover further disrupt energy output (Nematchoua, 2021).

Meanwhile, climate change is projected to have a slightly beneficial Sierra Leone stands out as one of the few African nations where impact on solar PV productivity. The combination of stable solar radiation levels and moderate temperature increases is expected to lead to a modest yet notable rise in PV output, estimated at 0.013% per year. While this growth is incremental, it contrasts sharply with the declining trends seen in many neighbouring countries, highlighting Sierra Leone's potential for resilient solar energy development (Bazyomo et al., 2016).

#### 4. Hydro power

According to Figure 34, Africa is the only region where a significant increase in hydro potential is projected, but the uncertainty in long-term projections makes future trends less predictable (Russo et al., 2022).

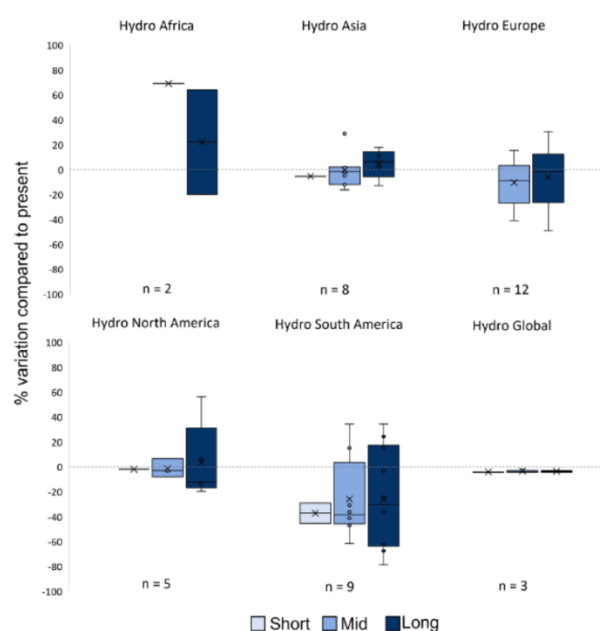


Figure 34. Percent variation estimated by the selected research articles in potential energy production from hydro RES-E caused by climate change.

Source: Russo et al., 2022.

As can be seen in the Figure 34, in the early term (present to 2030), the variation remains relatively low, indicating minimal impact from climate change. However, by the mid-term (2040 to 2060), hydro potential in Africa is projected to increase significantly, with a single estimate at approximately 70% above present levels. In contrast, the long-term period (2070 to 2100) exhibits high uncertainty, with a wide range of variation and a median increase of around 20% (Russo et al., 2022).

According to the study of Ochieng et al. (2021) on the Sondu Miriu River Basin, climate change has significantly affected hydropower generation in Kenya due to rising temperatures and changing rainfall patterns. Thus, projections indicate a temperature rise of 1.9°C by 2100 under both the RCP4.5 and RCP8.5 scenarios. Such warming trends accelerate evaporation rates and alter river flow dynamics, reducing water availability for hydropower generation. Rainfall patterns have also shifted considerably. While annual rainfall increased by 74.8 mm between 1950 and 2005, it declined by 193.14 mm between 2007 and 2018, leading to a

reduction in river discharge. Consequently, the mean daily river flow declined by 0.3 m<sup>3</sup>/s annually over this period, directly impacting hydropower output. The study reports that Sondu Miriu Hydropower Plant experienced a reduction of 8.3 GWh in electricity generation between 2007 and 2018, while Sang'oro Hydropower Plant recorded an even greater decline of 14.18 GWh from 2012 to 2018 (Ochieng et al., 2021).

Meanwhile, climate change is reshaping hydropower generation in Kenya's Tana River Basin, the country's primary source of hydroelectric power, by altering rainfall patterns and water availability. Projections indicate a 23% to 43% increase in rainfall by the late 21st century, with average annual rainfall rising from 640 mm (baseline) to between 787 mm (RCP 4.5) and 912 mm (RCP 8.5). This increase is expected to boost water yield by up to 197.3%, groundwater recharge by 160.2%, and base flow by 391.9% under RCP 8.5, enhancing hydropower potential. However, these benefits come with challenges. The rainy seasons are expected to start earlier, with greater seasonal variability and peak flows increasing by up to 84.9 mm per year for the period 2070–2099 under RCP 8.5, complicating dam operations. Additionally, natural flow regulation is projected to decrease by 17.6% under RCP 4.5 and by 18.5% under RCP 8.5 during the period 2070–2099, raising flood risks and threatening infrastructure stability (Muthuwatta et al., 2018).

Meanwhile, for Madagascar, rising temperatures and shifting precipitation patterns influence runoff, with some regions experiencing reduced river flow due to increased evaporation, while others may see intensified floods. In the Mangoky River, future climate projections indicate a substantial reduction in runoff, which could severely impact hydropower production. Under SSP 3–7.0 and SSP 5–8.5 scenarios, annual runoff is expected to decrease by 60.59% and 73.77% in the 2040s, respectively. Although some recovery is projected by the 2090s, reductions of 25.18% and 23.45% are still expected under the same scenarios. While increased rainfall in the late 21st century could enhance water availability, it may also introduce operational challenges due to greater variability and flooding risks (Rabazanahary Tanteliniaina et al., 2021).

Sierra Leone, a West African nation heavily reliant on hydropower, faces increasing threats from climate change. The Bumbuna Hydroelectric Plant, which serves as a primary source of energy, is particularly vulnerable to shifting rainfall patterns, rising temperatures, and extreme weather events. These climatic changes disrupt water availability, affect hydropower efficiency, and compromise energy security. A study on hydropower in West Africa indicates that climate change is likely to reduce available water by 10%–20% under the RCP4.5 scenario and up to 40% under RCP8.5 by 2050 (Obahoundje & Diedhiou, 2022). In Sierra Leone, decreasing rainfall in the northwest and more erratic rainy seasons could lower river flows, impacting the energy output of hydroelectric plants (Wadsworth et al., 2019). At the same time, shifts in hydrological patterns are already being observed, with significant implications for water resources. A study on the Rokel-Seli River Basin, which supplies water to the Bumbuna Hydropower Plant, found a 31.7% increase in annual surface runoff from 2002 to 2010, but only a 0.9% increase from 2010 to 2016, largely due to reservoir construction (Wilson et al., 2018). It is also critical to highlight that Sierra Leone is experiencing more frequent extreme weather events in the nearest future, including storms, landslides, and floods, which pose serious threats to hydropower infrastructure. Heavy rainfall can lead to sedimentation, clogging hydroelectric turbines and reducing efficiency. Additionally, floods

can damage dams and transmission lines, causing prolonged power outages (Akiwumi & Butler, 2008).

## 2.6 Challenges for integrating energy modelling with climate projection

The integration of energy modeling with climate projection is critical for Africa's sustainable development, considering the continent's vulnerability to climate change and its growing energy demands. However, several challenges hinder effective integration, including the complexity of climate models, limited access to high-quality climate data, and the lack of region-specific energy models (Musonye et al., 2020; Singh et al., 2018; Tesfamichael & Fuchs, 2024).

### 1. Climate models in Africa

Climate models play a pivotal role in predicting future climate scenarios and assessing the impacts of climate change on energy infrastructure. However, Africa faces specific challenges in climate modeling due to sparse meteorological data, high spatial variability in climate patterns, and computational limitations (Soares et al., 2019). The uncertainty in climate projections arises from several factors, including differences in model physics, emissions scenarios, and parameterization techniques, which affect how models represent key climate processes (Ddamulira, 2016).

A major issue is the resolution of climate models, as many global models operate at coarse spatial resolutions (~100–250 km), making it difficult to capture localized climate dynamics, such as extreme weather events, coastal climate impacts, and regional precipitation changes (James et al., 2018). High-resolution regional climate models (RCMs), such as those used in the Coordinated Regional Downscaling Experiment (CORDEX-Africa), aim to improve spatial detail but still face challenges in accurately simulating convective rainfall patterns, cloud cover variability, and land-atmosphere interactions (Gerasu et al., 2024).

Furthermore, data scarcity exacerbates uncertainty, particularly in remote and arid regions where meteorological station networks are sparse. The lack of long-term, high-frequency observational records leads to biases in model outputs and limits the accuracy of future energy-related climate risk assessments (Sylla et al., 2013). Computational limitations also restrict the ability to run ensemble simulations with multiple climate models and emissions pathways, further increasing uncertainty in regional climate predictions (Gerasu et al., 2024; Nikulin et al., 2012).

### 2. Energy modelling in Africa challenges

Energy models are essential for planning and optimizing energy systems, yet their integration with climate data in Africa remains underdeveloped. One major issue is that most energy models used in Africa are adapted from Western contexts and fail to consider local socio-economic and environmental conditions (Musonye et al., 2020). Additionally, energy models often lack real-time climate variability considerations, making them less effective in addressing climate-induced disruptions.

Furthermore, a significant portion of Africa lacks access to reliable electricity, with nearly 600 million people (43% of the population) still without electricity as of 2024 (IEA, 2024). Rural areas are particularly affected, where grid infrastructure is either non-existent or severely

underdeveloped. Countries such as South Sudan, Chad, and Burundi have some of the lowest electricity access rates, below 15% (World Bank, 2021). Additionally, even in urban areas with established grids, frequent power outages and unreliable supply hinder economic and social development.

The absence of a well-established grid in many regions makes the integration of renewable energy solutions challenging. Off-grid solutions such as solar mini-grids and decentralized energy systems are being deployed as alternatives to traditional grid expansion, but their implementation remains uneven due to financial and technical barriers (IRENA, 2024).

### 3. Key integration challenges to solutions

Challenges arise in integrating energy modelling with climate data, including issues such as data scarcity, computational limitations, policy gaps, and technological constraints. For instance, many African countries lack consistent and reliable climate datasets, making it difficult to calibrate and validate energy models. To address this, investment in localized climate data collection and energy modeling initiatives is crucial (Singh et al., 2018).

Also, high-resolution climate modeling requires advanced computational resources, which are often unavailable in many African research institutions. Strengthening computational infrastructure and increasing funding for technology development can help overcome this barrier (Lemba et al., 2019).

Moreover, lack of institutional collaboration and weak policy frameworks limit the integration of climate data into national energy strategies. Implementing stronger institutional frameworks and encouraging collaboration between climate scientists and energy policymakers is necessary (Lemba et al., 2019).

Furthermore, limited access to energy modelling tools and insufficient technical expertise hinder the adoption of advanced climate-energy integration techniques. Expanding regional and international partnerships for capacity building and technology transfer can help address this limitation (Teshfamichael & Fuchs, 2024).

## 2. Kenya

### 3.1 Case study description

This study focuses on the regional power system of Kenya to investigate how climate change impacts influence future energy system strategies in eastern Africa. Kenya was selected as the case study due to its leading position in electricity supply in the region and its role as a demonstration site for the ENERGICA project, which provides a feasible foundation for regional power system modeling. The country possesses outstanding renewable energy potential, including significant geothermal, solar, wind, and hydro resources that are central to its sustainable energy expansion (International Energy Agency, 2022).

In 2023, Kenya's installed electricity capacity stood at 3,321 MW (EPRA, 2024). Renewable sources accounted for 73.3% of this total, with an energy mix dominated by geothermal (28.4%), followed by hydropower (25.3%), thermal power (20.6%), wind (13.2%), and solar (6.4%) (International Trade Administration, 2024). Furthermore, Kenya has demonstrated a strong commitment to climate mitigation through its Long-Term Low Emission Development Strategy (LT-LEDS), which aims to achieve net-zero emissions by 2050 (African Union, 2023). This commitment, combined with the nation's reliance on climate-sensitive resources, explains the critical need for a robust, climate-adaptive energy strategy to support stable and sustainable growth in the region (Gachanja et al., 2023).

### 3.2 Research questions

While numerous energy modelling studies have been conducted for African regions, most focus on decarbonization strategies based on historical weather conditions. This approach may lead to inaccuracies in the design and investment of future energy systems, as it overlooks the direct impacts of climate change on energy demand and renewable resource potential. Although some research has explored this link in Europe, a significant gap exists for Africa.

Specifically in Kenya, a systematic review of the energy modeling landscape revealed that while climate change is a recognized theme, there is still a lack of climate-informed energy system modeling that is directly connected with future climate projections (Fields et al., 2025). To address this gap, this study contributes to the field by exploring the following key research questions:

1. What are the impacts of climate change on energy demand and renewable resources in Kenya?
2. How does climate change affect the optimal design of the future power system in Kenya?
3. What are the life cycle greenhouse gas (GHG) emissions of the power system across different decarbonization pathways under the influence of climate change?

### 3.3 Methodology

#### 3.3.1 Climate projections and data processing

##### 3.3.1.1. EC-Earth3 Earth System Model

Earth System Models (ESMs) are essential tools for forecasting future climate change and its consequences. These models combine data from the planet's atmosphere, oceans, and land to project future trends in temperature, wind, radiation, and precipitation. Such projections are vital for renewable energy planning because they help determine the future availability of resources. Furthermore, by modelling the effects of temperature changes and extreme weather, ESMs can also help predict future shifts in energy demand for heating and cooling (Gasser, 2024; IIASA, 2024).

This study utilizes the state-of-the-art EC-Earth3 Earth System Model to project future climate conditions for Kenya towards 2050. As a key contributor to the Coupled Model Intercomparison Project Phase 6 (CMIP6), EC-Earth3 provides high-quality simulations that have informed multiple reports from the Intergovernmental Panel on Climate Change (IPCC). The model's standard configuration offers a comprehensive representation of the Earth system by integrating the IFS atmosphere model (including the HTESSEL land surface module) with the NEMO3.6 ocean model and its LIM3 sea ice module. This integrated approach allows for robust modelling of complex processes such as monsoons and vegetation growth (Döscher et al., 2022).

The EC-Earth3-Veg model represents an enhanced version of EC-Earth3, distinguished by the incorporation of the LPJ-GUESS dynamic global vegetation model to simulate crucial vegetation-climate feedback. Figure 35 details the model's standard-resolution architecture, illustrating the coupling links and typical update frequencies among its various components (Döscher et al., 2022).

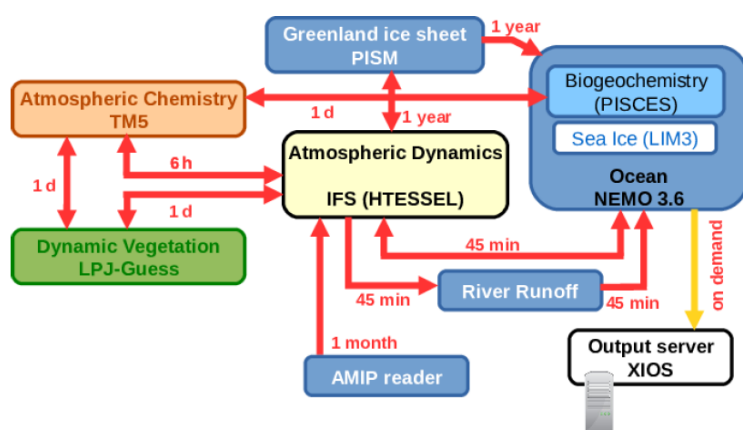


Figure 35. Schematic of the model's comprehensive coupling architecture at a standard resolution.

The diagram illustrates all potential links and their typical data exchange frequencies between every component that can be coupled. In practice, specific model configurations typically implement a subset of these components and their associated couplings.

Source: Ministry of Energy Kenya, 2022.

For this study, climate projection data from the EC-Earth3-Veg model were acquired from the Earth System Grid Federation (ESGF) CMIP6 archive. These datasets serve as the primary climate inputs for the power system modelling. The temporal resolution of the data varies by variable; for instance, near-surface wind speed and temperature are provided at a 3-hourly resolution, whereas key variables such as total runoff and clear-sky radiation flux are available at a monthly resolution (Earth System Grid Federation, 2024).

### 3.3.1.2. Climate data processing

A primary challenge in utilizing future climate projections for energy system analysis is the significant discrepancy between the coarse resolution of climate model outputs and the high-resolution input requirements of energy system models. This mismatch is apparent in both temporal and spatial domains. For example, while the EC-Earth3-Veg climate model provides data at spatial resolutions of up to 100 km and temporal resolutions ranging from 3-hourly to monthly, energy system models like PyPSA-Earth typically demand hourly data at a much finer spatial resolution of approximately 30 km. Consequently, raw climate model outputs are often incompatible with these energy models and necessitate significant downscaling and processing to generate viable renewable energy resource data (Formayer et al., 2023).

This challenge of bridging the gap between coarse climate data and the fine-grained input requirements of energy models is particularly evident in the case of wind speed. Climate models typically provide near-surface wind speed at a standard height of 10 meters with low spatiotemporal resolution. In contrast, energy models require high-resolution wind speed data at a turbine's hub height—commonly 100 meters—to accurately assess wind power generation potential (Formayer et al., 2023).

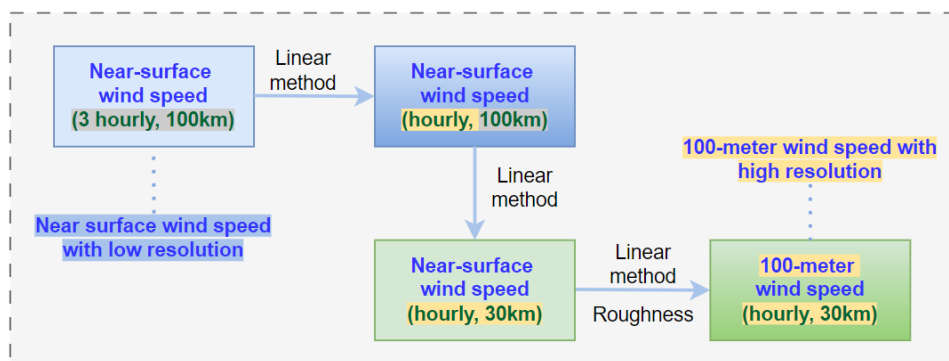


Figure 36. Converting process from near-surface wind speed with low resolution to 100-meter wind speed with high resolution.

As illustrated in Figure 36, the raw near-surface wind speed data undergoes a three-step conversion process to meet the input requirements of the energy system model. First, the data is spatiotemporally downsampled: the temporal resolution is increased from 3-hourly to hourly, and the spatial resolution is refined from 100 km to 30 km, with both steps accomplished using linear interpolation methods. Finally, the downsampled near-surface wind speed is vertically extrapolated to a hub height of 100 meters. This final conversion is

performed using the logarithmic wind profile, as formulated in Equation (1), which assumes conditions of flat terrain and neutral atmospheric stratification and incorporates a specified surface roughness length (Wind energy data for Switzerland, 2024):

$$v_2 = v_1 \cdot \frac{\ln \frac{h_2}{z_0}}{\ln \frac{h_1}{z_0}} \quad (1)$$

$v_1$ : Wind speed at height  $h_1$ ;  
 $v_2$ : Wind speed at height  $h_2$ ;  
 $z_0$ : The roughness length;

### 3.3.1.3. Cooling demand estimation

There are various methods to evaluate the impact of climate change on cooling demand. Traditionally, this is done through the calculation of Cooling Degree Days (CDDs), a technique commonly employed by electric utilities to forecast upcoming cooling loads based on climate change predictions.

CDDs measure how much the daily average temperature exceeds a baseline, usually set at 18°C (65°F). Each CDD represents one degree above this threshold on a given day. These values are totaled over periods like months or years to estimate cooling demand and analyze energy needs influenced by climate.

Equation (2) describes that the CDDs calculated by the summation of all days in one year where  $T_{avg,i,j}$  exceeds  $T_{base}$  (Al-Hadhrami, 2013; Ding et al., 2007):

$$CDD_{i,j} = \sum (T_{avg,i,j} - T_{base}) \quad (2)$$

$T_{avg,i,j}$ : The average daily temperature of region/country  $i$  in year  $j$ ;

$T_{base}$ : The base temperature (18°C);

The study by Ding et al. (2007) investigates the relationship between cooling demand and Cooling Degree Days (CDDs), introducing a method where cooling demand is calculated based on the number of CDDs and a coefficient that captures how historical cooling demand changed with each unit increase in CDDs (Ding et al., 2007). Building on this methodology, our study estimates Kenya's cooling demand under the SSP1-2.6 and SSP5-8.5 scenarios, using a coefficient derived from the relationship between cooling demand and variations in CDDs up to 2013. These estimates are further adjusted to account for projected electricity access rates relative to the 2013 baseline, assuming that 75% of the demand reflects served cooling demand (IEA, 2023; Ministry of Environment, Climate Change and Forestry, 2023). Projections of Kenya's CDDs were sourced from the Climate Change Knowledge Portal using the Multi-Model Ensemble (World Bank, 2021).

### 3.3.2 Energy system optimization

This study employs the PyPSA-Earth model to perform power system optimization. PyPSA-Earth is an open-source, global energy system optimization model that integrates a highly customizable data extraction pipeline with the established PyPSA modeling framework (Parzen et al., 2023). First demonstrated in an application to the African continent, the model is distinguished by its significant flexibility and powerful optimization capabilities. Its flexibility is evident in a modular architecture—designed for the straightforward integration of new features and datasets—and an adaptable modeling scope that ranges from global analyses down to specific subregions. In terms of optimization, it supports high spatiotemporal resolutions, allows for the co-optimization of both long-term investment and short-term operational strategies over single or multi-year horizons, and enables the inclusion of diverse technical, economic, or socio-economic constraints. Ultimately, PyPSA-Earth is designed to serve as a collaborative platform for policymakers, businesses, and researchers to conduct the complex macro-energy system analyses essential for navigating the energy transition (Parzen et al., 2023).

The methodology of this study is based on the PyPSA-Earth model. As an open-source energy system optimization model, PyPSA-Earth has been extensively validated across the African continent and tested in a 2060 net-zero planning study for Nigeria, confirming its suitability for this research (Parzen et al., 2023). The model's core function is to optimize the power system to achieve minimum total system cost, subject to constraints including regional energy demand, weather profiles, renewable potential, technology costs, and carbon emission limits.

For the present analysis of Kenya, scenarios were developed by customizing these key inputs. Specifically, future energy demand was projected using GDP, population, and energy efficiency factors from various Shared Socioeconomic Pathways (SSPs), with the underlying demographic and economic data sourced from the IIASA SSP database (IIASA, 2024). Furthermore, the CO<sub>2</sub> emissions limit for the “green path” scenario (SSP1-2.6) was defined using the KCERT 2050 Carbon Calculator from the Ministry of Energy Kenya (2022) (Ministry of Energy Kenya, 2022). A detailed description of all datasets and their derivation processes is provided in the supplementary material.

### 3.3.3 Framework of integrated climate and energy models

The framework of regional integrated energy and climate models consists of the PyPSA-Earth power system model, the EC-Earth3 Earth System Model and the Multi-Climate Model Ensemble. Figure 37 displays how the data flows from the input to the output in the integrated model framework and penetrates between the energy and climate models.

The input data include the energy demand and climate data in different shared socioeconomic pathways, technology data of power systems, grid OSM data, and economic and environmental data such as cost and CO<sub>2</sub> emissions.

The flowchart illustrates the integrated climate and energy modelling framework, showing the flow of data and information between various components.

**Input Data (Left Column):**

- SSPs
- Tech data
- Grid OSM data
- Electricity demand
- Economical data (Cost, Pop, GDP)
- Environmental data (hydro, land)
- Climate data

**Core Modelling (Center):**

- Energy system model (Pypsa-earth)** receives input from SSPs and Tech data.
- EC-Earth3 Earth System Model** receives input from Grid OSM data, Electricity demand, and Climate data.
- Future Climate Data with low resolution (Wind speed, solar radiation, inflow)** is processed by EC-Earth3.
- High resolution hourly, 30km** data is derived from the low resolution data.
- Future Climate Data with high resolution** is derived from the high resolution data.
- Climate variables adjusting to be usable for renewable resources** are derived from the high resolution data.
- Multi-Climate Model Ensemble** receives input from the Future Climate Data with low resolution and the Future Climate Data with high resolution.
- Future CDDs** are derived from the Multi-Climate Model Ensemble.
- Cooling demand** is derived from the Future CDDs.

**Output and Feedback (Right Column):**

- Climate change impact on energy system designing** is derived from the Energy system model.
- Feedback of energy system to the climate change adaption** is derived from the Energy system model.
- Integrated Climate and energy modelling sensitivity analyses** is derived from the Multi-Climate Model Ensemble.
- Climate change mitigation potential** is derived from the Multi-Climate Model Ensemble.

### 3.3.4 Integrated climate and energy scenario design

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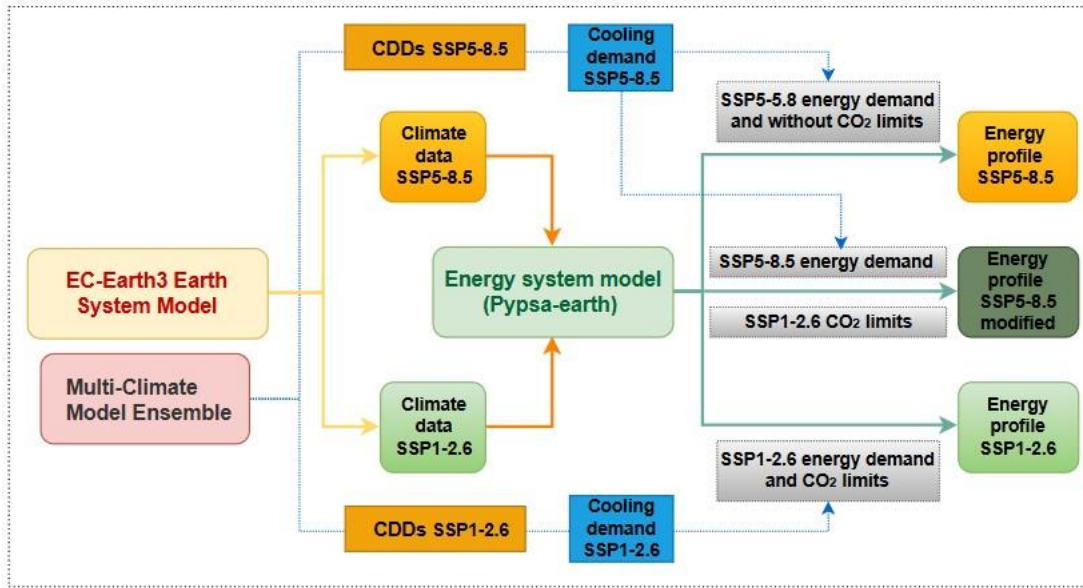


Figure 38. Integrated climate and energy scenarios design

### 3.3.5 Life cycle assessment

Process-based life cycle assessment (LCA) [40] is employed as a holistic approach to analyze the climate change impacts of the power systems optimized in different scenarios. LCA covers all energy and material flows that occur in all life cycle stages, including the construction, operation, and end-of-life phases. It enables the evaluation of different technologies completely and comparably. Hence, LCA avoids problems shifting from one life-cycle stage to another.

In this study, the functional unit for the LCA is 1 kWh of electricity generated, transmitted, or stored. The system boundary of the LCA includes the foreground and background systems. The foreground system consists of all the processes from energy production to supply, including energy generation, transmission, and storage. The background system contains the upstream of all the energy infrastructures. Figure 39 shows the integral energy system for LCA.

The life cycle climate impacts of the optimized power systems are calculated by the sum of products of the impact intensity and energy supply (generation, transmission, and storage) of various technologies in each scenario towards 2050.

$$I_{\text{life}} = \sum_j (I_{\text{life},j} \cdot E_j) \quad (3)$$

$I_{\text{life}}$ : Total life cycle impact of climate change, gCO<sub>2</sub>eq/year;

$I_{\text{life},j}$ : Climate change impact intensity of technology j, gCO<sub>2</sub>eq/kWh;

$E_j$ : Energy supply of technology j in each scenario towards 2050, kWh/year;

The life cycle climate impact intensity factors of various technologies are derived from existing literature. The energy mix data of the generators, transmission line, and storage are based on the energy system optimization results, displayed in the supplementary material. These two datasets enable a complete assessment of the life cycle climate impacts for the optimized power system within three scenarios towards 2050.

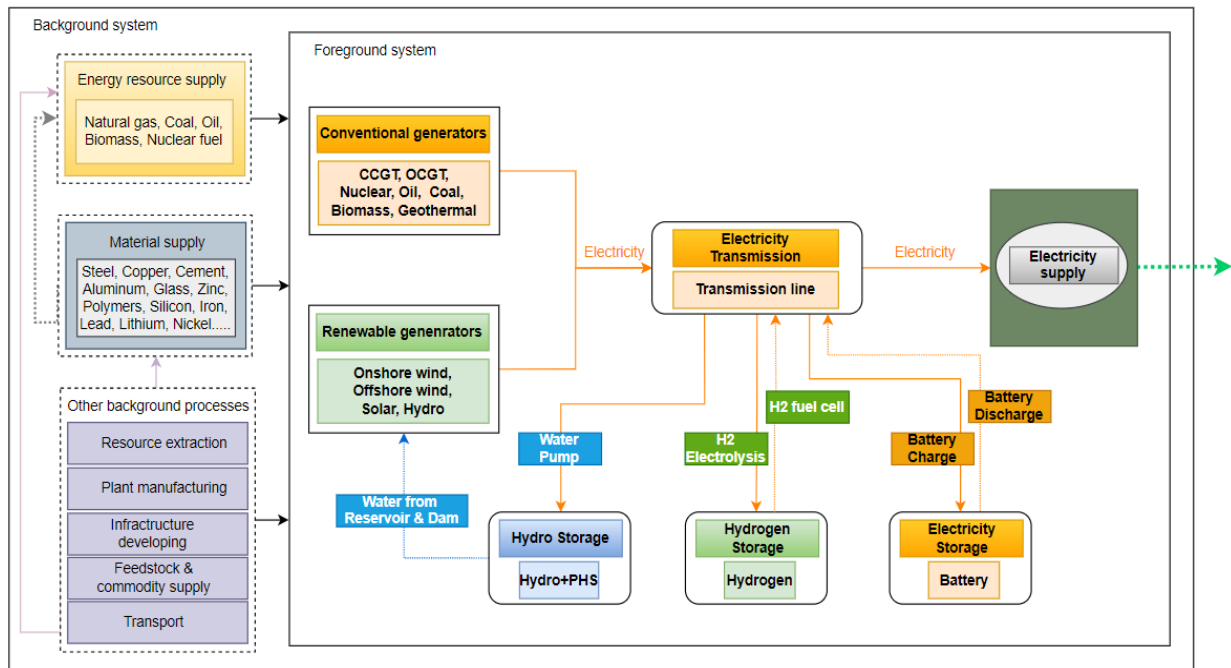


Figure 39 Energy system boundary of life cycle assessment

### 3.4 Results

#### 3.4.1 Climate projection and cooling demand

##### Temperature

The annual average near-surface air temperature distribution in Kenya in 2050, projected by EC-Earth3-Veg under SSP1-2.6 and SSP5-8.5, is compared with the historical temperature in Figure 40. From a geographical perspective, Kenya's northwest and east are generally warmer, while the southwest is the coolest region. From the time distribution, the predicted temperature will increase significantly from May to July and from November to January in Nairobi in 2050.

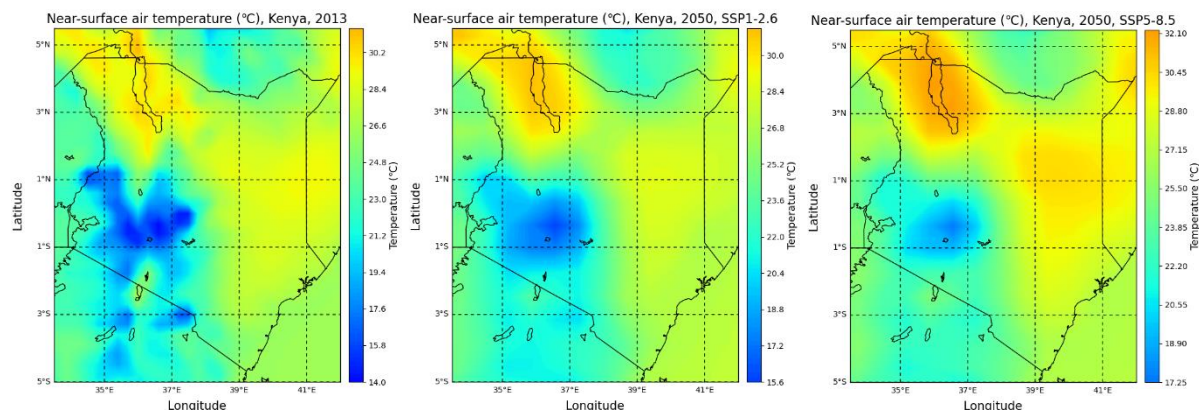


Figure 40 Near-surface annual temperatures in Kenya in 2050 projected by EC-Earth3-Veg compared with historical temperature in 2013

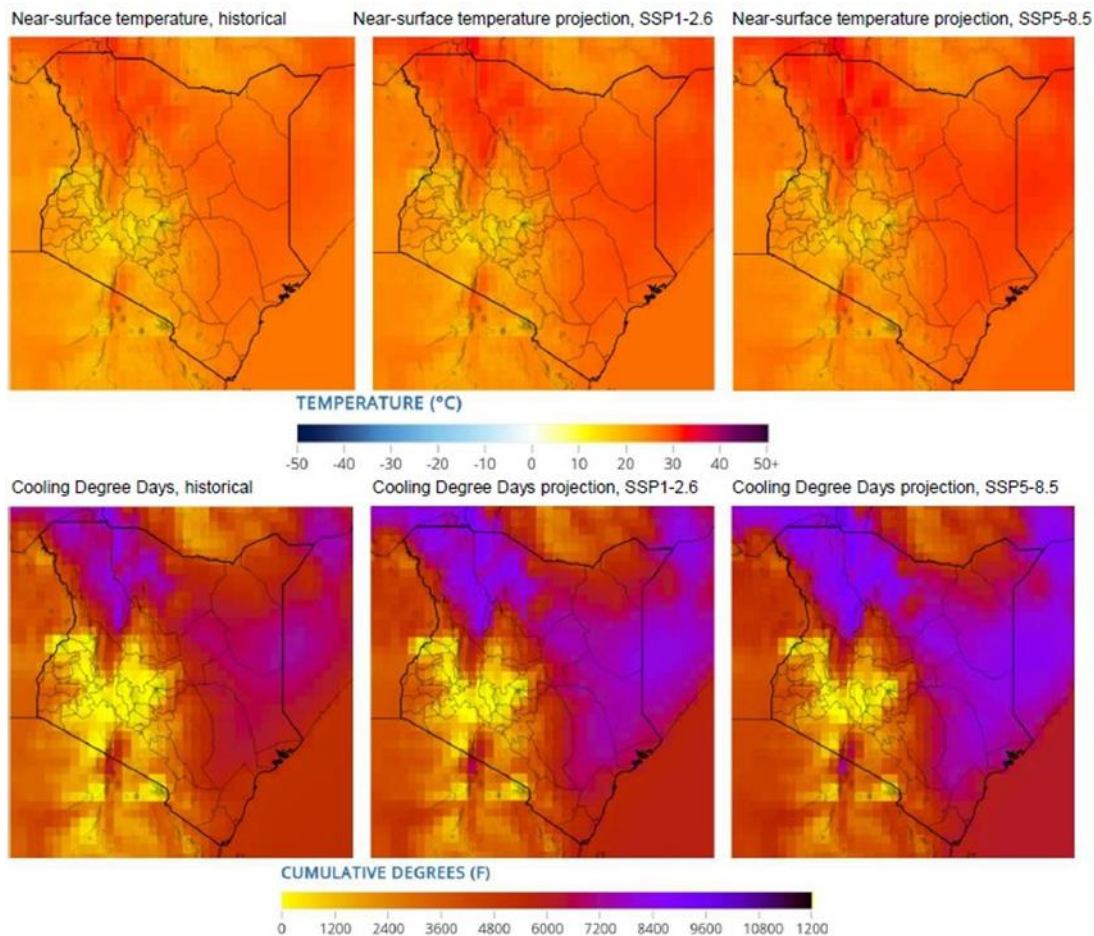


Figure 41 Near-surface annual temperatures and Cooling degree Days (CDDs, ref-65F) in Kenya projected by the Multi-model Ensemble compared with historical temperature

As expected, the projected future temperature in the baseline SSP5-8.5 is higher than in the green path SSP1-2.6. Compared to the climate projection from the Multi-model ensemble (World Bank, 2021), the difference in the temperature increase between these two scenarios projected by EC-Earth3-Veg is the same at 0.5 °C in 2050, which highlights the effectiveness of stringent emission reductions under SSP1-2.6 in moderating temperature rise compared to the high-emission SSP5-8.5 pathway for Kenya.

However, the mean near-surface air temperatures projected at 26.5°C and 27°C by the Multi-model ensemble under SSP1-2.6 and SSP5-8.5 for Kenya towards 2050, displayed in Figure 41, are higher than those projected by EC-Earth3-Veg, possibly due to the feedback function from the vegetation model. Considering the uncertainty of the climate projection reduced by the Multi-model ensemble and the data availability of projected cooling degree days (CDDs), the cooling demand is computed from the CDDs by the Multi-model ensemble, shown Figure 41.

### Cooling demand

To estimate cooling demand in Kenya, this study uses projected cooling degree days (CDDs) along with a coefficient representing the change in electricity demand per unit change in CDDs, adjusted for future electricity access rates relative to the 2013 baseline, and assuming that 75% of cooling demand corresponds to served cooling usage under both the SSP1-2.6

and SSP5-8.5 scenarios (IEA, 2023; Ministry of Environment, Climate Change and Forestry, 2023; World Bank, 2023).

Figure 42, shown below, presents the projected electricity demand for cooling in Kenya from 2014 to 2050 under the SSP1-2.6 and SSP5-8.5 scenarios. As illustrated, cooling demand steadily increases in both scenarios, reaching approximately 5,375 GWh under SSP1-2.6 and 5,718 GWh under SSP5-8.5 by 2050. This represents about a 6.4% higher demand in the SSP5-8.5 scenario compared to SSP1-2.6 in 2050, reflecting the additional cooling needs driven by higher temperatures and reduced climate mitigation efforts in SSP5-8.5. This highlights the significant influence of climate policy pathways on future electricity infrastructure requirements.

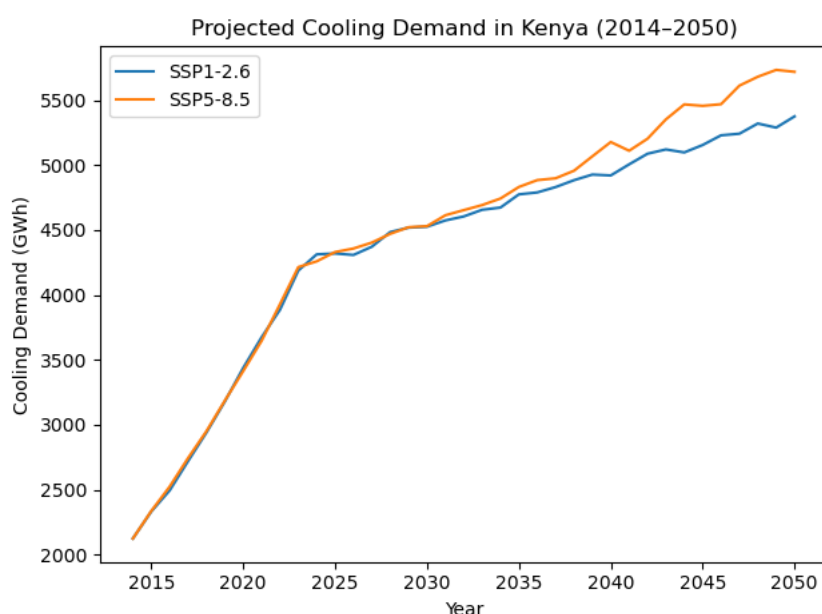


Figure 42. Comparison of Predicted Cooling Demand for SSP1-2.6 and SSP5-8.5 for Kenya.

### Wind speed

The changes in wind speed are complicated. The distribution of near-surface wind speed of Kenya in 2050 in scenarios SSP1-2.6 and SSP5-8.5 projected by EC-Earth3-Veg, compared to historical wind speed, is presented in Figure 43.

Generally, the predicted annual mean near-surface wind speed, including onshore and offshore, decreases by 12-15% in 2050. However, the annual mean onshore wind speed is predicted to decline by around 14-16% towards 2050. While the annual mean offshore wind speed is projected to rise by 15-20%. The SSP1-2.6 scenario has slightly lower onshore wind speeds but higher offshore wind speeds than the SSP5-8.5 scenario.

Geographically, the onshore wind speed is higher in the east than in the west. The offshore wind speeds are much higher than the onshore.

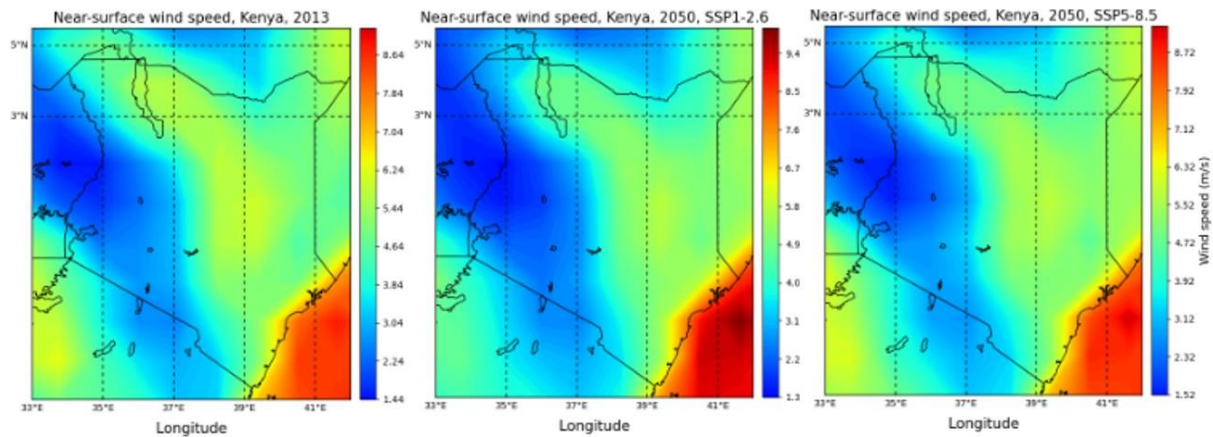


Figure 43 Annual mean near-surface wind speed in Kenya in 2050 projected by EC-Earth3-Veg compared to the historical

The processed hourly 100-meter onshore and offshore wind speeds on the typical locations in 2050 are presented in Figure 44. The average 100-meter onshore wind speeds in Nairobi are projected at 2.6m/s and 2.5m/s respectively, in SSP1-2.6 and SSP5-8.5, compared with the historical wind speed of 3.5m/s, decreasing by 25.0% and 28.6% in 2050. It is noticed that the patterns of the three curves of hourly 100-meter wind speeds and near-surface wind speeds are similar.

The average 100-meter offshore wind speeds in the coordinate (-2.4 S, 41.4 E) as a typical coastal position are dramatically increased in 2050, predicted at 12.7 m/s and 12.2 m/s respectively in SSP1-2.6 and SSP5-8.5.

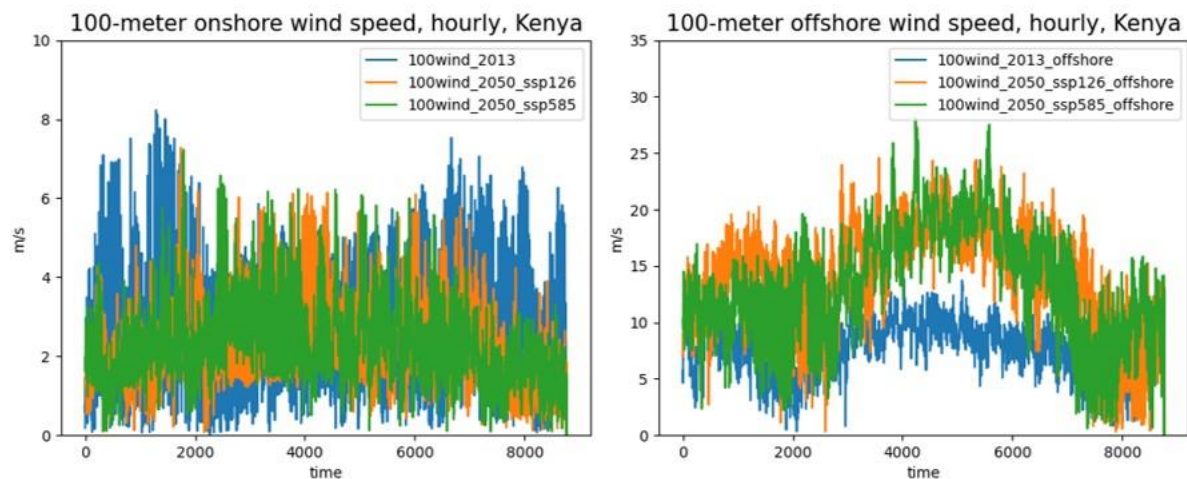


Figure 44 The hourly 100-meter onshore (Nairobi) and offshore (-2.4 S, 41.4 E) wind speed in 2050 projected by EC-Earth3-Veg, compared with the historical wind speeds in 2013

### 3.4.2 Climate adaptation from energy system design

The optimization results of the future power system modeling for Kenya are shown in Figures Figure 45 to Figure 48. Generally, Kenya's electricity generator projection for 2050 in different scenarios shows that electricity demand and CO<sub>2</sub> limits greatly impact the energy system profile, including the total amount of generator capacity, generation, and the energy mix. The

capacities of the generators in scenarios of SSP1 and SSP5 integrated with future climate are 7.6 GW and 10 GW, respectively. The generations of them are 27.2 TWh, and 50 TWh under the two scenarios. In scenario SSP5m with strict CO<sub>2</sub> limits and high energy demand, the capacity is much higher than in SSP5 with the same energy load but no CO<sub>2</sub> limits, by increasing 132% from 10 GW to 23 GW, in which solar and wind are the main components. SSP1 has the lowest capacity and generation due to its lowest energy demand. The capacity of biomass increases from 34 MW in 2023 to 721 MW in both future scenarios, SSP1 and SSP5m, while the hydropower drops from 780 MW currently to 356 MW in all three scenarios. The projected increased cooling demand due to global warming contributes 18.4% and 11.5% to the total energy demand in SSP1 and SSP5(m). The capacities are growing by 52.3% and 21.0% in scenarios SSP1 and SSP5m where solar and wind power are the two main technologies, increasing their capacity to meet the increased cooling demand.

However, regarding the general energy profile optimized with historical and projected future climate, the generator capacities for both SSP1 and SSP5m are lower with the future climate than with the historical climate, by 12.8% and 21.5% for each. Kenya's wind power profile significantly changes after integrating the future climate into its power system modeling in scenarios of SSP1 and SSP5m due to the projected change in onshore and offshore wind speed in 2050. Especially in SSP5m, the capacity of the onshore wind power significantly shrinks from 5.7 GW to 0.4 MW, while the offshore wind power substantially rises from 0 MW to 3.4 MW. In scenario SSP5 Without CO<sub>2</sub> limit, there are no large differences in the capacity and generation between the historical climate and future climate.

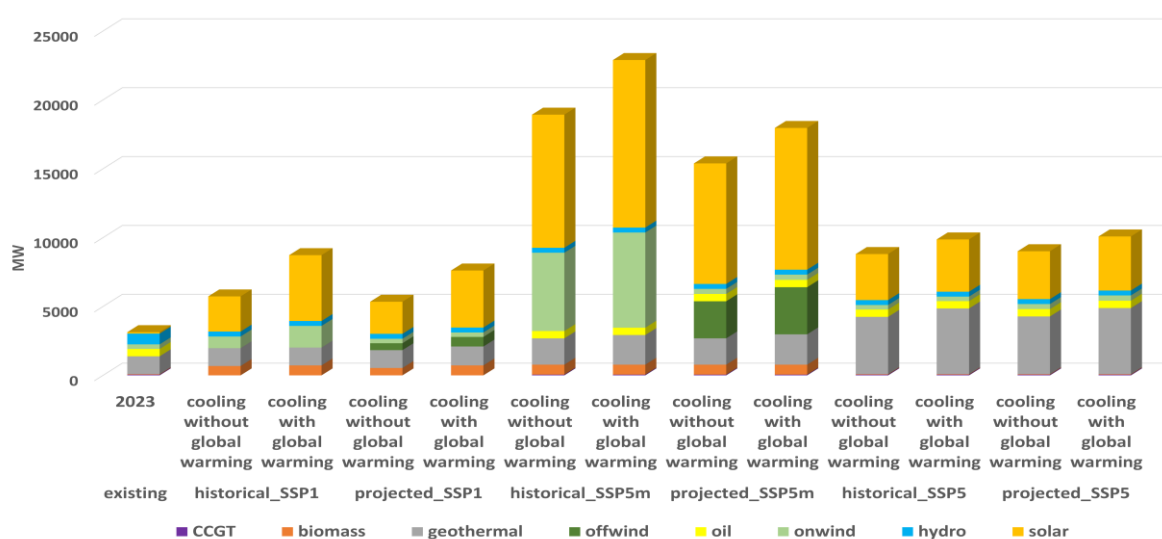


Figure 45. Electricity capacity projection in 2050 for Kenya with historical and future climate, MW

For the capacity composition in Figure 46, solar and wind power take a dominant position when CO<sub>2</sub> constraints are strict. Solar power grows the fastest and takes the largest share in the future, increasing from 3.4% in 2023 to more than 50% in 2050 for both scenarios of SSP1 and SSP5m in Kenya when CO<sub>2</sub> emissions of the power system are very low. Geothermal climbs to 48.3% when there are no CO<sub>2</sub> limits in SSP5. For SSP1 and SSP5m, geothermal shrinks to 14.8-18.0% and 9.4-12.3% respectively. It is worth mentioning that the capacity share of hydro reduces significantly from 24.9% to 4.7%, 2.0% and 3.5% in the three future scenarios.

Biomass share grows from 1.1% to 9.5% and 4.0% in scenarios of SSP1 and SSP5m but declines to 0.3% in SSP5.

In respect of the comparison between the historical and future climate, offshore wind significantly increases in SSP1-2.6 and SSP5m, replacing the majority share of onshore wind. Peculiarly, the capacity of onshore wind power dramatically diminishes from 30.2% to 2.1%, and offshore wind power remarkably goes up from 0% to 19.0% in SSP5m.

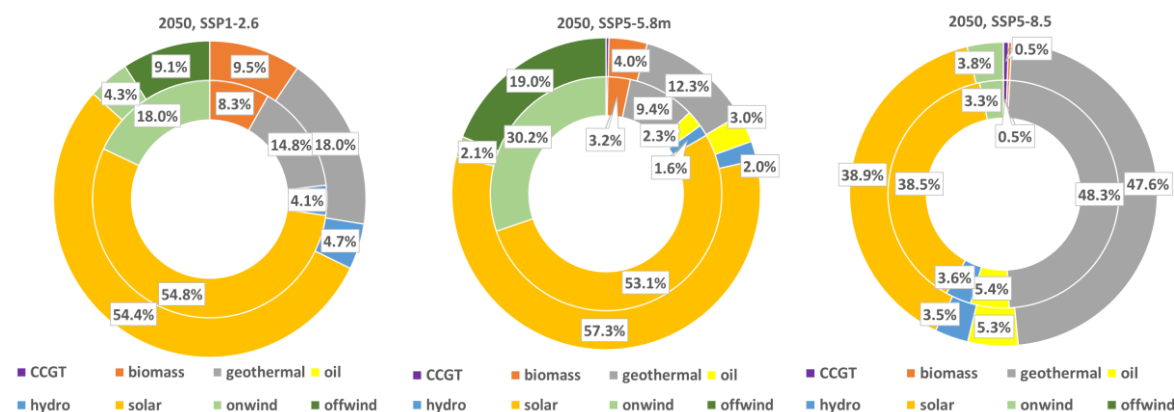


Figure 46 Projected electricity capacity composition in 2050, Kenya (the outside circle is the energy system integrated with the future climate, the inside circle is integrated with the historical climate, both considering cooling demand with global warming)

In terms of electricity generation in Figure 47, SSP5 and SSP5m have the same total amount of generation at 50 TWh due to the same energy demand setting in 2050. However, geothermal generation jumps and takes a prominent share in SSP5, at 42.0 TWh. In SSP1 and SSP5m, the share of geothermal is restricted at 9.2 TWh and 7.9 TWh, respectively. Wind power generation is higher than solar but with a lower capacity in SSP5m. The generation of solar and wind are almost the same when the energy system integrating with the projected future climate and historical climate, while the total capacity of wind integrating with projected future climate is lower than that with historical climate.

Similar to the capacity composition, the generation share of the offshore wind with future climate significantly expands in SSP1 and SSP5m. However, it is noticeable that Offshore wind power has an even larger portion of total generation, at 15.9% and 39.9% in SSP1 and SSP5m, than its portion of the total capacity. Meanwhile, solar generation share reduces to 21.7% and 29.3% in SSP1 and SSP5m compared to over half share of the capacity. In SSP5, geothermal delivers the most electricity generation, by 85.5% of the power system. Biomass supplies 23.2% and 11.7% of generation in SSP1 and SSP5m, much larger shares than their capacity shares. Hydro has a similar low share of the generation at 2.1%-3.8% as their capacity share.

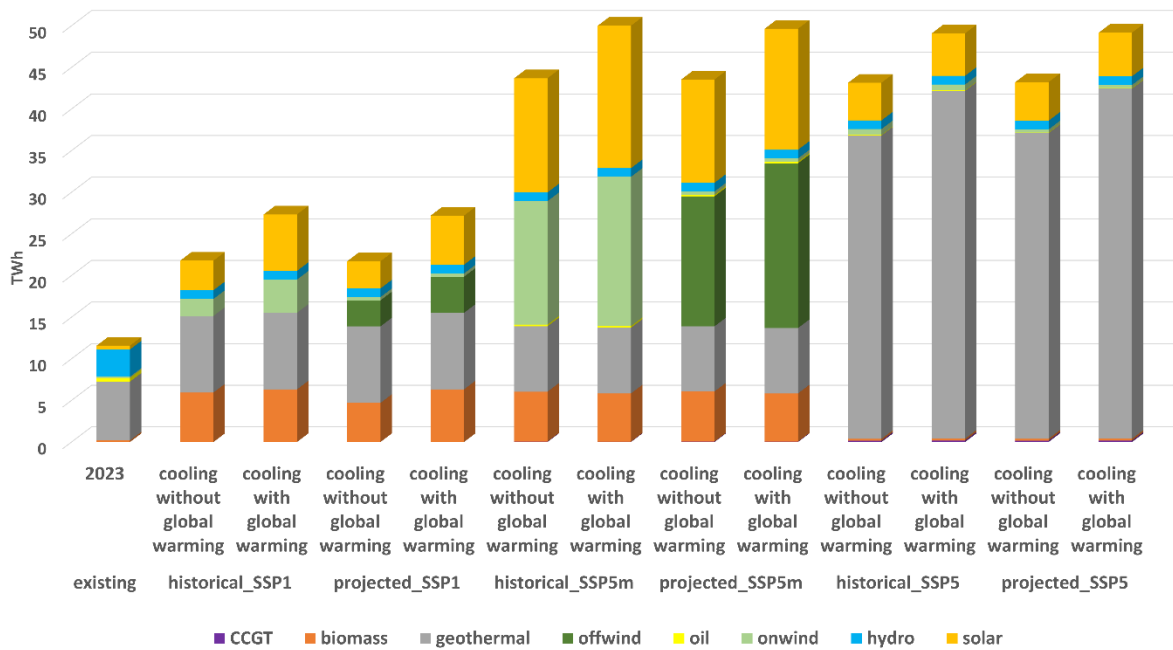


Figure 47. Electricity generation in 2050 for Kenya with historical and future climate

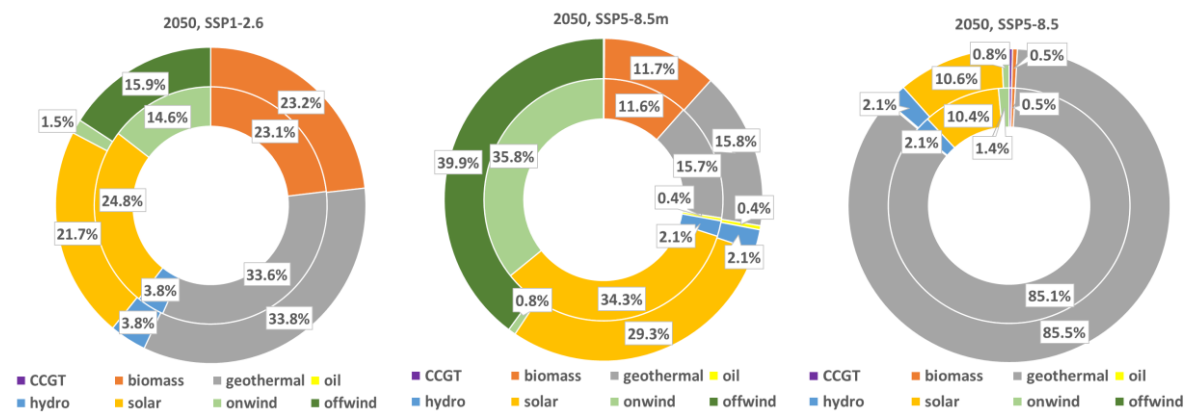


Figure 48. Projected electricity generation composition, Kenya (the outside circle is the energy system integrated with the future climate, the inside circle is integrated with the historical climate, both considering cooling demand with global warming)

Figure 49 display the capacity projection of transmission line and storage in 2050 for Kenya, which exhibits the similar pattern as the capacity of generators. The total capacities of transmission and storage are the highest in SSP5m. There are no significant differences of the transmission line capacity within three scenarios, but the storage capacities are much higher in SSP5m than in SSP5 due to the higher share capacity of renewable powers. The capacity of store hydrogen storage is generally higher than the battery storage.

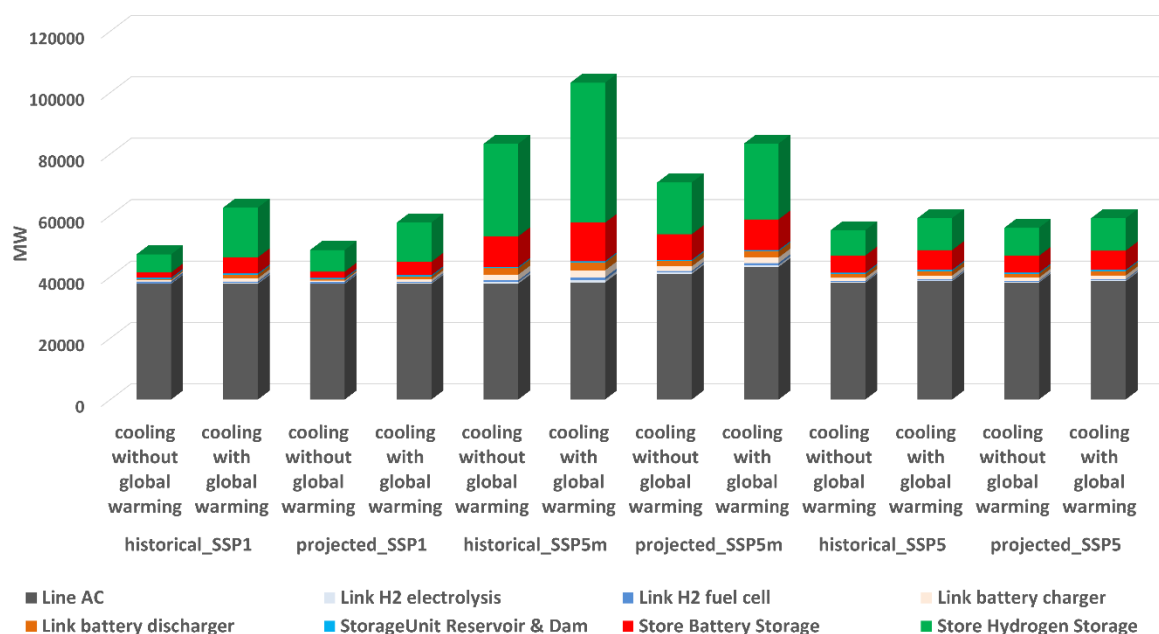


Figure 49. Capacity Projection of Transmission Line and Storage in 2050 for Kenya, MW

### 3.4.3 Comparisons of the total system cost of the power system

Figure 50 and Figure 51 show the capital cost of generators, transmission lines, and storage under the historical and the projected future climate. Scenario SSP5m has the highest capital cost of the generators at nearly 2.5 billion Euros under the predicted future climate for Kenya in 2050, slightly higher than the generators under the historical climate by 5.4%. Offwind, geothermal, and solar take the top three shares at 33.5%, 30.2%, and 21.4% respectively. SSP5-8.5 has the second-highest cost of generators, close to 2 billion Euros, about 20% less than the generator cost in scenario SSP5m. Geothermal occupies a dominant share at 81.2%, followed by solar taking 10.1% of total generator cost. SSP1-2.6 has the lowest capital cost of generators at around 1.2 billion Euros, nearly 70% lower than scenario SSP5-5.8.

Regarding the capital cost of the transmission line and storage, SSP5m still has the highest cost within the historical climate, at 550 million Euros, 8.4% higher than the scenario under the projected climate. SSP5-8.5 and SSP1-2.6 have the middle and the lowest cost at 348 and 300 million Euros. However, the distance between these two scenarios is much smaller, with only a 16% difference. In terms of transmission and storage, the transmission line cost takes the largest share in the range of 41.8%-55.4% in the three scenarios, followed by the battery storage in the range of 23.1%-31.4%. The third highest one is the battery charger, taking the share from 11.2% to 14.0%. The rest of the cost is taken care of by hydrogen systems, including electrolysis, fuel cell, and storage, taking 8.8%-13.0% in the three scenarios.

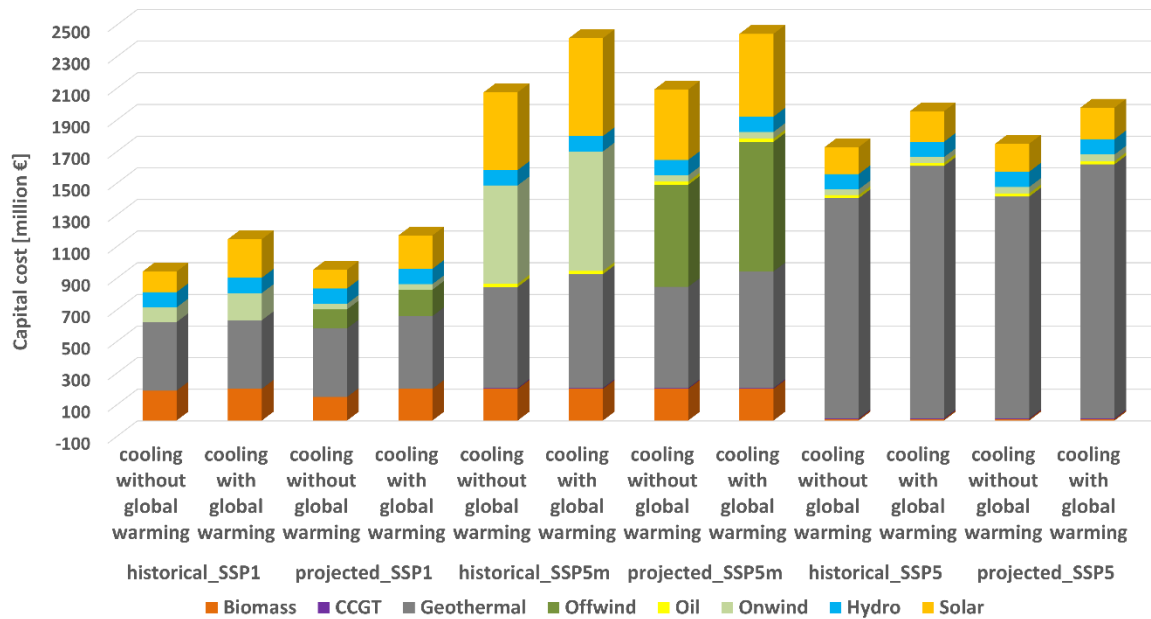


Figure 50. Capital cost of the generators in 2050 for Kenya with historical and future climate

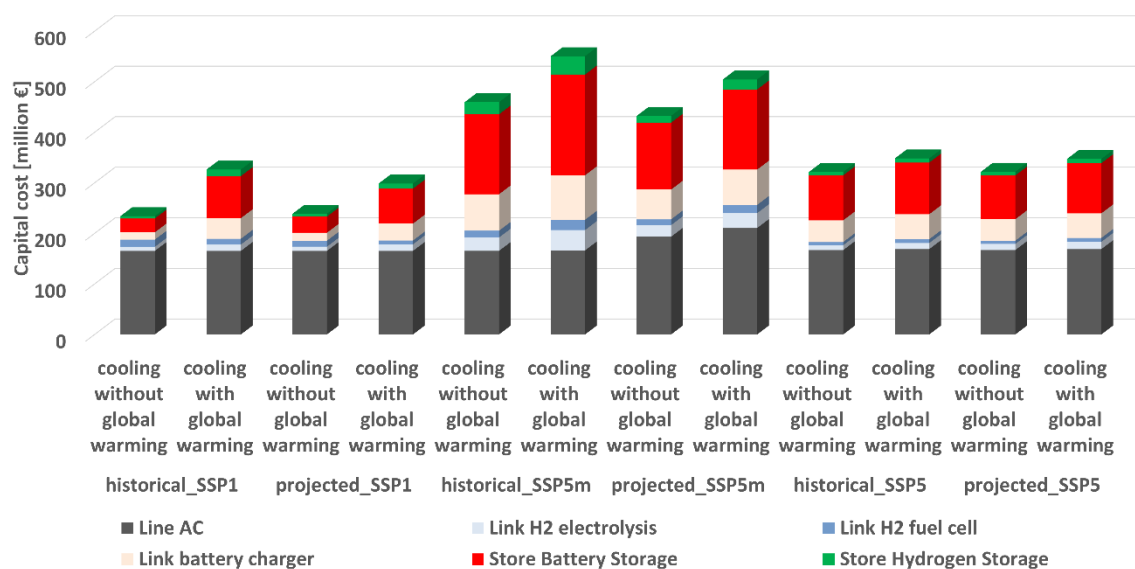


Figure 51. Capital cost of the transmission lines and storage in 2050 for Kenya with historical and future climate

Figure 52 and Figure 53 show the total system capital cost and composition. In the scenarios SSP1-2.6, SSP5m, and SSP5-8.5, the total system capital cost is 1.5 billion, 3.1 billion, and 2.3 billion euros, respectively. Geothermal, solar, biomass, offshore wind and transmission lines are the main five costs in SSP1-2.6, taking 31.3%, 14.3%, 13.7%, 11.3% and 11.3%, respectively. In SSP5m scenario, the cost of offshore wind energy occupies 27.8%, outweighing the geothermal cost by 25.0%. The solar cost takes 17.8%, followed by the transmission line 7.1% and the biomass 6.8%. In SSP5-8.5 scenario, the share of geothermal cost rises to 69%, while solar and transmission line costs drop to 8.6% and 7.3%, respectively. The share of onshore wind, offshore wind, and biomass are negligible in this scenario. Hydropower costs only take 3.3%-6.6% in the three scenarios due to its higher capital cost

than solar and wind power. Battery storage and charge costs take the shares in the range of 6.3%-7.5% in the three scenarios.

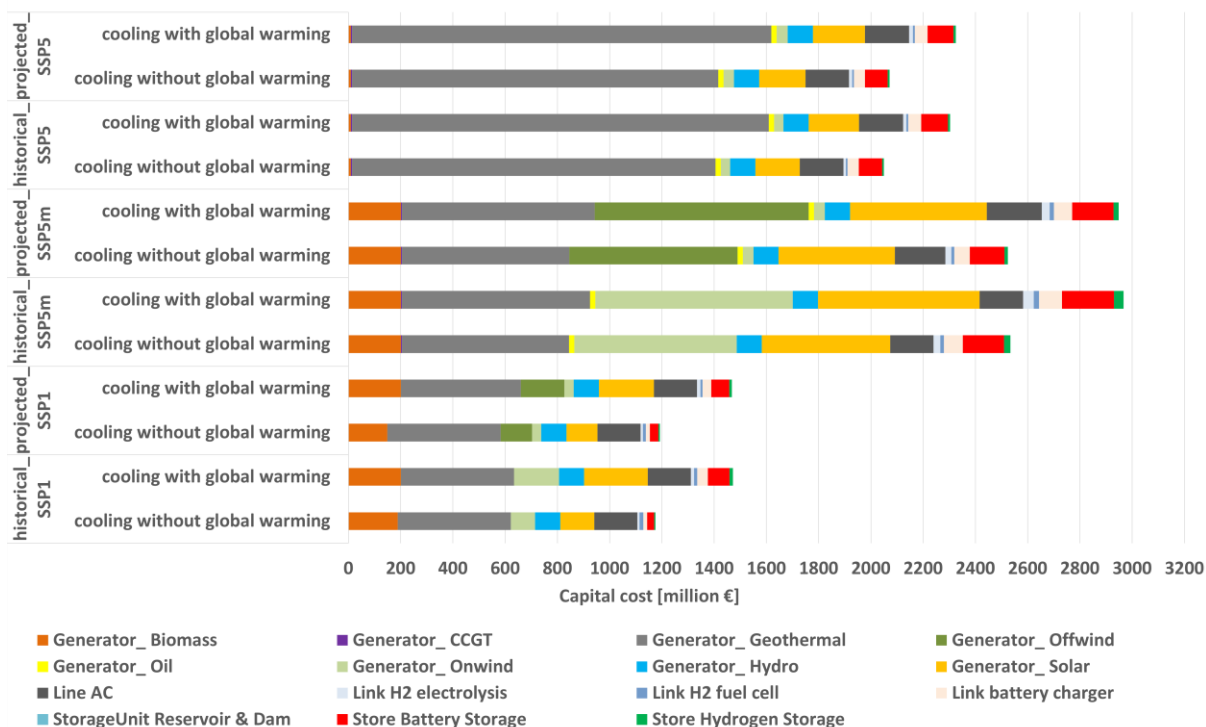


Figure 52. Total system capital cost projection in 2050 for Kenya with historical and future climate

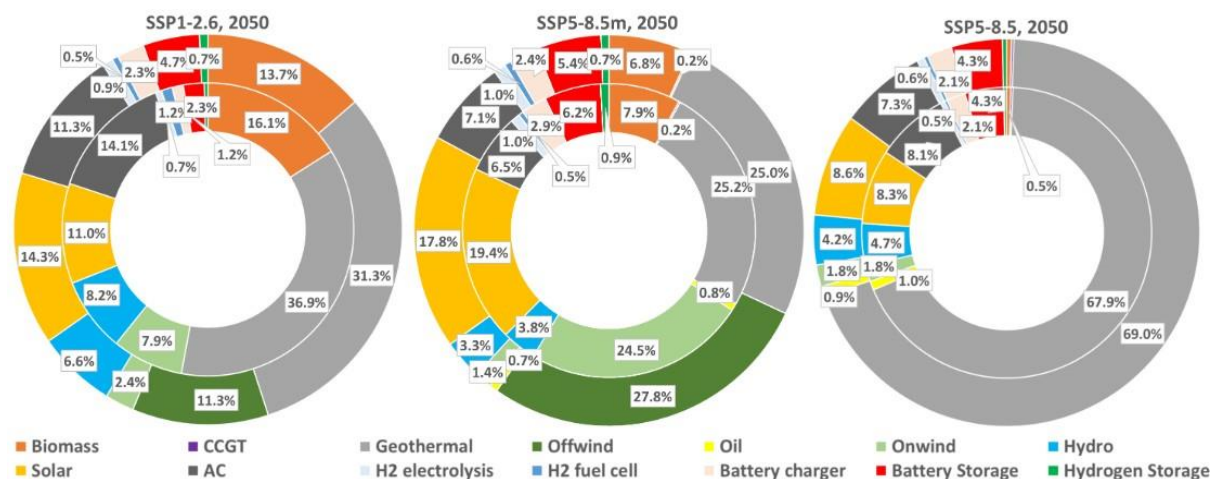


Figure 53. Total system capital cost composition (the outside circle is the energy system integrated with the future climate, the inside circle is integrated with the historical climate)

Figure 54 shows that the operation costs of the power system in scenarios SSP1-2.6 and SSP5-8.5m are much higher, projected at 102 million euros and 134 million euros, than in scenario SSP5-8.5 at 34 million euros. The operation cost mainly comes from the consumption of fossil fuels such as biomass, oil, and natural gas. Renewables including geothermal, wind, and solar have much lower operation costs compared to fossil fuels considering their capacity scales. In scenario SSP1-2.6, biomass takes a 92.3% share of the operation cost. In SSP5m, biomass and oil take 64.4% and 19.5%. While in SSP5-8.5, the operation costs are distributed in oil,

natural gas, geothermal and biomass. Comparing the operation costs of the energy system integrating with the future climate and integrating with the historical climate, there are no large differences.

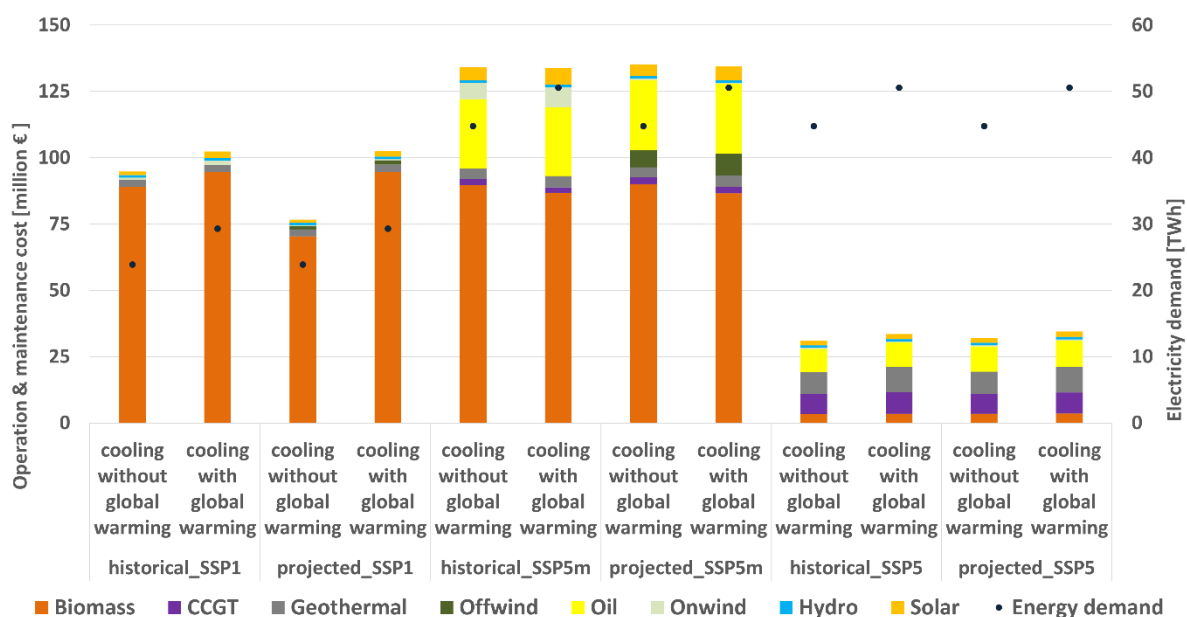


Figure 54. Operation cost and energy demand in 2050 for Kenya with historical and future climate

### 3.4.4 Life cycle assessment of future energy system

Figure 55 displays the total life cycle GHG emission of the power system, including generation, transmission, and storage in these three scenarios. Generally, scenario SSP1 has the lowest life cycle GHG emissions at 1.2 megatons, and scenario SSP5 has the highest emissions at 2.3 megatons. Biomass, geothermal, and solar contribute the most to SSP1, taking 36.8%, 31.8%, and 17.6%, respectively. Geothermal has the dominant share of 76.9% in SSP5. However, in scenario SSP5m, solar, biomass, geothermal, offshore wind, oil, and battery all contribute significantly to the life cycle emission in the complete energy system, taking the share of 27.9%, 21.7%, 17.5%, 11.0%, 8.3%, and 6.2% respectively, which is close to 2 megatons. It is noticeable that the life cycle emissions from energy storage batteries and hydrogen play a role, especially in scenario SSP5m. There is no significant difference between SSP5 and SSP5m for the total life cycle CO<sub>2</sub>eq emissions, although the CO<sub>2</sub> limits in the operation phase are largely different between these two scenarios. It shows that when the energy demand is high with a strict CO<sub>2</sub> limit, emission reductions from large-scale renewables such as solar, wind, and battery have little gain in the life cycle but with very expensive total system costs, compared to geothermal for Kenya.

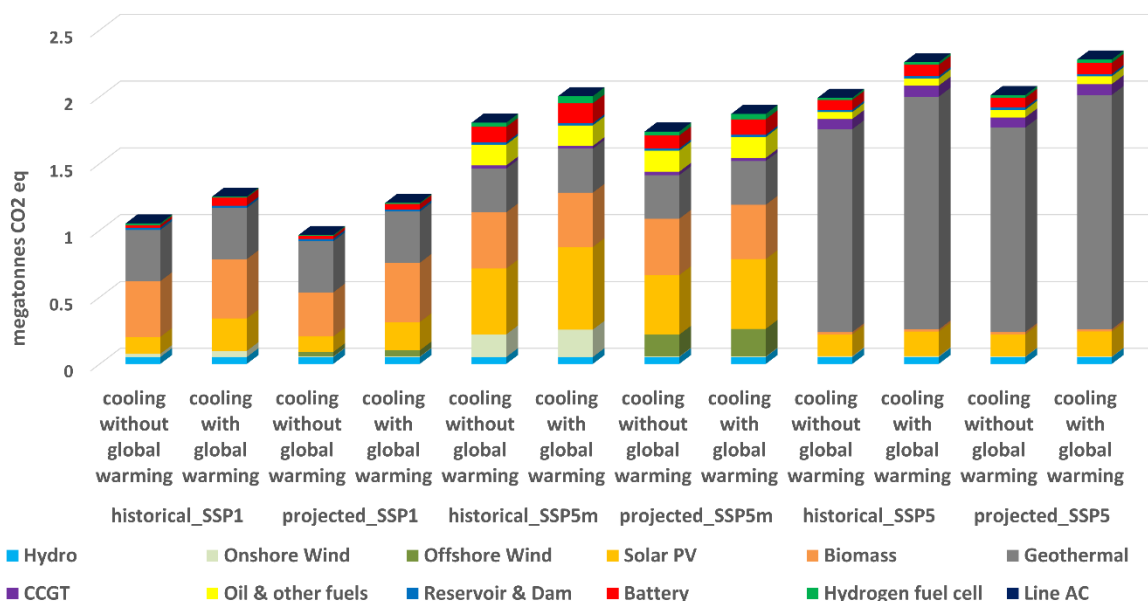


Figure 55. Estimation of the life cycle GHG emissions of the energy system in Kenya in 2050 for different scenarios.

### 3.4.5 Sensitivity analysis

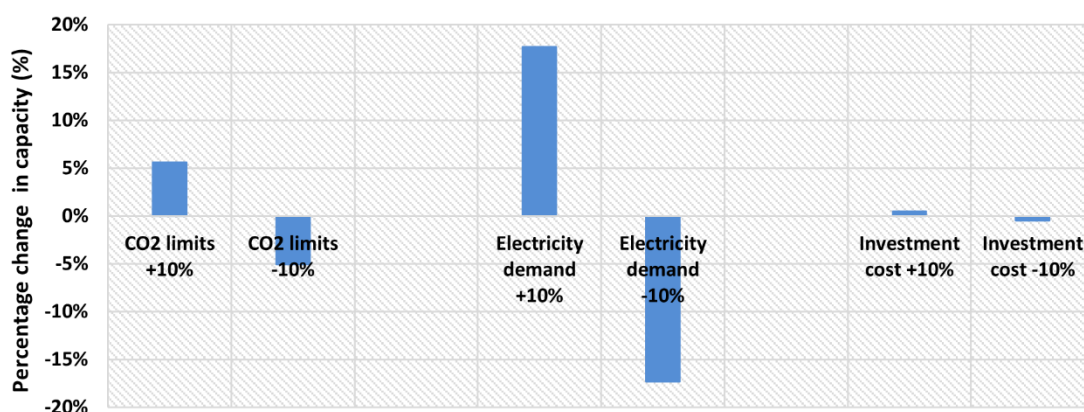


Figure 56. Sensitivity analysis of power system, percentage change in total capacity of generators

The sensitivity assessment of CO<sub>2</sub> emission limits, electricity demand, and capital cost to the total installed capacity of the power system is exhibited in Figure 56. The total capacity is highly sensitive to electricity demand changes. A 10% increase in demand results in a 17.7% rise in capacity, while a 10% decrease leads to a 17.3% reduction. For CO<sub>2</sub> limits, the capacity has a moderate sensitivity. A 10% relaxation in CO<sub>2</sub> limits leads to a 5.05% decrease in capacity, while a 10% tightening of emission limits creates a 5.63% rise in capacity. Regarding the investment cost, a positive and negative 10% change in investment cost only causes small changes at +0.5% and -0.5% for each direction. The sensitivity analysis of the operational costs is also conducted. The operational cost changes were inconsequential for total capacity, showing negligible variation.

### 3.5 Discussion

#### 3.5.1 Climate change trends

Africa is experiencing climate change through rising temperatures, changing rainfall patterns, and more frequent extreme weather events. These changes have a greater impact on the continent because it depends heavily on climate-sensitive sectors and lacks strong adaptive systems, even though it contributes very little to global greenhouse gas emissions (Giordano & Bassini, 2019; Kwakwa, 2023).

In Kenya, these challenges are made worse by changes in land use, such as deforestation for agriculture, which reduces the land's ability to absorb carbon and leads to soil degradation. This in turn makes the country more vulnerable to severe weather (Giordano & Bassini, 2019). Additionally, rapid population growth and urban expansion put pressure on ecosystems and make sustainable resource management more complicated (African Development Bank Group, 2021). Kenya's dependence on rain-fed agriculture increases its risk, as irregular rainfall and prolonged droughts threaten agricultural productivity and food security. Cities face their own set of problems due to unplanned growth, resulting in poor infrastructure that makes them more susceptible to flooding, disrupting transport, housing, and healthcare systems (IASS & SERC, 2021). Drier regions of the country are especially vulnerable to declining rainfall, affecting farming, energy supplies, and wildlife preservation (Kenya Meteorological Department, 2023).

One major obstacle in addressing climate change is uncertainty. While most models agree that temperatures will rise, predictions about rainfall are inconsistent—some forecast more rain in certain areas, while others anticipate longer dry periods. This makes it difficult to plan for farming, water use, and disaster readiness (Kenya Meteorological Department, 2023). Local issues like deforestation and urban sprawl can intensify or reduce these broader climate trends, making local conditions unpredictable. Damaged forests and farmland reduce resistance to extreme weather, while poorly planned urban growth increases exposure to floods and heat waves. The lack of sufficient weather monitoring infrastructure further complicates matters by limiting accurate data collection and model refinement (World Bank Group, 2023).

Our analysis, which uses the EC-Earth3 model, shows similar results to those from the Climate Change Knowledge Portal (CCKP), which uses the ENSEMBLE model from the Coupled Model Intercomparison Project Phase 6 (CMIP6). This CMIP6 effort, managed by the World Climate Research Program (WCRP), underpins the IPCC's Sixth Assessment Report. The ENSEMBLE model provides data at a finer resolution (25 km), while EC-Earth3 offers a broader view (80 km) but still yields reliable projections. Both models forecast a significant increase in Kenya's average annual temperature by 2050 under high-emission scenarios. Specifically, under the low-emission SSP1-2.6 pathway, our study estimates a temperature of 25.5°C—a 0.26°C rise from 2013—while the CCKP projects 26.47°C, or a 0.84°C increase. Under the high-emission SSP5-8.5 scenario, both models agree on a future temperature of 27.0°C, although our model predicts a 1.74°C increase compared to 1.37°C in the ENSEMBLE model (World Bank, 2021).

Despite these minor differences, both models show consistent warming trends. Their agreement on the SSP5-8.5 projection enhances confidence in the overall climate trajectory,

while the differences under SSP1-2.6 underscore how resolution and methodology can influence results. Since both models are part of the CMIP6 framework, their outcomes reinforce the reliability of global climate projections and support their use in Kenya's climate adaptation strategies.

The study emphasizes the uneven nature of climate change impacts across Kenya, noting that the northwestern parts of the country are expected to warm more rapidly than the cooler southwestern regions. This localized variation mirrors broader global climate trends discussed in prior research. Both this study and existing literature stress that temperature increases are largely driven by differing emission trajectories, underscoring the urgent necessity for mitigation and adaptation strategies to safeguard Kenya's agriculture, energy systems, and overall climate resilience.

In terms of wind dynamics, the study identifies distinct changes in wind speed under the SSP1-2.6 and SSP5-8.5 climate pathways. By 2050, average near-surface wind speeds across both land and sea are projected to decline by 13–15%. For instance, onshore wind speeds in Nairobi are expected to drop from 2.8 m/s in 2013 to 2.1 m/s under SSP1-2.6 and 2.0 m/s under SSP5-8.5 (Masson-Delmotte et al., 2021). These reductions are linked to local influences such as the weakening of the Turkana jet, caused by smaller thermal differences between inland East Africa and the Indian Ocean, as well as increased surface roughness and changes in land use (Bloomfield et al., 2022). In contrast, offshore wind speeds are projected to rise significantly, increasing from 7.3 m/s in 2013 to 12.7 m/s under SSP1-2.6 and 12.2 m/s under SSP5-8.5 by mid-century—an increase of 73.7% and 66.7%, respectively. This is attributed to intensifying pressure gradients over the western Indian Ocean, which strengthen southeasterly winds that feed the Turkana jet, particularly during the boreal summer when the ocean's temperature gradient is at its peak (Bloomfield et al., 2022).

These projections are consistent with findings from the IPCC's Interactive Atlas, which uses CMIP6 data. According to the Atlas, average wind speeds under SSP1-2.6 are projected to remain stable around 3.9 m/s, with minor fluctuations (ranging from 3.6 to 4.3 m/s). Under SSP5-8.5, wind speeds are expected to slightly decline from 4.0 to 3.9 m/s by 2100, marking a 2.5% decrease, although the 90th percentile values may increase slightly from 4.4 to 4.5 m/s (Masson-Delmotte et al., 2021). The projected rise in offshore wind speeds in Kenya aligns with scenario-based studies exploring the country's offshore wind potential. These studies highlight the transformative effect of technological innovation—such as floating wind platforms capable of accessing deeper waters—in vastly expanding energy resource availability. Conversely, reliance on outdated shallow-water technologies significantly limits energy potential (Elsner, 2019). While numerical forecasts are not always provided, the literature affirms the crucial role that emerging technologies could play in scaling up offshore wind energy in Kenya.

Climate change also influences solar energy potential by affecting solar radiation. During rainy periods, cloud cover and atmospheric particles reduce solar output, whereas dry, arid regions maintain high solar potential due to minimal cloud presence (IASS & SERC, 2021). Therefore, incorporating future climate projections is essential for optimizing Kenya's renewable energy planning. However, the current study excludes future solar radiation changes due to the

substantial uncertainties associated with regional modeling and current limitations of climate projection tools (Kariuki & Sato, 2018).

### 3.5.2 The relationship between climate change and energy system profile

Climate change is expected to profoundly influence Kenya's future power system, primarily by increasing electricity demand due to rising temperatures. The higher need for cooling leads to greater overall energy consumption, which in turn drives expansion in electricity generation and system capacity. This indicates a direct, positive correlation between temperature increases and the required capacity of the power sector.

Shifts in wind patterns also play a crucial role, fundamentally changing the outlook for renewable energy in Kenya. Forecasts suggest a reduction in onshore wind speeds, whereas offshore wind potential is expected to grow. As a result, onshore wind energy capacity is projected to decline, while offshore capacity is set to expand. This evolving dynamic calls for a strategic reassessment of Kenya's energy portfolio to ensure an optimized future power system.

In optimizing the energy mix, minimizing total costs while fulfilling electricity demand is a key objective. Although the capital investment for offshore wind installations is approximately 57.7% higher than for onshore setups (Danish Energy Agency, 2023), offshore wind delivers greater benefits. This is largely due to its superior capacity factor—meaning it can produce electricity more efficiently, particularly under the projected 2050 wind conditions. Offshore systems require significantly less capacity to achieve the same output as their onshore counterparts, positioning them as a cost-effective option over the long term despite higher initial expenses.

According to this study, under the SSP5m climate scenario, offshore wind energy is projected to produce 19.8 TWh of electricity—an increase of 10.5% compared to historical climate conditions. Importantly, this growth is achieved using 50.5% less installed offshore capacity than what was historically needed for equivalent onshore output. However, the reduced availability of onshore wind energy creates a shortfall in generation capacity. To address this, additional renewable sources, particularly solar power, will need to be integrated into the energy system. This underscores the need for a diversified renewable energy strategy to maintain system reliability and resilience.

Another key insight from the study reveals that, under future climate projections, the total system capacity is 21.5% lower than under historical climate conditions—assuming constant electricity demand. This reduction stems from the increased efficiency of offshore wind, which delivers more energy with fewer installations.

The system optimization model also considers the operational reliability of different energy sources. Offshore wind becomes increasingly attractive when its overall cost per unit of electricity delivered falls below that of onshore wind. Furthermore, the consistency of wind speeds greatly affects turbine performance. Wind turbines typically require a minimum speed of 3 to 5 m/s to begin generating electricity (Crespo Del Granado et al., 2016), though

production remains low at these levels (Adeyeye et al., 2022). Power generation significantly improves in the optimal wind speed range of 12 to 14 m/s (Crespo Del Granado et al., 2016). Offshore wind speeds in Kenya are projected to reach 13.8 m/s and 13.2 m/s by 2050, placing them squarely in this ideal operating range—making offshore wind both dependable and efficient for future energy needs.

In essence, increased temperatures are projected to result in a 21.0% rise in generator capacity by driving greater cooling demand, whereas changes in wind patterns could lead to a 21.5% reduction in total system capacity under the SSP5m scenario.

When comparing future climate scenarios with historical data, total generator capacity under SSP5m is expected to be 5.1% lower. However, under SSP1, future capacity is forecasted to be 32.82% higher than historical levels. This contrast arises because the effect of higher cooling demand due to warming outweighs the impact of declining wind speeds.

In conclusion, the link between climate change and energy infrastructure is intricate. To develop a comprehensive understanding, the individual impacts of different climate variables must be carefully quantified and analyzed. Notably, when climate model outputs are averaged, the resulting changes in energy system performance tend to appear modest (Bloomfield et al., 2021).

### 3.5.3 Contribution of different factors to the future energy system

Multiple factors play a role in shaping Kenya's future energy system, each exerting a distinct level of influence on the country's energy profile. According to the results of a sensitivity analysis, fluctuations in electricity demand have the most substantial effect on total installed capacity. This suggests a nearly one-to-one relationship between rising demand and capacity expansion. In a context like Kenya—where economic growth and a rising population are expected to boost electricity usage—this finding underscores the importance of accurate demand forecasting to prevent both overbuilding and underinvestment in infrastructure (Carvallo et al., 2017).

The second most influential factor is the limitation on CO<sub>2</sub> emissions. The analysis shows that stricter emission caps prompt a shift towards renewable energy sources, which generally require more installed capacity due to their lower capacity factors compared to conventional, dispatchable fossil fuel-based generation (International Renewable Energy Agency, 2023). This dynamic makes the future energy profile highly sensitive to CO<sub>2</sub> policy constraints. For instance, in scenarios without emission restrictions, geothermal power production rises sharply—a trend clearly reflected in the energy mix under scenario SSP5.

Crucially, electricity demand and CO<sub>2</sub> limits are intertwined with climate projections. Each scenario combines different assumptions about these two variables. For example, SSP1-2.6 combines lower energy demand with stringent emission limits, while SSP5 assumes high demand without CO<sub>2</sub> constraints. Both of these scenarios permit emissions greater than 0.034 kg CO<sub>2</sub> per kWh of electricity.

In contrast, SSP5m presents a high-demand future paired with strict emissions limits, allowing fewer than 0.02 kg CO<sub>2</sub> per kWh. This leads to the highest level of installed capacity, dominated by renewables. The most rigorous scenario is a zero-emission policy, which mandates zero operational emissions, regardless of demand levels. Although this drastically increases overall system cost and installed capacity, it is necessary to rely entirely on zero-emission technologies with low capacity factors to meet energy needs.

Investment costs, by comparison, have minimal influence on total capacity. A 10% change in capital costs results in less than a 0.5% change in capacity, indicating that Kenya's long-term planning is robust enough to handle modest financial fluctuations without derailing expansion targets (Republic of Kenya Ministry of Energy, 2020).

Changes in operational costs have even less impact than capital costs, contributing negligibly to variations in total capacity. This resilience is likely due to Kenya's reliance on renewable sources with inherently low operational expenses, which limits the financial exposure to cost variability (International Renewable Energy Agency, 2023).

To streamline modeling and reduce complexity, investment and operational costs for each technology type are held constant across all scenarios. This methodological decision minimizes the confounding influence of variable inputs, making it easier to isolate the drivers of energy system transformation.

Climate change further affects the energy system by altering the capacity factors of different renewables and raising cooling-related electricity demand. Specific changes—such as fluctuations in onshore and offshore wind speeds, solar irradiance, and water inflow—alter the share of wind, solar, and hydropower in the energy mix.

In addition to performance, capital costs significantly influence which renewables dominate the system. A renewable technology's competitiveness typically hinges on a combination of its capacity factor and upfront cost. Technologies that maintain a lower share of installed capacity but contribute a larger share to electricity generation often exhibit high and stable capacity factors (Sun et al., 2024).

For example, when modeling incorporates future climate projections rather than historical data, the total installed capacity tends to be lower. This is because gains in offshore wind performance offset the losses from declining onshore wind capacity, despite the higher capital cost of offshore installations.

In SSP5, where there are no CO<sub>2</sub> restrictions and all generation technologies are permitted, fossil fuels and geothermal are both included in the mix. However, fossil fuels—namely oil and natural gas—contribute less than 0.5% to total generation. Geothermal, on the other hand, accounts for more than 85% due to its cost-effectiveness, long operational life, stability, and dispatchability. Solar energy provides over 10% of total output, highlighting its economic potential in Kenya's climate and its growing competitiveness with fossil fuels.

#### 3.5.4 Life cycle emission analysis within scenarios

A life cycle assessment (LCA) of Kenya's energy system under various 2050 scenarios reveals that the green development pathway, SSP1-2.6, performs best in reducing climate impact. This scenario achieves a 52% reduction in climate-related impacts compared to the baseline SSP5-8.5 scenario. However, the SSP5m scenario—despite applying equally strict CO<sub>2</sub> constraints during the operational phase—only yields a modest 9% reduction in life cycle emissions compared to SSP5m. This outcome indicates that even with tight emissions limits, high energy demand significantly diminishes the life cycle emissions benefits of deploying large-scale renewable technologies like wind and solar, especially when paired with energy storage. These systems require substantial capacity to meet energy demands, making them more costly and less effective in overall emissions reduction when compared to Kenya's geothermal options.

Each energy technology undergoes three primary phases during its life cycle: upstream supply chain processes, infrastructure development, and operational use. The extent to which each of these phases contributes to total climate impact varies significantly depending on the technology involved (Al-Breiki & Bicer, 2021).

For variable renewable sources such as wind and solar, the majority of their climate impact comes from the materials and energy consumed during infrastructure development, rather than during operation. In contrast, fossil fuels—like coal, oil, and natural gas—generate most of their emissions during the operational phase, which could be mitigated with greenhouse gas reduction technologies like carbon capture and storage (CCS). However, the PyPSA-Earth model used in this analysis does not incorporate CCS. Should CCS be included, it could potentially increase the roles of biomass and geothermal in a zero-emission energy mix.

Across all scenarios and regardless of climate conditions—whether historical or projected—the two main factors influencing life cycle climate impact are the installed capacity of each technology and its specific life cycle emissions. Generally, systems optimized for future climate conditions require less capacity than those based on historical data, which results in slightly lower life cycle emissions for future-oriented systems.

Among the technologies assessed, wind energy has the lowest life cycle emissions at approximately 10 g CO<sub>2</sub>eq/kWh, followed by solar photovoltaic (PV) systems at 36 g CO<sub>2</sub>eq/kWh. In contrast, coal and oil have the highest emission factors, at 960 g CO<sub>2</sub>eq/kWh and 775 g CO<sub>2</sub>eq/kWh respectively.

Kenya's geothermal resources are particularly valuable, offering a dependable, dispatchable energy source with minimal operational costs. Although geothermal produces negligible emissions during operation, its total life cycle emissions remain highly competitive at 41.7 g CO<sub>2</sub>eq/kWh—about 16% lower than hydropower's figure of 49.6 g CO<sub>2</sub>eq/kWh.

It is also important to note that batteries and other storage technologies contribute meaningfully to life cycle emissions. In the SSP5m scenario, storage systems such as batteries and hydrogen account for 6.2% to 7.4% of total life cycle emissions. These emissions result from supporting the intermittency of renewable sources like wind and solar and are often overlooked in models that focus solely on emissions during operation. However, they add a

significant layer of complexity and challenge in truly decarbonizing the energy system from a life cycle perspective.

### 3.5.5 Limitations

According to this paper, it is anticipated a sharp rise in Kenya's cooling electricity demand through the 21st century, particularly under a high-emissions pathway (SSP5-8.5). Demand plateaus by mid-century in a low-emissions scenario (SSP1-2.6), emphasizing the significant influence of climate mitigation. This projection is strongly reinforced by updated regional literature highlighting both climatic and socio-economic factors that drive demand for cooling.

Sackey, Levin, and Nock (2022) provide a comprehensive review of electricity planning in sub-Saharan Africa and introduce the concept of "latent demand"—the suppressed electricity use that would emerge if income, affordability, and infrastructure access were improved. In Kenya, a substantial portion of the population resides in regions climatically in need of cooling but economically constrained from accessing such services. This latent demand, as the authors argue, is critical in future system planning and is currently underestimated in most supply-side models. The report's findings echo this concern by projecting significantly higher demand under urbanization and economic growth trends.

Earlier foundational work by Isaac and van Vuuren (2009) similarly affirms that space cooling will dominate new electricity demand in warm developing countries like Kenya. Their modeling confirms that temperature and income growth have a multiplicative effect on residential cooling electricity use—especially in regions approaching the CDD threshold for air conditioning uptake.

Together, the literature and this report's findings suggest a critical convergence:

- Without strong energy efficiency policies, cooling demand could outstrip grid capacity during peak periods.
- Latent demand remains a major uncertainty and likely underestimates total future energy needs.
- Urban planning and technology deployment will be essential to avoid energy poverty, heat stress, and inequitable access to comfort cooling.

### 3.6 Conclusion

Generally, energy demand has a larger impact on Kenya's energy system profile compared to other factors. However, climate change in temperature leads to an increase in cooling demand, which contributes to the increase in energy demand. From this perspective, climate change generally tends to result in a rise in electricity capacity and generation due to the growth of the energy demand.

The other climate change impacts on the energy system optimization are complicated in Kenya. The change in wind speed causes the offshore wind to replace the onshore wind because the projected offshore wind speed rises and the projected onshore wind speed declines. Moreover, as the capacity factor of the projected offshore wind power is higher than

the projected onshore wind in 2050 due to the difference between offshore and onshore wind speed, offshore wind power generates higher electricity with lower capacity than onshore wind.

Scenario SPP1-2.6 has a significantly lower capacity, generation, as well as capital cost, and operation cost of the future power system of Kenya than Scenario SPP5-8.5 and SSP5m. It shows that a sustainable path leads to a mitigated climate change with lower energy demand and energy costs.

Life cycle assessment results indicate that the decarbonization strategy of energy systems with only focus on the operation phase could mislead the Climate change mitigation effectiveness. When there is a requirement for a regional energy system with high energy demand and strict direct CO<sub>2</sub> emission, the capacity of renewables such as wind, solar and battery will be dramatically increased. Such energy systems with large-scale renewables have very limited climate change mitigation in a life cycle but are significantly expensive.

For Kenya, geothermal will continue to play a significantly important role in the energy strategy due to its excellent resources, stable dispatchable performance, limited emission, and cost-effectiveness. Key priorities for Kenya's future energy transition include limiting the growth of energy consumption, enhancing energy efficiency and further reducing geothermal emissions. Furthermore, offshore wind is expected to replace onshore wind as a preferred resource due to projected changes in wind speed in Kenya. Alongside offshore wind, solar, and biomass will play essential roles in shaping Kenya's power system profile.

## 4. Sierra Leone

### 4.1 Case study description

Sierra Leone represents an urgent and relevant case study within the ENERGICA project, where the scars of conflict, institutional fragility, and economic dependence on volatile external actors converge with one of Africa's most severe energy access crises. Energy sits at the heart of this struggle. Without affordable, reliable power, Sierra Leone's efforts to rebuild state legitimacy, cultivate economic resilience and escape cycles of debt-driven dependency remain stifled.

Despite decades of reforms and external assistance, the country continues to rank among the lowest in Africa for infrastructure development, largely due to chronic failures in the energy sector (Millennium Challenge Corporation, 2022). By 2023, only 35.5% of the population had access to electricity (Africa Energy Portal, 2020), while nearly 40% of generated power was lost in transmission and distribution (Hirmer, George-Williams, Rhys, McNicholl, & McCulloch, 2021). The country's infrastructure still suffers from the devastation of the eleven-year civil war, which ended in 2002 and left tens of thousands of dead, millions displaced, and much of the energy system destroyed. The legacy of war, compounded by the shocks of Ebola and COVID-19 (Millennium Challenge Coordinating Unit, 2020) hollowed out institutions and left the grid fragile, patchy, and deeply unequal.

In response, Sierra Leone has recently pursued an electricity sector reform. In 2011, the National Power Authority was unbundled into the Electricity Generation and Transmission Company (EGTC) and the Electricity Distribution and Supply Authority (EDSA), regulated by the Electricity and Water Regulatory Commission (EWRC). With support from international institutions such as the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE), Millennium Challenge Corporation (MCC), Japan International Cooperation Agency (JICA), and the World Bank, the Government of Sierra Leone (GoSL) launched the Electricity Sector Reform Project (ERSP), which set out a reform roadmap and institutional strengthening agenda. Its goals focused on expanding generation, rehabilitating and extending transmission and distribution networks, reducing service costs through improved coordination and technical capacity, and fostering public–private partnerships to create a more reliable and inclusive electricity system. Since 2015, more than USD 100 million in domestic and donor financing has been committed, underlining Sierra Leone's long-term plan to strengthen the national grid and ensure affordable access to electricity (World Bank, 2025).

#### *Sierra Leone Power Sector*

The current electricity network remains limited, centred on a 204 km 161 kV line linking the Bumbuna hydropower plant to Freetown and a 33 kV line serving Kenema and Bo in the east and south Figure 57(b). The largest ongoing investment is the 1,300 km, 225 kV CLSG interconnection with Côte d'Ivoire, Liberia, and Guinea, with five substations planned in Sierra Leone, three already completed, including one supplying Kenema and Bo (World Bank, 2025).

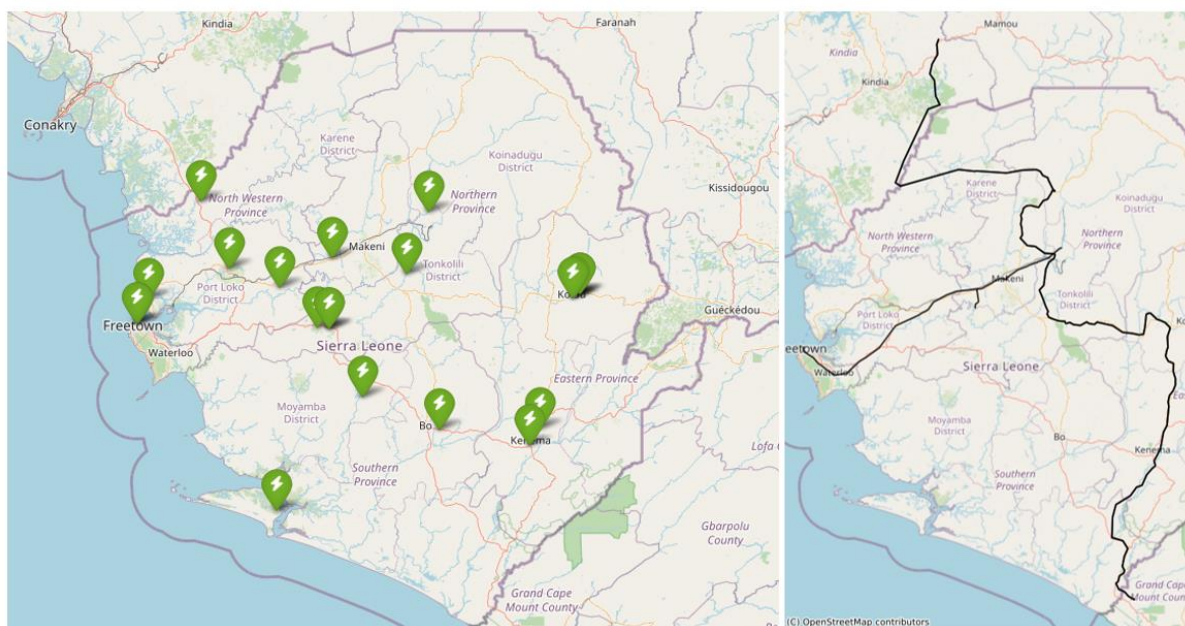


Figure 57 - Power plants location (a) and electricity power network (b) in Sierra Leone. Created by the authors using data from OpenStreetMap

The publicly owned power sector currently has approximately 176.9 MW of installed capacity, of which 22.6% is renewable (91% hydropower and limited solar utility power), 23.5 MW is imported, and more than half (53.9%) relies on fossil fuels. This includes the floating Turkish power ship Karpowership, anchored off Freetown since 2018, which supplies 65 MW at a staggering cost of about USD 2 million per month, an expense the country struggles to meet, deepening arrears and exposing Sierra Leone to external leverage and political vulnerability. Thermal capacity is supplemented by the Kingtom Power Station (33.6 MW) and the Marampa Mine plant (22 MW), while smaller diesel units operate in Koidu and other mining centers. Renewables make up roughly a quarter of capacity, led by the 50 MW Bumbuna I dam on the Seli River and the smaller 6 MW Dodo plant. Solar power has grown in recent years with projects in Makoth (25 MW), Bo–Kenema (12 MW), Kono (10 MW), and smaller arrays in Port Loko, at Freetown airport, and across institutional sites Figure 57(a).

Looking ahead, the national expansion plan centres on large hydropower: Bumbuna II (143 MW) upstream of the existing dam, Bekongor on the Sewa River (120 MW), Betmai Falls on the Pampana River (27 MW), and Singimi Falls in Moyamba District (14 MW). Together with an expected scale-up of utility solar PV to ~60 MW after 2030, these projects aim to diversify the supply mix, reduce dependence on costly thermal plants, and strengthen Sierra Leone's long-term energy security. In the modelled trajectory this portfolio progressively displaces today's heavy reliance on liquid fuels and imports: the late-2020s commissioning wave swings the system decisively toward hydropower, while solar begins to make a visible contribution and thermal output recedes to a supporting role. By the 2050s, hydro has consolidated its position as the backbone of supply, with solar stabilising as a meaningful complement and imports used mainly at the margin Figure 58.

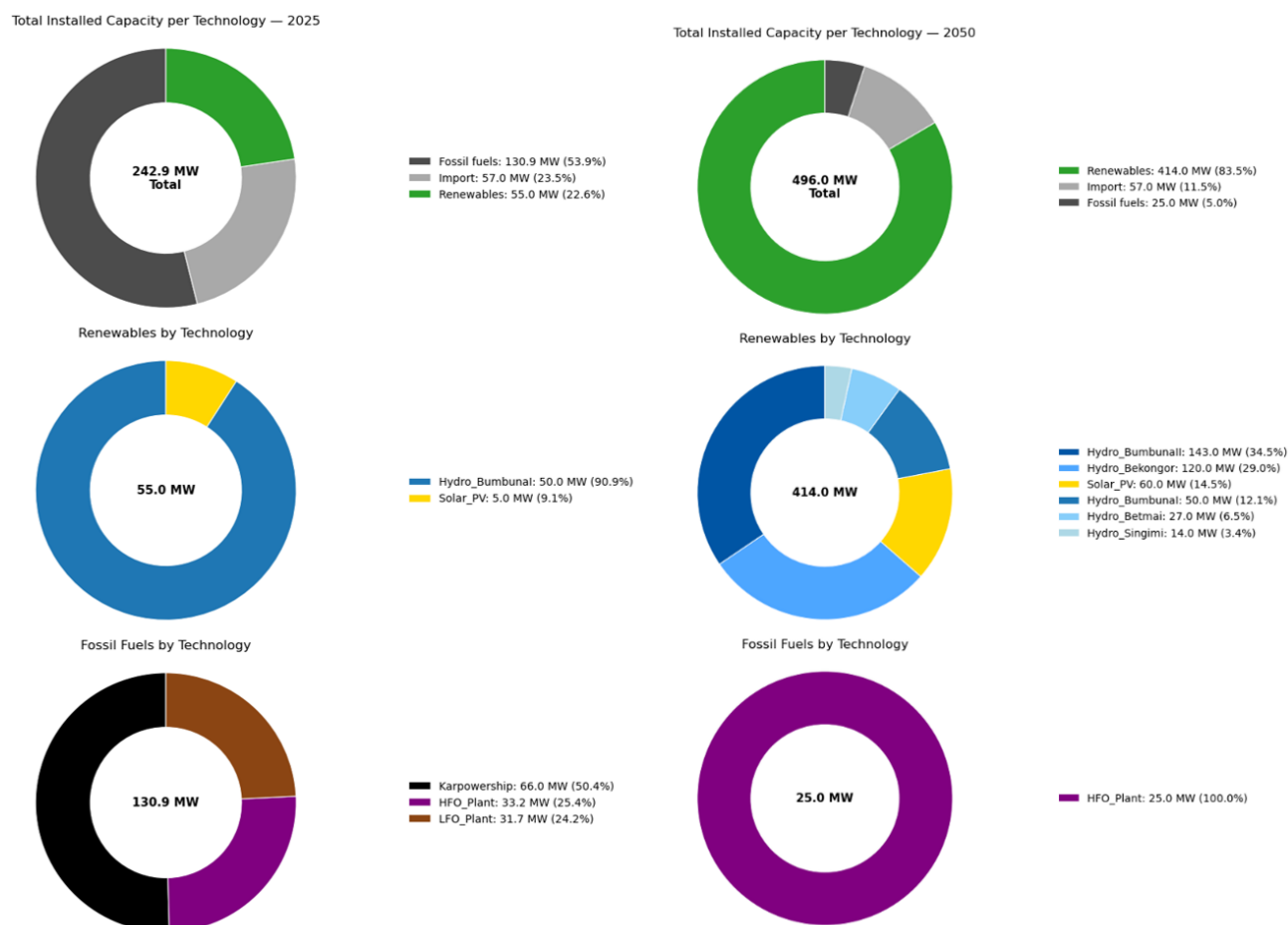


Figure 58 - Total Installed Capacity and Technology share related to the Sierra Leone power sector in 2025 (a) and expected, based on current commitments and plans, in 2050 (b). Created by the authors using data from IRENASTAT (IRENA, 2023).

This path, however, carries a structural exposure: the same concentration that delivers low variable costs also ties system adequacy to rainfall. With more than nine-tenths of renewable generation expected from rivers, variability in seasonal inflows or multi-year droughts becomes a central planning risk. Without explicit climate stress-testing and diversification measures, a hydro-heavy strategy could lock the sector into higher vulnerability precisely as climate extremes intensify.

#### *Hydro Power Availability and Climate Change*

Past assessments identified abundant untapped hydro resources: a 1996 master plan catalogued 27 potential sites totaling ~1,513 MW, and a UNIDO survey in 2013 estimated about 5,000 MW of theoretical hydropower potential across 300 sites (Government of Sierra Leone, 2016). In line with these findings, recent national policies and plans call for scaling up hydropower to boost electricity access and cut reliance on expensive diesel generation. The 2020 Integrated Resource Plan and Sierra Leone's renewable energy policy explicitly list large hydro projects (e.g. Bumbuna expansions and new dams) as priority investments to achieve universal access and reduce power costs and emissions (World Bank, 2025). Expanding domestic hydropower is seen as the least-cost, most sustainable pathway for Sierra Leone's

power sector growth, offering huge savings on fuel imports and significant carbon emission reductions compared to the status quo. Table 2 summarizes the main existing and planned hydropower plants in Sierra Leone, indicating their capacity, location, river basin, and type. These projects, ranging from the operational Bumbuna I to upcoming large-scale developments such as Bumbuna II, Betmai, and Bekongor, highlight the central role of hydropower in future generation expansion strategies.

Table 2 Main hydropower plants in Sierra Leone, including installed or planned capacity, location, river basin, and plant type Source: Sterl et al 2024.

| Name       | MW         | Coordinates           | River      | Type         |
|------------|------------|-----------------------|------------|--------------|
| Bumbuna I  | 50         | 9.0568° N, 11.7361° W | Upper Seli | Reservoir    |
| Bumbuna II | 143 (2026) | 9.0719° N, 11.7225° W | Upper Seli | Reservoir    |
| Bekongor   | 28 (2030)  | 8.5572° N, 11.2629° W | Sewa       | Reservoir    |
| Betmai     | 120 (2030) | 8.4349° N, 11.4109° W | Pampan     | Run-of-River |
| Singimi    | 20 (2030)  | 7.9200° N, 12.5078° W | Gbangba    | Run-of-River |

However, the heavy reliance on hydropower also exposes Sierra Leone's energy system to climate change risks, and this is where a critical planning gap emerges. Hydropower generation depends on consistent water flow, so changing precipitation patterns and extreme weather can directly impact electricity output. Sierra Leone is projected to face more erratic rainfall and extreme hydrological events under future climate scenarios, including more frequent droughts and intense storms. West Africa is expected to become drier in many areas as the climate warms, which would bring negative impacts on hydropower and lower river levels mean turbines generate less electricity. In fact, Sierra Leone is cited as one of the African countries most vulnerable due to its high dependence on hydropower and limited backup options (World Bank, 2025). The stark seasonal swings already observed at Bumbuna (wet vs. dry season output) illustrate this vulnerability, and future climate shifts could exacerbate such fluctuations. Recent analyses warn that in a worst-case climate scenario, Sierra Leone's hydropower output might decline by 15–25% by 2030–2050 (Figure 59).

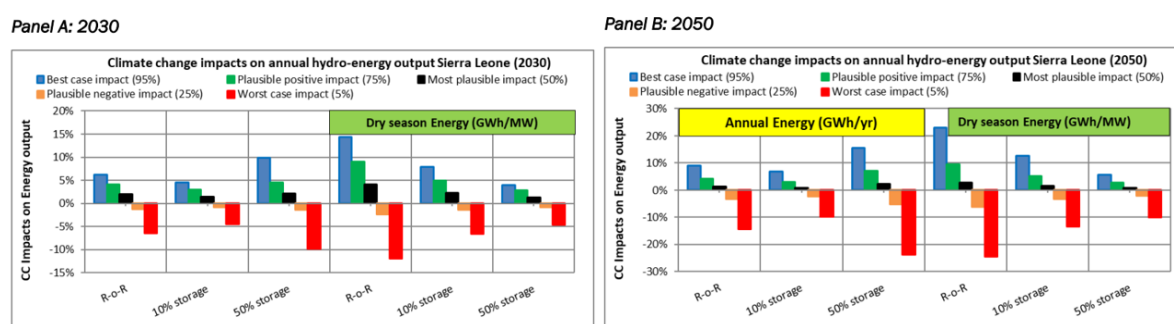


Figure 59 - Potential impacts of climate change on hydropower generation in Sierra Leone in 2030 and 2050. Source: World Bank Group (2025) Sierra Leone Country Climate and Development Report.

Even if moderate scenarios show smaller impacts, this potential drop is significant: it could undermine energy security and reliability if not anticipated in advance.

Recent literature further underscores vulnerabilities tied to Sierra Leone's hydro-heavy energy strategy. Karim and Bah (2022) stress that climate change represents a systemic threat

to Sierra Leone's green growth ambitions, highlighting that rising temperatures, extreme weather, and ecosystem degradation will exacerbate existing fragilities in energy, water, and infrastructure systems. This broad framing reinforces the urgency of integrating climate adaptation into the power sector, as hydropower is central to the country's low-carbon strategy.

Regionally, Obahoundje and Diedhiou (2022) provide a systematic review of West African hydropower under climate and land use/cover change. They find repeated disruptions to hydropower generation across the region due to rainfall variability and droughts in recent decades. Projections suggest that under RCP4.5 and RCP8.5 scenarios, water availability could decline by 10–20% and up to 40% by 2050, respectively, with strong implications for hydropower generation. While some basins may see localized runoff increases (including parts of coastal Guinea, Liberia, and Sierra Leone), the broader trend is toward heightened variability, floods, and droughts that undermine dam reliability. The review also points to the absence of systematic climate and land-use change integration in West African dam planning, noting that dam managers typically lack access to climate services and decision-support tools. For Sierra Leone specifically, where large new dams (e.g., Bumbuna II, Bekongor) are planned, this translates into high exposure to climate shocks without robust adaptation frameworks.

A third strand of evidence comes from Strobl & Strobl (2011), who empirically analyzed 1,500 African hydropower plants using river flow and rainfall data. They demonstrate that hydropower output in West Africa is among the most sensitive globally to rainfall shocks, with prolonged droughts reducing annual production by up to 50% in some facilities. Their study warns that “hydro-dependency” in fragile states can intensify economic vulnerability, as rainfall variability transmits directly into fiscal instability and energy insecurity.

On the other side, some of the recent Sierra Leone's flagship planning documents, the 2020 Integrated Resource Plan (IRP) and the 2024/25 Energy Transition & Green Growth Plan (ETGP), continue to prioritize large hydro (Bumbuna II, Bekongor, Betmai, Singimi) alongside solar PV and CLSG imports, but they do not present hydrology-linked climate stress tests of dam inflows; hydro is treated as a least-cost anchor rather than a climate-exposed asset. The World Bank's synthesis of the IRP explicitly highlights hydro and solar as the core replacements for liquid fuels, with ~140 MW of solar and major hydro build-out, yet offers no quantitative assessment of climate-driven runoff risk to those hydro assets, underscoring the absence of climate integration in current expansion logic.

Likewise, SEforALL's ETGP positions hydro at the center of the long-term transition but does not disclose basin-specific climate/hydrology scenario analysis to test generation reliability under shifting rainfall. Project-level documentation mirrors this gap: the Bumbuna II ESHIA carefully specifies operational rule curves and environmental flows and acknowledges major flow-regime changes (higher dry-season releases, reduced wet-season peaks), but it does not evaluate future inflows under GCM/RCM scenarios, implying operations have been optimized to historical hydrology rather than future climate.

## 4.2 Research questions and objectives

As part of the deliverable objectives, the analysis focuses on the viability of Sierra Leone's hydropower-dependent energy system under a changing climate. Specifically, it asks:

1. How resilient are Sierra Leone's hydropower-based future energy plans to climate-change induced drought and shifting rainfall patterns?
2. What are the economic, emissions, and system implications of substituting lost hydropower capacity with alternative energy sources under different climate futures?

Our main objectives are to:

1. Assess the vulnerability and adaptive capacity of Sierra Leone's hydropower-intensive energy mix to projected climate variability, including shifts in rainfall intensity, seasonality, and drought frequency.
2. Quantify the potential impacts of hydrological changes on electricity generation capacity, grid reliability, and access to power at national and regional scales.
3. Model alternative energy pathways to evaluate how different energy configurations (renewable and fossil-fuels) could offset hydropower losses under diverse climate scenarios.
4. Estimate the economic and emissions trade-offs associated with these adaptation strategies to inform sustainable investment and policy decisions.

## 4.3 Methodology

### 4.3.1 Climate projection and climate risk analysis

To assess future hydroclimatic risks affecting Sierra Leone's hydropower potential, we combine physically based climate projections with a data-driven downscaling and drought analysis to evaluate changes in precipitation, drought, and hydrological stress across priority basins.

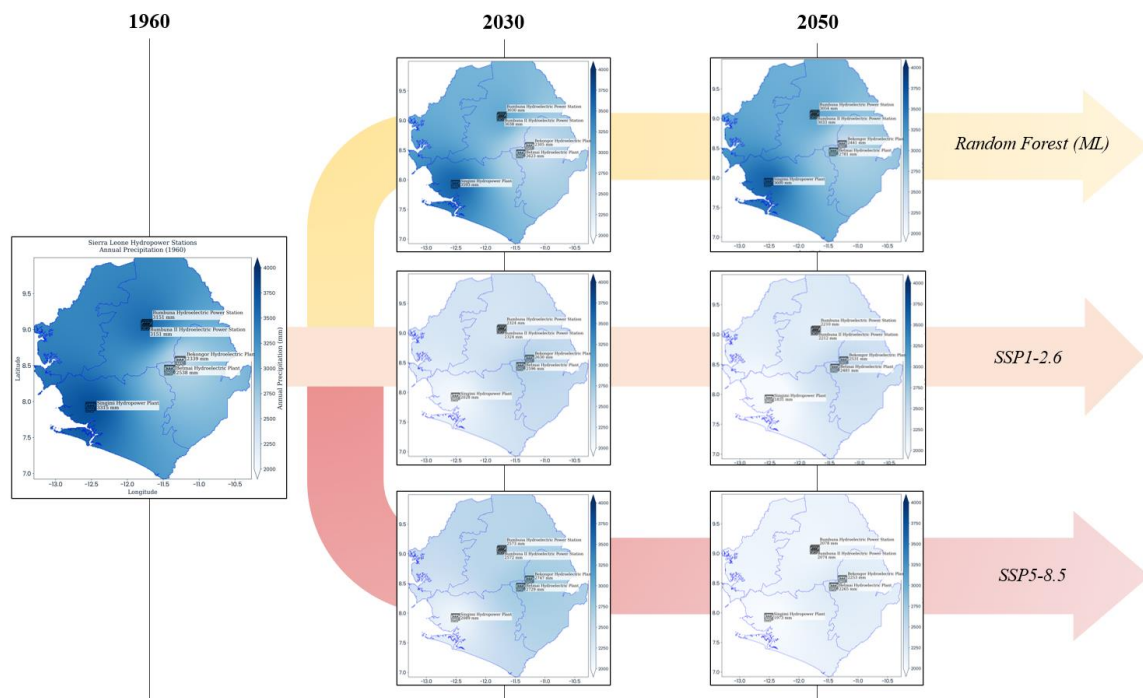


Figure 60 - Spatial distribution of annual precipitation across Sierra Leone's major hydropower basins in 1960, 2030, and 2050 under different climate projections. Image created by the authors.

Future precipitation patterns were first modelled using the Coupled Model Intercomparison Project Phase 6 (CMIP6) framework (World Climate Research Programme [WCRP], n.d.). We selected MRI-ESM2.0 for its demonstrated skill in representing West African rainfall dynamics and its availability in the ISIMIP3b bias-adjusted archive (Romanovska et al., 2023). MRI-ESM2.0 provides a robust physical basis for near-term (2030) and mid-century (2050) assessments under SSP1-2.6 (sustainability) and SSP5-8.5 (high emissions) (O'Neill et al., 2016). While CMIP6 outputs are physically consistent at large scales, they remain constrained by coarse spatial resolution and structural/model uncertainties (John et al., 2022).

To improve local fidelity, and for comparison, we developed a Random Forest (RF) model trained on ERA5-Land historical reanalysis data (1960–2023) to refine basin-scale precipitation and to predict SPEI-based drought severity (Figure 60). The RF captures non-linear relationships among predictors (precipitation, maximum temperature, minimum temperature, evapotranspiration, humidity proxies). Model skill was evaluated via k-fold cross-validation, reporting MAE and  $R^2$  on held-out folds to ensure predictive robustness (Breiman, L., 2001).

To characterize intra-annual hydroclimatic variability, we computed the SPEI-6, using rainfall, temperature and potential evapotranspiration (PET) derived from the Hargreaves formulation. The 6-month time scale provides sensitivity to both dry-season deficits and wet-season surpluses, enabling assessment of short- to medium-term drought and rainfall dynamics (Vicente-Serrano, S. M et al 2010)(Hargreaves, G. H., & Samani, Z. A. 1985).

SPEI-informed precipitation signals were mapped to river discharge (streamflow) and hydropower availability. For run-of-river plants, inflow changes were represented via first-order proportional scaling based on projected basin-level precipitation changes (). For storage

hydropower, we employed a linear storage-operation module that optimizes releases under hydraulic, storage, and environmental constraints using plant-specific parameters, summarized in Table 3. This distinction captures the differential buffering of storage systems versus the immediacy of run-of-river response to hydroclimatic variability.

Table 3 Plant-specific parameters for run-of-the-river hydropower plants in Sierra Leone. Source: Sterl et al 2024.

| Name    | Catchment Area (m <sup>2</sup> ) | Run-off Coefficient (-) | Head (m) | Efficiency (-) | Capacity (MW) |
|---------|----------------------------------|-------------------------|----------|----------------|---------------|
| Singimi | 25,000,000                       | 0.8                     | 30       | 0.88           | 16            |
| Betmai  | 400,000,000                      | 0.8                     | 80       | 0.90           | 27            |

Table 4 Plant-specific parameters for storage hydropower plants in Sierra Leone, used in the linear storage–operation module. Source: Sterl et al 2024.

| Name       | Head (m) | Efficiency (-) | Capacity (MW) | Reservoir Size (m <sup>3</sup> ) |
|------------|----------|----------------|---------------|----------------------------------|
| Bumbuna I  | 100      | 0.90           | 50            | 445,000,000                      |
| Bumbuna II | 147      | 0.90           | 143           | 1,911,900,000                    |
| Bekongor   | 100      | 0.90           | 120           | 527,700,000                      |

We evaluate three climate inputs: (i) the RF-based empirical projection (trend-consistent baseline), (ii) SSP1-2.6, and (iii) SSP5-8.5. For each, we derive monthly capacity-factor profiles and inflow time series for Bumbuna, Bumbuna II, Bekongor, Betmai, and Singimi.

#### 4.3.2 Energy system optimization

The results from the hydropower inflow (discharge) projections derived from climate analysis were used as inputs to OSeMOSYS energy system model to evaluate the implications of climate variability on Sierra Leone’s power sector.

##### *OSeMOSYS Modelling Framework*

The Open Source energy Modelling SYStem (OSeMOSYS) is a comprehensive, open-source, linear optimization framework designed for long-term energy planning and integrated assessment. For this case study, OSeMOSYS was selected after considering both commercial and open-source capacity-expansion tools. Established proprietary frameworks, MARKAL/TIMES and MESSAGE/MESSAGEix, are powerful and widely used for long-term planning, but they generally rely on commercial solvers and licensed ecosystems, come with steeper training demands, and carry higher maintenance costs for national institutions. Among open-source options, PyPSA/PyPSA-Earth excels at network-aware, hourly dispatch with detailed spatial resolution, making it ideal for operational studies, nodal congestion, and transmission planning rather than multi-decadal, national-scale capacity expansion. Calliope (Pfenninger & Pickering, 2018) offers a very flexible optimisation canvas for system design and short- to medium-term operations, but it is not inherently vintage-dynamic and lacks the multi-period stock evolution, which is pivotal for representing investment, retirement, and policy pathways to 2050. Against that backdrop, OSeMOSYS was selected as the best fit for this case study. Critically for Sierra Leone, a curated country dataset consistent with the “data-to-deal” pipeline is already available, reducing preparation time and improving reproducibility for policy dialogue (Kiley, F., 2024).

OSeMOSYS minimizes discounted total system cost subject to technology, fuel, policy, and balance constraints, with technology vintaging, user-defined time slices, and optional penalties for unserved energy or curtailment. The formulation is transparent and tractable for national-scale planning horizons and supports policy levers such as renewable targets, emissions caps, build-rate limits, and imports. The functionality of OSeMOSYS can be relatively easily modified since it is being developed in a series of functional blocks, where each block is divided into different levels of abstraction (Figure 61).

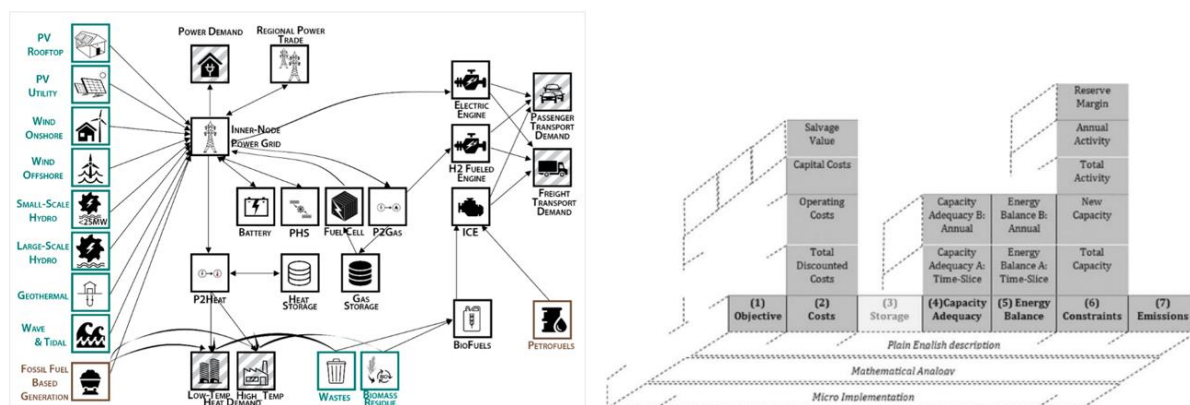


Figure 61 - OSeMOSYS framework showing energy resource transformation into final services through functional blocks, with parameters and time-slice detail. Source: [www.osemosys.org](http://www.osemosys.org).

At its core, OSeMOSYS applies a linear, least-cost optimization framework to simulate long-term energy system development. It determines optimal investment and dispatch decisions that minimize total discounted system costs over a multi-decadal horizon. The model tracks technology vintaging (new builds and retirements), applies user-defined capacity factors, and enforces full energy balance across carriers and time slices. Cost components include capital, O&M, fuel, and trade, while policy levers—such as emission caps, renewable targets, or build-rate limits—can be applied directly. Storage dynamics are represented through linear charge–discharge balances. The deterministic structure abstracts from detailed operational constraints (e.g., ramping, reserves, or grid physics) to maintain transparency and tractability for national-scale energy planning. All of these inputs were taken from (Kiley, F., 2024).

### *Modelling the Sierra Leone Power Sector in OSeMOSYS*

The implementation provides a cost-optimal pathway for investment and operation of the national electricity generation system over a 25-year planning horizon, from 2025 to 2050. The model structure, assumptions, and scope are aligned with the needs of national-level strategic planning rather than operational dispatch optimization. A central element of the modelling approach is the Reference Energy System (RES). It represents a simplified yet comprehensive abstraction of the country's on-grid electricity system, illustrating the flow of energy from primary resources through various transformation technologies to final electricity demand (Figure 62). It captures key domestic energy resources, hydro, solar, and biomass potentials, alongside imported fossil fuels such as diesel (LFO) and heavy fuel oil (HFO), which serve as inputs to conventional thermal power plants. The generation technologies modelled include HFO-fuelled Karpowerships, diesel (LFO) and HFO power plants, as well as a suite of hydroelectric technologies that reflect existing and committed

plants in Table 2, and new hydropower options differentiated by their expected capacity factors (high, medium, and low) based on historical average behaviour. Utility-scale solar PV and biomass power plants represent renewable alternatives, contributing to a diversified technology mix. The system serves a single aggregated electricity demand node, reflecting only grid-connected electricity consumption. Off-grid demand and supply technologies are excluded, as are non-electric energy uses such as transport, cooking, or industrial heat. Electricity imports are included as an option for meeting demand, but electricity exports and transmission network constraints are not represented. The RES therefore focuses on centralised supply technologies feeding into national on-grid electricity demand, forming the structural backbone for the cost-optimization and scenario analysis carried out within the OSeMOSYS modelling framework.

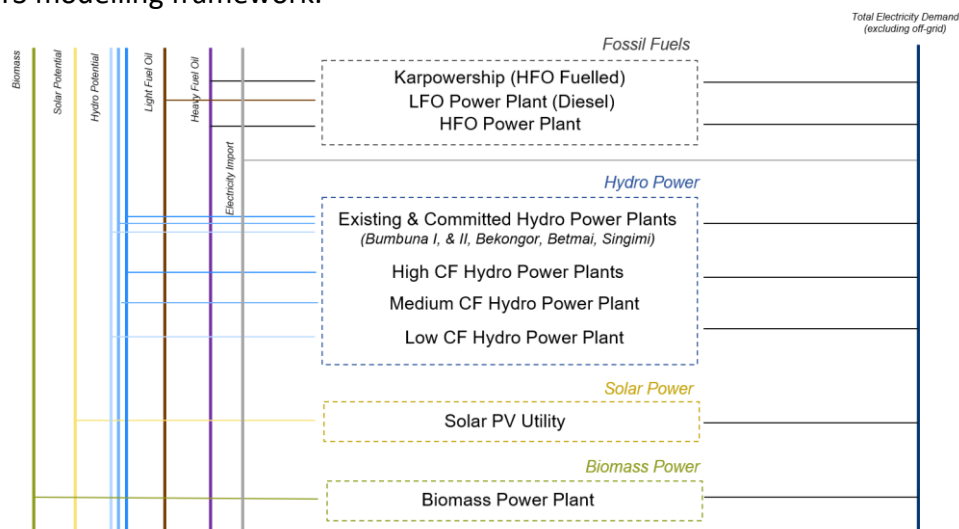


Figure 62 - Reference energy system diagram of the Sierra Leone power sector in OSeMOSYS. Image created by the authors.

The temporal resolution of the model is structured to effectively capture both long-term investment dynamics and intra-annual operational variability, while remaining computationally efficient for strategic planning purposes. The modelling horizon extends over a 26-year period, from 2025 to 2050, with discrete annual investment steps. This allows for detailed representation of system evolution over time, including capacity expansions, retirements, and the progressive integration of new technologies. To represent operational characteristics within each year, the model incorporates a set of 24 time slices, offering a simplified but meaningful depiction of seasonal and diurnal load and resource variability. The year is divided into 12 calendar months (January to December), and each month is further split into two representative periods: Day and Night. As a result, each time slice accounts for approximately 4.16% of the total annual hours, ensuring balanced coverage of time-dependent patterns in supply and demand (Figure 63). This time-slice structure provides the granularity needed to reflect key operational features, such as the daily variation in solar PV output and the seasonal fluctuation in hydropower availability or electricity demand. While not designed for detailed dispatch modelling, such as unit commitment or real-time balancing, the resolution is sufficient for analysing capacity adequacy, technology mix, and the broad effects of temporal variability on system planning outcomes.

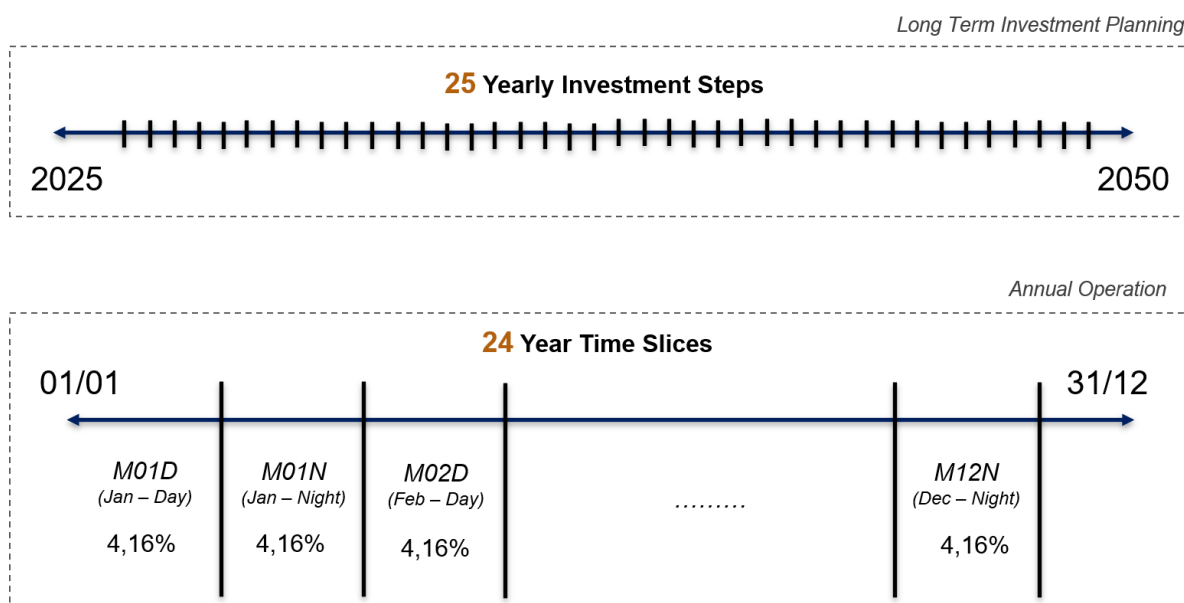


Figure 63 - Representation of the time resolution implemented in OSeMOSYS. Image created by the authors.

The techno-economic assumptions implemented in the OSeMOSYS model, such as investment costs, fixed and variable operating costs, fuel efficiencies, capacity factors, and operational lifetimes, are primarily derived from the comprehensive dataset published by (Kiley, F., 2024). This paper presents an open-access, country-specific dataset tailored to the Sierra Leonean context, developed through collaboration with national stakeholders and aligned with international data sources including IRENA, the World Bank, and the Africa Energy Outlook. The dataset reflects the characteristics of existing and planned infrastructure, as well as regionally appropriate assumptions for renewable energy technologies. It ensures consistency with local planning needs while maintaining transparency and replicability. This resource serves as the foundation for parameterizing the model, offering a validated and policy-relevant evidence base to support long-term energy planning in Sierra Leone.

### 2.3.3 Framework of integrated climate and energy models

The integrated framework (Figure 64) connects climate projection and energy system optimization through a two-stage, data-driven pipeline.

First, on the climate side, two complementary sources generate future hydroclimatic signals:

1. A Random Forest (RF) model trained on ERA5-Land (historical daily precipitation and Tmin/Tmax) to reproduce and extend observed rainfall behaviour.
2. The MRI-ESM2.0 Earth System Model, providing physically based projections for SSP1-2.6 and SSP5-8.5 emission pathways.

A climate-data processing module harmonizes these inputs through bias adjustment, resampling, and scenario alignment, producing consistent daily precipitation and temperature series.

These data are then translated into hydropower inflows and capacity factors: for run-of-river plants via direct precipitation-to-power scaling, and for reservoir systems using a linear storage-optimization module that simulates releases under hydraulic, technical and environmental constraints. The resulting monthly capacity-factor profiles form the interface between the climate and energy models.

Secondly, on the energy side, OSeMOSYS is parameterized with national techno-economic and policy data (costs, efficiencies, emissions, demand, and system limits). Scenario-specific hydro capacity factors are input as exogenous availabilities, allowing OSeMOSYS to compute least-cost expansion and dispatch pathways to 2050.

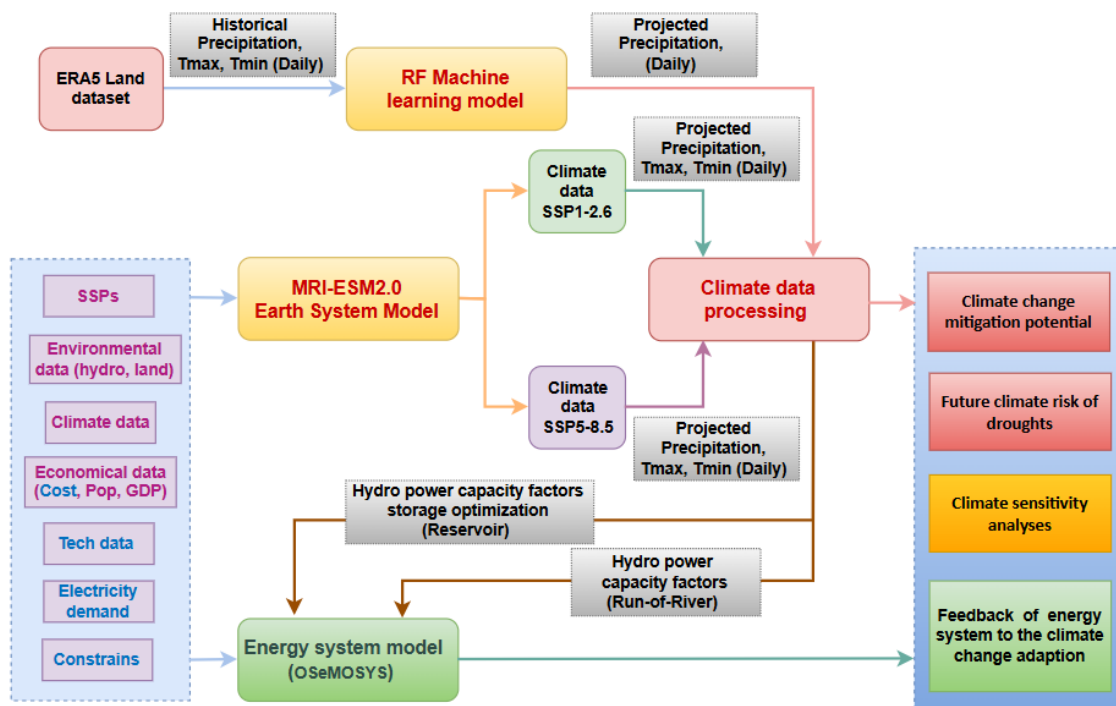


Figure 64 - Flowchart of the integrated framework applied in the analysis. Image created by the authors.

By decoupling climatic inputs from socio-economic drivers, the framework allows systematic comparison of climate futures under consistent baseline conditions. The integrated outputs quantify mitigation potential, hydrological and reliability risks, and the sensitivity of least-cost expansion pathways to climatic variability, providing an explicit feedback link between power system planning and climate adaptation policy.

#### 4.3.4 Scenario design for the Integrated Climate-Energy Framework

The OSeMOSYS scenarios isolate the effect of climate-induced hydrological variability on Sierra Leone's power system while holding demand, technology costs, and policy assumptions constant.

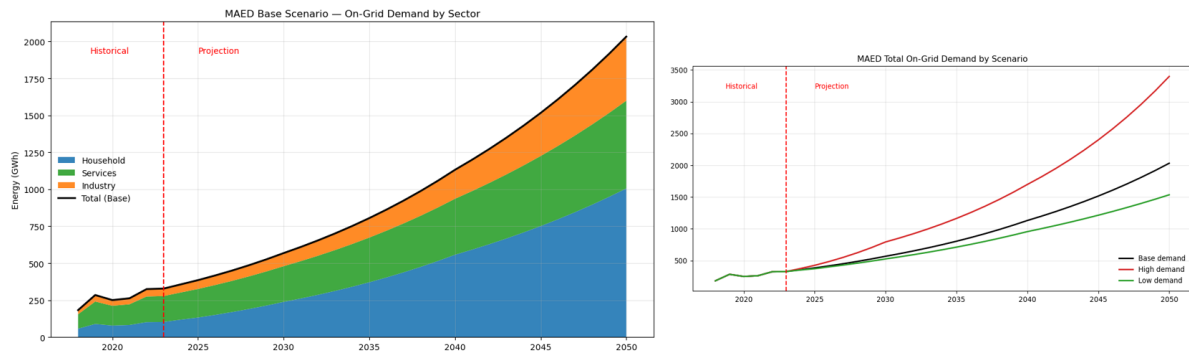


Figure 65 -MAED demand projections for Sierra Leone. Left: Baseline on-grid electricity demand by sector (households, services, industry) for 2018–2050; dashed line marks the transition from historical data (2018–2023) to projections. Right: Total on-grid demand. A single MAED-based baseline demand trajectory, calibrated to the Integrated Resource Plan (IRP), is used across all runs. The demand trajectory represents moderate GDP and population growth, steady electrification, and gradual efficiency gains consistent with national targets (Figure 65).

On the climate side, three precipitation datasets, corresponding to the RF projection, SSP1-2.6, and SSP5-8.5 pathways, were converted into monthly hydropower capacity-factor profiles for each major plant. These were supplied to OSeMOSYS as scenario-specific availability parameters, replicated across day/night sub-slices.

Each run therefore represents the same macroeconomic and policy environment but with different hydropower inflow conditions. The resulting comparison quantifies the impact of hydroclimatic stress on system costs, generation mix, emissions, and reliability, providing a clean experiment to test the climate resilience of least-cost energy pathways.

## 4.4 Results

### 4.4.1 Climate projection and Hydroclimatic Risks

#### Precipitation Trends and Variability

To assess spatial and temporal precipitation patterns relevant to Sierra Leone’s hydropower potential, multiple climate projection and statistical learning approaches were compared. Historical precipitation (1960) serves as the baseline, against which projections for 2030 were generated using the MRI-ESM2.0 CMIP6 model under SSP1-2.6 and SSP5-8.5, as well as a RF downscaling approach trained on ERA-5 land historical observations.

#### Historical Baseline:

In 1960, Sierra Leone exhibited high and evenly distributed precipitation across its territory, with annual rainfall exceeding 3,000 mm in most regions. Hydropower catchments such as Bumbuna, Singimi, and Bekongor benefited from abundant rainfall, ranging between 2,500 mm and 3,300 mm, supporting favorable hydrological conditions for energy generation. This baseline illustrates the historically wet climate that underpinned the country’s reliance on hydropower as a primary energy source.

### Random Forest 2030 Forecast:

The machine learning-based prediction, in Figure 66, shows a moderate intensification of rainfall in the southern basins, particularly around Singimi ( $\approx 3593$  mm), while central and northern stations such as Bumbuna ( $\approx 3030$  mm) and Bekongor ( $\approx 2305$  mm) display slight declines relative to 1960. This suggests that data-driven downscaling techniques may capture localized increases associated with coastal convection while maintaining regional heterogeneity.

### Random Forest 2050 Forecast:

By 2050, the RF model predicts relatively stable precipitation across Sierra Leone, with only marginal decreases from 2030 levels (Figure 66b). Hydropower basins such as Bumbuna, Bekongor, and Singimi continue to receive between 2,800–3,000 mm of rainfall annually, showing no significant drying trend. This stability contrasts with climate scenario projections, suggesting that mid-century hydropower generation may remain largely resilient, though local seasonal variability could still affect reliability.

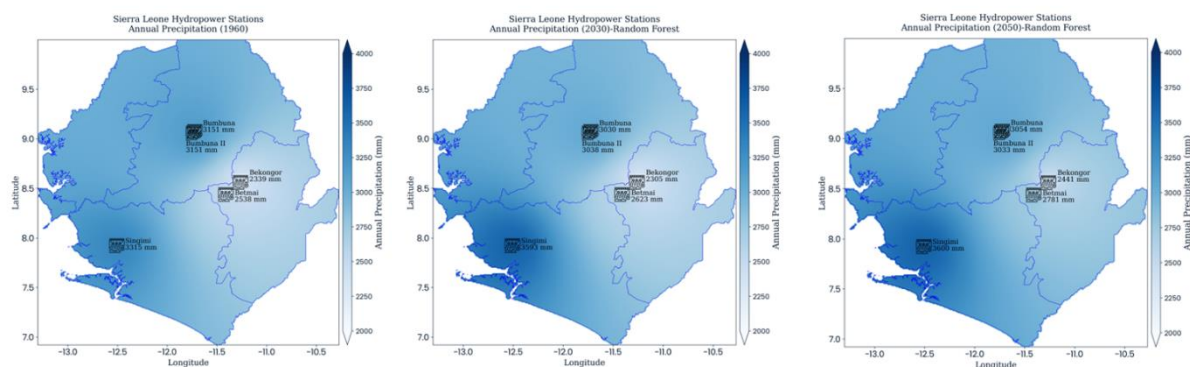


Figure 66 - Past Annual precipitation 1960 (a) and Random Forest Predicted for 2030 (b) and 2050 (c). Created by the authors using administrative boundaries from (Humanitarian Data 2023) and opendatasoft (2019).

### CMIP6 MRI-ESM2.0 SSP1-2.6:

As illustrated under a low-emission stabilization scenario, the model indicates a marked decrease in precipitation across all hydropower basins by 2030. Reductions are strongest in the southern region (Singimi, from 3315 mm to 2028 mm) and central plateau areas (Bumbuna, from 3151 mm to 2324 mm). The spatial drying pattern aligns with weakening monsoonal dynamics projected under mitigated warming conditions.

By 2030, projections under the SSP1-2.6 climate pathway show a notable decline in precipitation across much of Sierra Leone, particularly in the central and southern interior (Figure 66b). Average rainfall in key hydropower zones such as Bumbuna and Singimi decreases by about 25–30% compared to 1960 levels, dropping from over 3,100 mm to around 2,300 mm. While some northern areas, retain relatively higher rainfall, the overall drying trend may constrain water inflows and reduce seasonal generation capacity.

By 2050, the drying trend intensifies, with annual rainfall in most hydropower catchments declining by 700–1,200 mm relative to the historical baseline (Figure 67c). Bumbuna,

Bekongor, and Singimi show the steepest reductions, with precipitation levels near or below 2,200 mm. The spatial distribution of rainfall also becomes more uneven, indicating potential increases in hydrological variability and drought risk. These shifts suggest significant long-term implications for Sierra Leone's hydropower reliability, underscoring the need for diversified generation sources and climate-adaptive infrastructure planning.

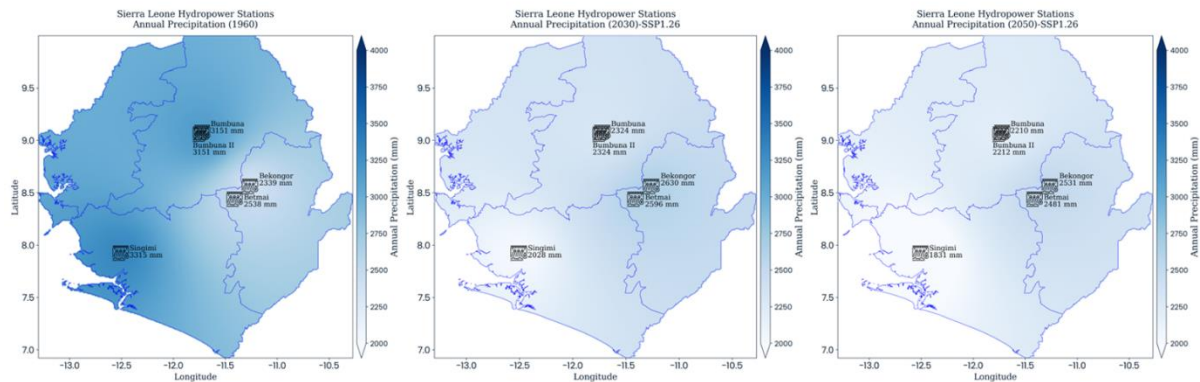


Figure 67 - Past Annual precipitation 1960 (a) SSP1-2.6 Projected for 2030 (b) and SSP1-2.6 Projected for 2050 (c). Created by the authors using administrative boundaries from (Humanitarian Data 2023) and opendatasoft (2019).

#### CMIP6 MRI-ESM2.0 SSP5-8.5:

In contrast, as shown in Figure 67 (b), the high-emissions trajectory suggests a partial recovery or increase in precipitation in parts of the northeast and central regions, with Bekongor ( $\approx 2747$  mm) and Betmai ( $\approx 2729$  mm) surpassing baseline values, while the southern coast remains comparatively drier (Singimi  $\approx 2089$  mm). This heterogeneity reflects enhanced convective activity and greater atmospheric moisture under warmer global conditions.

By 2050, the high-emissions scenario, Figure 68(c) indicates a more pronounced spatial redistribution of rainfall, with continued drying along southern and coastal zones and modest wetting retained in the northeast and central basins. Annual precipitation at Bumbuna and Betmai declines further to around 2,070–2,265 mm, while Bekongor remains relatively wetter at approximately 2,253 mm. These patterns suggest intensified atmospheric convection but increased variability and seasonality—conditions that could heighten hydrological uncertainty despite modest gains in localized rainfall.

Together, these spatial patterns indicate that future precipitation responses in Sierra Leone are non-linear, with drying under low emissions and modest wetting under high emissions.

Coastal and southern catchments remain more variable than inland ones, underscoring regional contrasts in climate sensitivity.

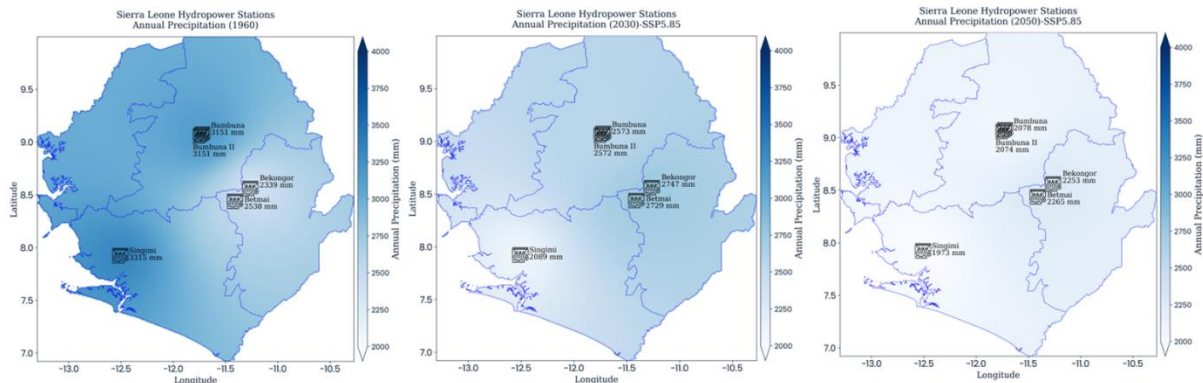


Figure 68 - Past Annual precipitation 1960 (left) SSP5-8.5 Projected for 2030 (b) and SSP5-8.5 Projected for 2050 (c). Created by the authors using administrative boundaries from (Humanitarian Data 2023) and opendatasoft (2019).

Temporal projections (Figure 69) of total annual precipitation across Sierra Leone indicate both declining totals and increased variability across emission scenarios. Over 2015–2050, cumulative precipitation is projected to be approximately 21% lower under SSP1-2.6 and 26% lower under SSP5-8.5 relative to the RF baseline. Interannual variability is estimated at 5.7% (SSP1-2.6), 8.4% (SSP5-8.5), and 7.3% (RF), signifying a generally drier and more variable hydroclimate under the high-emissions pathway.

While these percentages may appear modest, even small increases in interannual variability can have disproportionate hydrological impacts, particularly in monsoon-dominated systems where runoff responds non-linearly to rainfall (Allan et al., 2020; Haensler et al., 2013). In humid tropical basins, typical annual variability is around 3–6%; thus, values approaching 8–9% represent a 30–50% relative increase in variability, amplifying risks of both droughts and high-flow events (Quagraine et al., 2020). Such shifts can translate into 20–30% fluctuations in reservoir inflows and hydropower generation, underscoring the operational sensitivity of Sierra Leone’s hydropower system to even moderate climatic changes (World Bank, 2021).

The RF baseline shows higher mean precipitation totals (14–16 m<sup>3</sup> yr<sup>-1</sup>) than either CMIP6 scenario, reflecting a wetter bias likely associated with coastal rainfall interpolation. The SSP1-2.6 trajectory stabilizes around 11–12 m<sup>3</sup> yr<sup>-1</sup>, while SSP5-8.5 oscillates between 9–13 m<sup>3</sup> yr<sup>-1</sup>, suggesting amplified year-to-year fluctuations and an increased likelihood of short-duration, high-magnitude rainfall events typical of a warmer, moisture-laden atmosphere (Sylla et al., 2018). Overall, projections indicate that 2030 precipitation will become both lower and more erratic, posing heightened challenges for hydropower reliability, reservoir management, and long-term water resource planning.

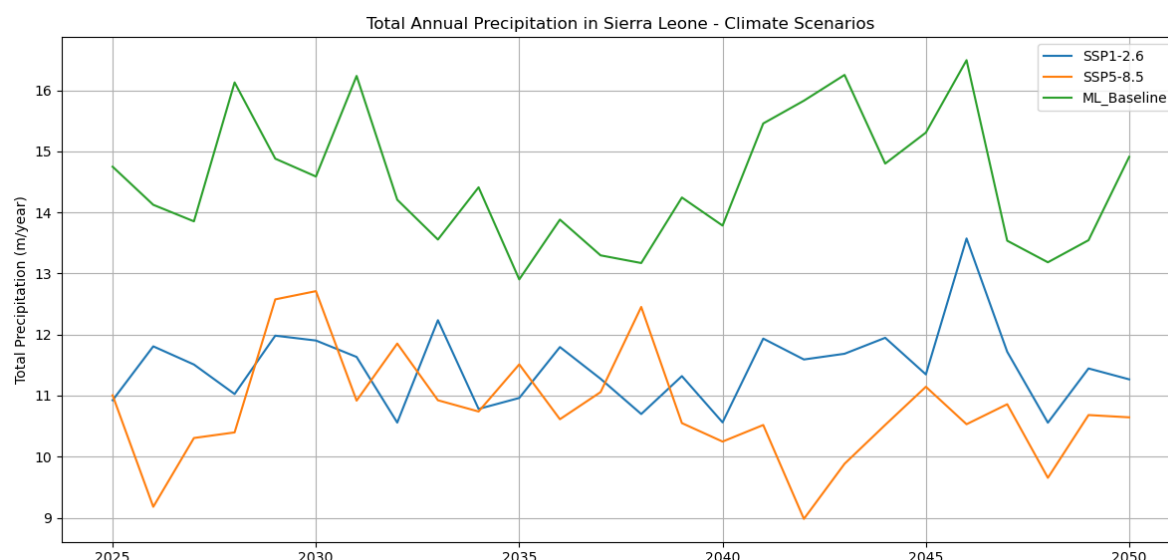


Figure 69 - Total Average Annual precipitation in Sierra Leone (2025–2050) under three climate pathways. Image created by authors.

### Drought Frequency and Severity

Because precipitation alone cannot capture the combined effects of rainfall deficits and temperature-driven evapotranspiration, we use the 6-month Standardized Precipitation–Evapotranspiration Index (SPEI-6) to assess hydro-climatic stress at each hydropower site. Whereas the precipitation maps showed spatial drying under SSP1-2.6 and mixed wetting under SSP5-8.5, the SPEI-6 series reveal temporal variability and the frequency of drought–wetness cycles at each hydropower basin.

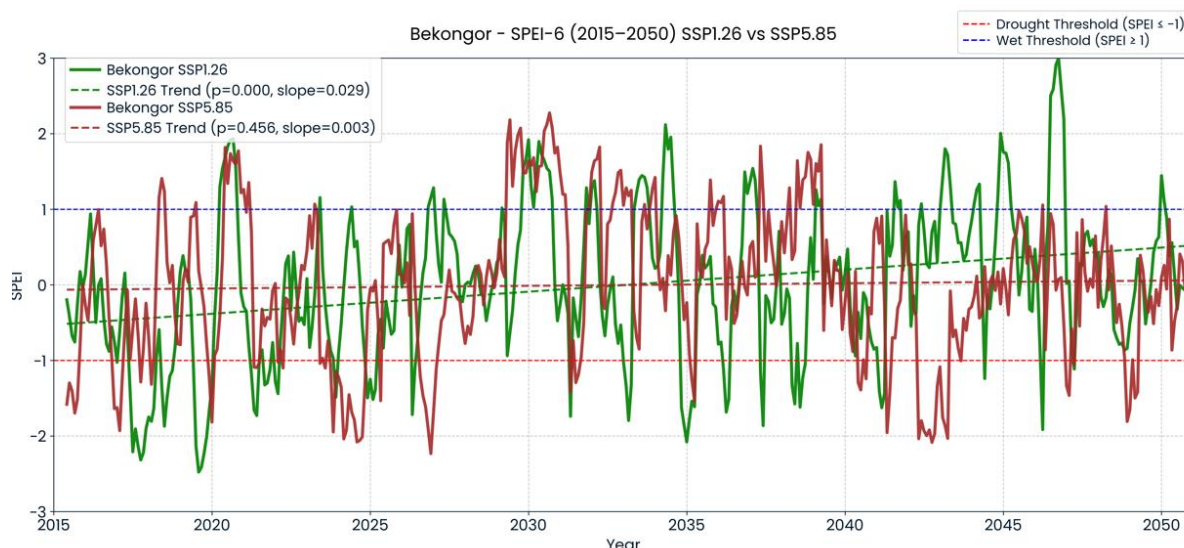


Figure 70 - Bekongor SPEI-6 (2015–2050) under low- (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. Data derived from the CMIP6 MRI-ESM2.0 model. Image created by authors.

In Figure 70, we observe SPEI-6 values under two SSP scenarios. Both scenarios fluctuate widely around zero, indicating recurrent transitions between wet and dry months. Under SSP1.26, a weak positive trend (slope = 0.029;  $p < 0.001$ ) suggests a marginal recovery toward

wetter conditions after 2030, but repeated drought episodes ( $\text{SPEI} < -1$ ) persist through the 2020s.

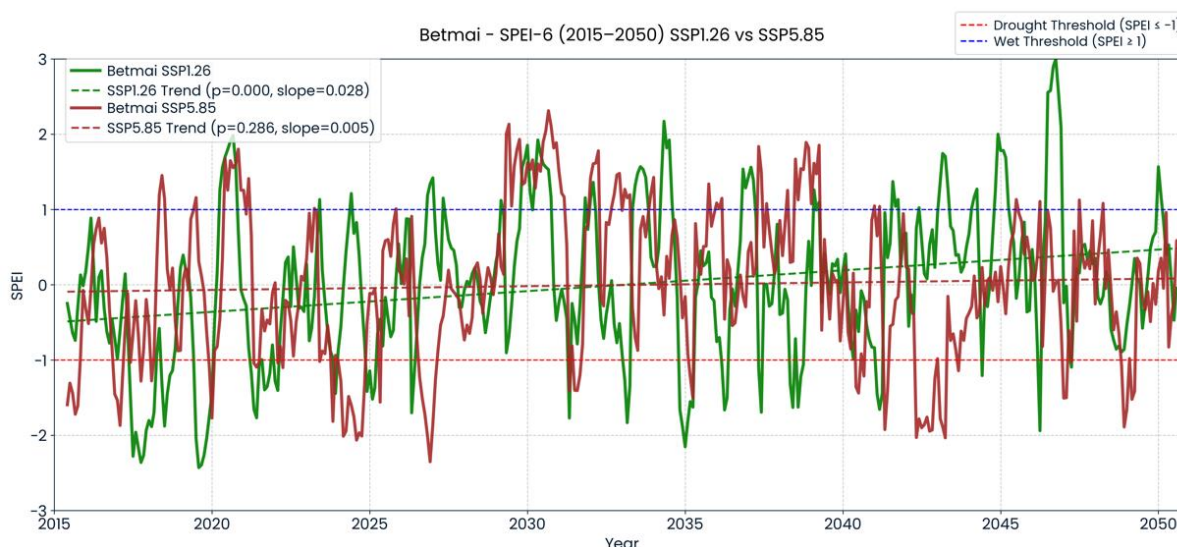


Figure 71 Betmai SPEI-6 (2015–2050) under low- (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. Data derived from the CMIP6 MRI-ESM2.0 model. Image created by authors.

In , both emission scenarios exhibit alternating wet and dry anomalies for Betmai. The SSP1-2.6 case shows a mild wetting trend (slope = 0.028;  $p < 0.001$ ), while SSP5-8.5 remains statistically insignificant (slope = 0.005;  $p = 0.286$ ). The pattern indicates transient wet periods followed by rapid drying, reflecting instability in short-term water balance conditions that could affect inflow reliability.

and represent Sierra Leone's most critical hydropower assets, supplying most of the the country's grid-connected electricity. Both plants exhibit positive yet subtle trends under SSP1-2.6 (slope  $\approx 0.027$ ;  $p < 0.001$ ) and near-zero trends under SSP5-8.5, indicating no pronounced long-term drying or wetting. However, frequent oscillations around the drought threshold ( $\text{SPEI} \leq -1$ ) reveal recurrent sub-seasonal water deficits, even where the long-term mean remains stable. These short but frequent dry spells could intermittently stress reservoir operations, affecting generation reliability despite relatively steady annual precipitation totals. Maintaining hydrological stability at Bumbuna I and II is therefore crucial for national energy security, as these fluctuations could translate into operational challenges for load balancing, storage optimization, and drought contingency planning.

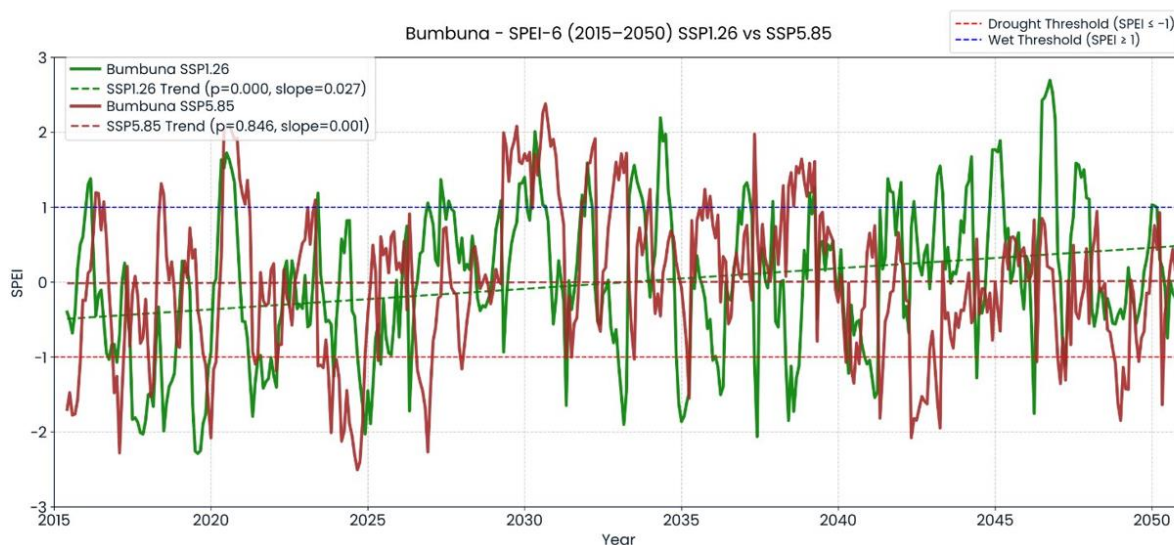


Figure 72 Bumbuna-I SPEI-6 (2015–2050) under low- (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. Data derived from the CMIP6 MRI-ESM2.0 model. Image created by authors.

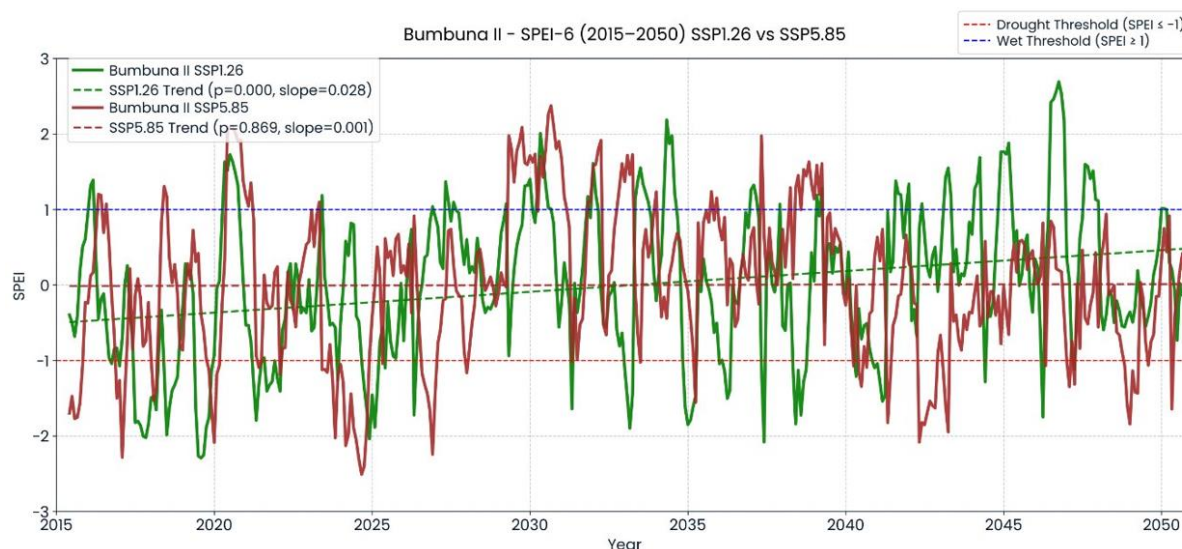


Figure 73 Bumbuna-II SPEI-6 (2015–2050) under low- (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. Data derived from the CMIP6 MRI-ESM2.0 model. Image created by authors.

Located in Sierra Leone's wetter southern zone, Singimi, in , shows the most pronounced amplitude between dry and wet phases. Under SSP5-8.5, the trend is slightly positive (slope = 0.011;  $p = 0.015$ ), yet oscillations intensify after 2030, implying increased hydro-climatic volatility. The SSP1-2.6 series, by contrast, displays smaller fluctuations but sustained negative anomalies between 2020 and 2035, highlighting potential mid-century drought stress.

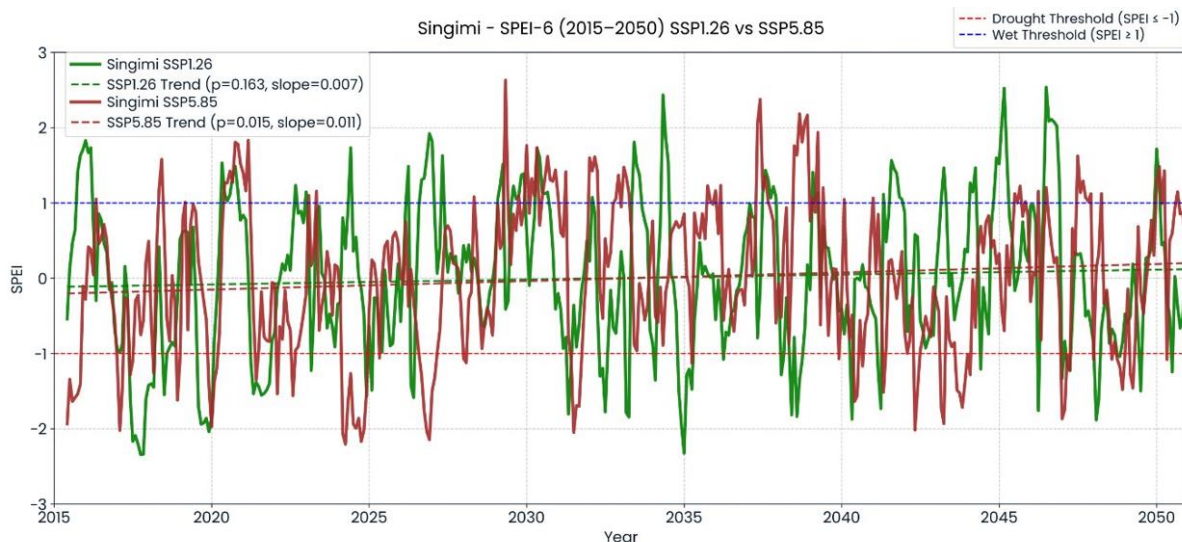


Figure 74 Singimi SPEI-6 (2015–2050) under low- (SSP1-2.6) and high-emission (SSP5-8.5) scenarios. Data derived from the CMIP6 MRI-ESM2.0 model. Image created by authors.

Across all basins, SPEI-6 values cluster within  $\pm 2$  standard deviations, indicating that moderate droughts ( $\text{SPEI} \leq -1$ ) and wet spells ( $\text{SPEI} \geq 1$ ) are recurrent but typically short-lived. Collectively, these results reinforce the precipitation-based findings: even as mean rainfall declines modestly under low-emission conditions, intra-annual hydro-climatic variability increases, particularly under high-emission forcing. The southern and eastern basins (Singimi and Bekongor) show higher amplitude fluctuations and frequent transitions across drought and wet thresholds, indicating greater exposure to short-term hydro-climatic shocks. In contrast, the central–northern stations (Bumbuna I, Bumbuna II, and Betmai) display more stable but persistently oscillating conditions, with subtle positive trends under SSP1-2.6 and neutral patterns under SSP5-8.5. Together, these findings suggest that while the core generation zones remain hydrologically steady, southern catchments may face increased volatility, highlighting the need for site-specific adaptation measures and flexible reservoir management that account for both short droughts and episodic intense rainfall events.

### Climate Impacts on Hydropower Inflows

We translate the precipitation and drought analysis into monthly capacity factors (CFs) for Sierra Leone’s five priority hydropower plants: Bumbuna I (storage), Bumbuna II (storage), Bekongor (storage), Betmai (run-of-river), and Singimi (run-of-river), under the three climate projections (ML baseline, SSP1-2.6, and SSP5-8.5). This step quantifies how changing rainfall and evapotranspiration patterns affect hydropower generation potential.

For run-of-river plants, daily inflows were mapped to power using design-flow and installed-capacity relationships, then aggregated and normalized by capacity-hours to obtain monthly CFs. For storage plants, a daily linear dispatch optimization was applied, respecting turbine limits, hydraulic conversion efficiency, and reservoir mass balance, before aggregating to monthly CFs. These monthly series were then supplied to OSeMOSYS as hydropower availability profiles, coupling the climate signal to long-term system planning.

summarizes the results across climate pathways. The top panels display annual CF trajectories (2025–2050), the right-hand tables report average, range, and standard deviation by plant.

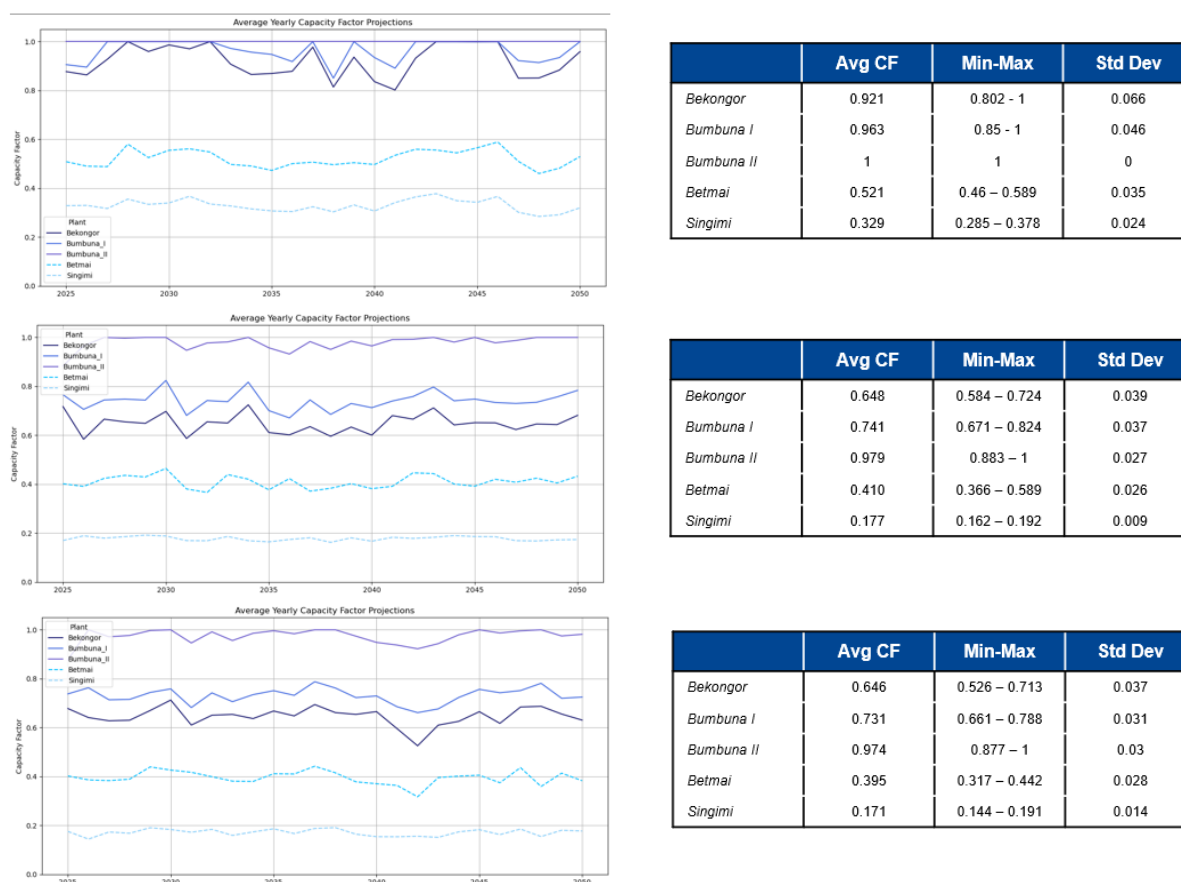


Figure 75 Hydropower capacity factors under alternative climates (top to bottom: ML-ERA5 baseline, SSP1-2.6, SSP5-8.5). For each climate pathway, the left panel shows annual CF trajectories for 2025–2050; the right panel reports plant-level summary statistics (mean, min–max, st. dev.). Images created by the authors.

Across all hydropower plants, CFs decline progressively from the RF to SSP1-2.6 and further to SSP5-8.5, with larger penalties for run-of-river systems and smaller impacts on regulated storage:

- Bumbuna II (storage) remains highly stable, with mean CF  $\approx 0.98$  across all scenarios, reflecting strong buffering against interannual and seasonal inflow variability.
- Bekongor (storage) declines from  $\approx 0.92$  (RF) to  $\approx 0.65$  under both SSPs, indicating sensitivity to limited reservoir volume and inflow seasonality.
- Bumbuna I (run-of-river) falls by about 25 % (from  $\approx 0.96$  to  $\approx 0.73$ – $0.74$ ), while Betmai declines by 20–25 %.
- Singimi (run-of-river) shows the steepest drop. It means CF roughly halves ( $\approx 0.33$  to  $\approx 0.18$  in SSP1-2.6 and  $\approx 0.17$  in SSP5-8.5), and by mid-century its dry-season CF dips below 0.1 in SSP5-8.5.

Seasonal patterns amplify these differences. Wet-season CFs remain near unity at major plants (Bumbuna I/II  $\approx 1.0$ ; Bekongor  $\geq 0.9$ ), but dry-season CFs erode sharply, dropping to  $\sim 0.6$ – $0.7$  at Bumbuna I,  $\sim 0.2$  at Betmai, and  $< 0.1$  at Singimi by 2050 under high emissions. This asymmetry mirrors the SPEI-6 results, indicating that short-duration droughts, not long-term mean drying poses the main operational threat.

Overall, the CF projections show that firm energy increasingly concentrates in large, regulated assets, while run-of-river plants become the first to experience shortfalls under intensified seasonal variability. Maintaining generation reliability under such conditions will likely require diversification, through solar, storage, flexible thermal backup, and regional trade, alongside adaptive reservoir operations tuned to sub-seasonal drought risk.

#### 4.4.2 Climate adaptation from energy production

As already mentioned, the results reported in this section, and the following ones show a least-cost, perfect-foresight dispatch for Sierra Leone's on-grid system. Market and contractual effects (e.g., take-or-pay, capacity payments) are not modelled, and the analysis is deterministic. Consequently, the figures should be read not as forecasts of actual operations, but as directional stress tests: by holding all non-climate inputs fixed and varying only hydro CFs, the comparisons indicate how the system would ideally reconfigure under different hydro-climate futures, giving relevant insights about the expected direction and scale of shifts in mix, costs, and emissions.

##### *ML-ERA5 baseline Results*

Under the ML-ERA5 baseline hydrology, the existing and already committed hydropower fleet is sufficient to meet demand across the horizon, with only minor imports in the early years and no new capacity additions required.

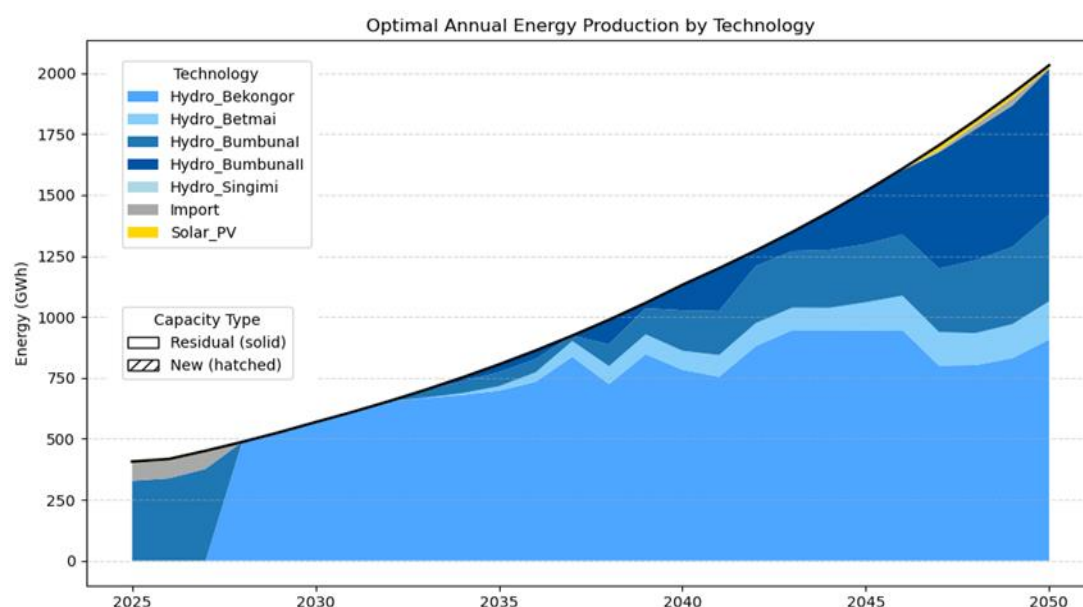


Figure 76 Least-cost annual on-grid electricity production by technology, 2025–2050. Image created by the authors.

Generation is hydro-dominated throughout (). In 2025 the system leans heavily on Bumbuna I, which supplies over four-fifths of total output while imports bridge roughly a fifth of supply;

solar PV and fossil units are essentially idle. From 2030 onward, Bekongor becomes the backbone resource and remains so to mid-century, delivering close to 70% of cumulative generation over 2025–2050. By the middle of the horizon the mix settles into a more balanced hydro portfolio, approximately Bekongor 45%, Bumbuna II 29%, Bumbuna I 18%, and Betmai 7%, with imports tapering to near zero by 2050. Implied utilisation rates highlight this pattern: Bekongor operates at high capacity factors, while Bumbuna I and Betmai (run-of-river) show lower utilisation with compare to Bumbuna II's storage capability which is used to smooth seasonal variability rather than to expand annual energy. In short, under the ML hydro-climate the least-cost system relies almost entirely on hydropower with negligible fossil dispatch and no solar uptake, delivering a low-cost, low-emissions outcome, but one whose robustness ultimately depends on the persistence of favourable inflows discussed in the subsequent climate-stress scenarios.

#### *SSP1-2.6 Scenario Results*

Under the SSP1-2.6 climate pathway, lower inflows reduce average hydropower availability to the point where the committed fleet alone cannot fully guarantee adequacy. In the no-expansion case, the model leaves around 2.37% of annual demand unmet, relying more heavily on imports during the 2020s. By 2026–2027 imports provide over 150 GWh per year, close to one quarter of supply, before fading as new storage hydro comes online. The early mix remains dominated by Bumbuna I ( $\approx 260$ – $280$  GWh/yr), but its run-of-river profile proves insufficient to meet rising demand as inflows decline.

As the system matures, the center of gravity shifts decisively toward storage. Bekongor first emerges as the anchor from the late 2020s, delivering well over 400 GWh annually and surpassing 600 GWh in wetter years of the 2040s. From the mid-2030s onward, Bumbuna II increasingly assumes the role of backbone, rising to more than 800 GWh by 2050 and becoming the single largest contributor to national supply. By contrast, the smaller run-of-river plants, Betmai and Bumbuna I, provide more variable support: Betmai adds around 50–90 GWh in most years after 2040, while Bumbuna I fluctuates more widely, from barely 50 GWh in dry periods to over 300 GWh by the end of the horizon. Solar PV remains marginal, contributing a handful of tens of GWh per year at most, and imports never disappear entirely, with small but recurring contributions even in the 2040s–2050. ( ).

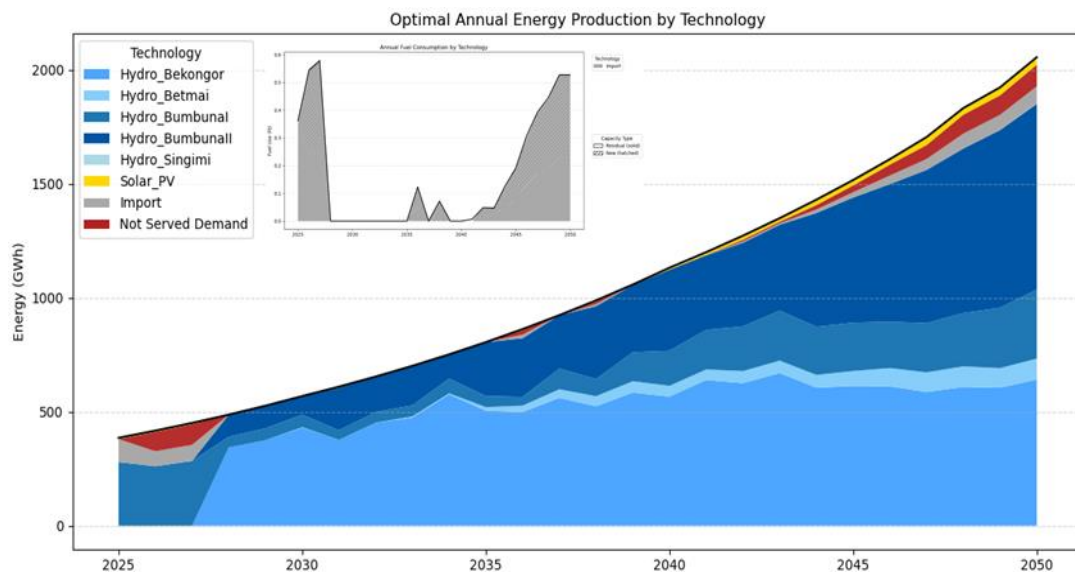


Figure 77 Optimal annual energy production by technology under SSP1-2.6. Image created by the authors.

Allowing new capacity alters this picture by adding a modest thermal backstop rather than restructuring the system away from hydro. In 2026 the model invests in roughly 130 MW of LFO and 35 MW of HFO, an upfront capital cost of about 141 M\$. These units remain largely on standby but provide strategic insurance: their actual dispatch is limited (for instance, only 2–3 GWh from HFO in dry years), yet their presence ensures adequacy during extended droughts and curbs the recurrence of large import spikes later in the century.

The implication is that hydropower continues to dominate under SSP1-2.6, but capacity expansion is required to supplement for lower expected rainfall. This raises system costs modestly through capital and fixed O&M, and introduces a non-zero emissions footprint when oil units are dispatched. Compared with the ML-ERA5 baseline, where the fleet alone suffices and new capacity is unnecessary, the SSP1-2.6 pathway highlights the cost of resilience: a permanent insurance premium to guard against hydrological risk.

### SSP5-8.5 Scenario Results

The high-emissions pathway is both drier and more volatile. In the fixed-fleet case, the system leaves a slightly larger shortfall than in BL-126: 2.42% of annual demand is not served (vs 2.37% in BL-126), and the peak gap rises to 110.7 GWh in 2050 (vs 94.9 GWh). Generation remains hydro-centric but shifts further toward storage as run-of-river performance weakens; Bumbuna II progressively carries more of the annual output, Bekongor stays important but more variable, solar is marginal, and imports reappear intermittently.

Allowing capacity additions produce a larger and earlier capacity expansion than in BL-126. The least-cost build adds ≈135 MW biomass in 2025 and ≈138 MW LFO in 2026: about 273 MW for ≈USD 446 m upfront. This commits roughly USD 13.4 m/yr of fixed O&M and, by mid-century, higher operating bills as LFO runs harder, and imports persist ().

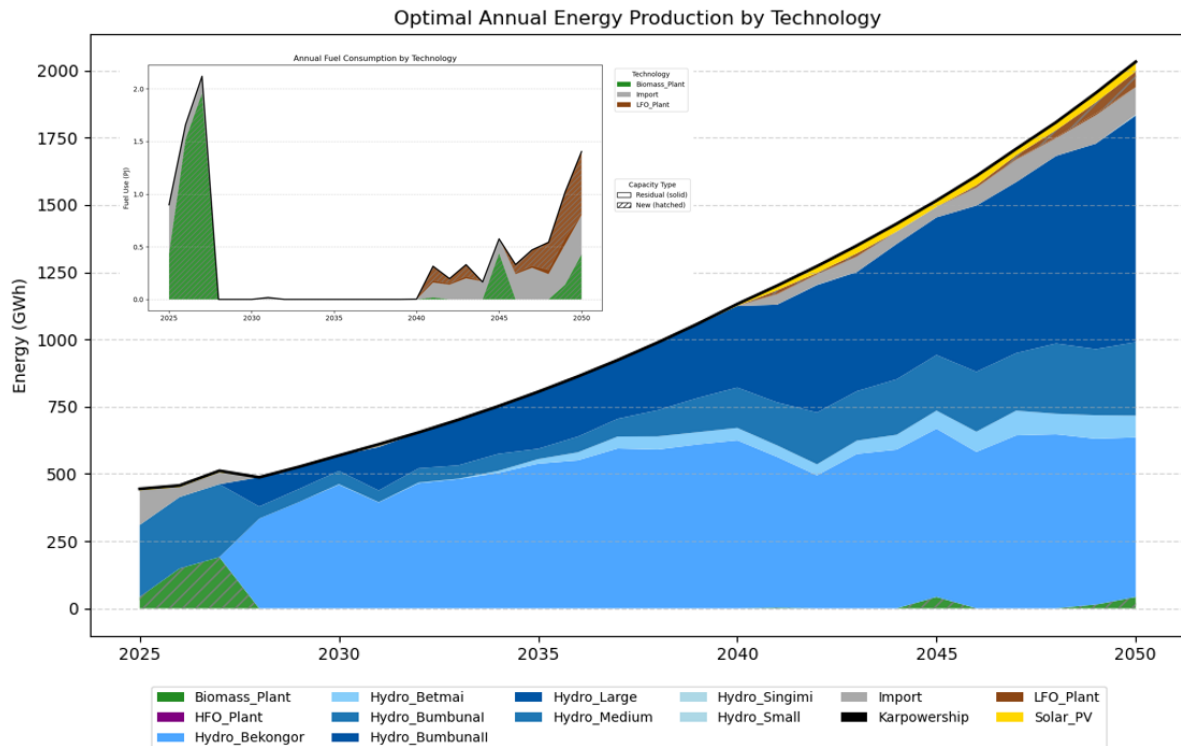


Figure 78 Optimal annual energy production by technology under SSP5-8.5. Image created by the authors.

Across climates, hydropower remains the backbone but reliance shifts toward storage hydro as dry-season firm energy from run-of-river plants declines. Under SSP5-8.5, adequacy requires more thermal capacity than under SSP1-2.6; these units dispatch infrequently but still raise total costs and emissions. The system is therefore hydro-led yet costlier and more carbon-exposed under severe drying, strengthening the case for resilience measures that add firm, flexible non-hydro supply or demand-side flexibility, alongside prudent reservoir operations.

#### 4.4.3 Comparisons of the total system cost of the power system

##### RF Results

presents the annual cost decomposition for the ML baseline scenario. With no new builds, CAPEX is zero throughout, so the profile is governed by the fixed-cost floor plus any import bills. The first year shows a pronounced spike driven by the Karpowership lease (~\$53 m/yr) even though the unit barely runs, an emblematic example of contractual costs that the least-cost model does not internalise in dispatch. Costs then drop sharply in 2026–27 as that rental charge falls away and imports ease. From the late-2020s the curve steps up to a stable plateau as the committed storage and large hydro come fully online: Bumbuna II and Bekongor set the floor (order of \$10–13 m/yr each), with smaller fixed O&M from Bumbuna I, Betmai and Singimi. Because hydro has negligible variable cost and imports largely disappear after the mid-2020s, the line stays flat through the 2030s–40s, with only a small bump near 2050 when imports reappear in a few dry years.

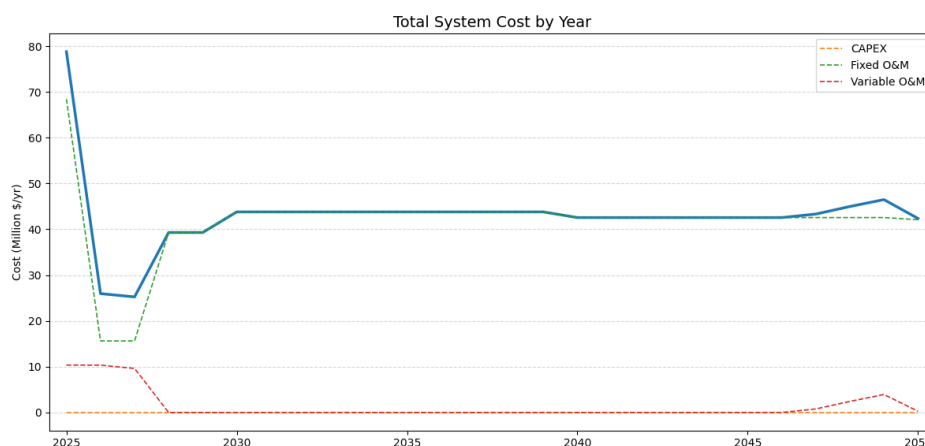


Figure 79 Annual total system cost under the ML-ERA5 baseline (2025–2050), decomposed into CAPEX, fixed O&M, and variable O&M. Image created by the authors.

### SSP1-2.6 Scenario Results

Under SSP1-2.6 the system remains hydro-led, but it chooses to invest for resilience rather than simply assume favorable rainfall. In the baseline, flexibility is provided through early imports and committed hydro assets, with no capacity expansion required: once the Karpowership contract and initial import bills fade, costs flatten at a relatively lean level. By contrast, SSP1-2.6 acknowledges greater hydrological risk and installs a block of firm oil-fired capacity in 2026 (about 165 MW in total). This decision requires a capital outlay of roughly 141 M\$, and more importantly it commits the system to carry an additional  $\approx 4$  M\$/yr in fixed O&M for the rest of the horizon. This choice reshapes the mid-horizon cost landscape. Fixed O&M remains dominated by the hydro fleet, Bumbuna II ( $\sim 12.9$  M\$/yr) and Bekongor ( $\sim 10.8$  M\$/yr) in particular, but the oil plants add a permanent layer on top. Compared with the baseline, which leans on imports and keeps fixed charges low, SSP1-2.6 creates a steadier but heavier fixed-cost profile: planners are essentially accepting to spend more every year to guarantee that the lights stay on when water inflows fall short.

Operating costs reveal another contrast. Both scenarios experience an initial import bulge in the mid-2020s (around 57 M\$ over 2025–2027), but in SSP1-2.6 costs re-emerge toward the end of the horizon. From the 2040s onwards, the system faces renewed expenditures: imports climb again (reaching nearly 15 M\$ in 2049), and for the first time the newly built LFO fleet is dispatched significantly, adding about 50 M\$ in variable O&M between 2046–2050. The trade-off is therefore straightforward: the baseline offers the cheapest pathway in “normal” conditions but leaves the system exposed to hydrological volatility, while SSP1-2.6 accepts higher fixed costs and occasional late-period operating expenses in exchange for robustness. In other words, one pathway is lean but fragile, the other slightly costlier but more resilient to climate risk.

### SSP5-8.5 Scenario Results

The high-emissions, drier climate pathway is both more capital-intensive and more costly to operate than either the baseline or SSP1-2.6. Whereas SSP1-2.6 adds a modest fossil backstop ( $\approx 165$  MW, 141 M\$ CAPEX) as insurance, SSP5-8.5 requires a much larger expansion. By 2025–2026 the model commits to nearly 273 MW of new capacity, about 135 MW of biomass ( $\approx 337$  M\$) and 138 MW of LFO ( $\approx 109$  M\$), a combined  $\approx 446$  M\$ of capital investment, roughly three

times higher than SSP1-2.6. This upfront choice locks in a substantially heavier fixed-cost burden:  $\approx 13.4$  M\$/yr from the new biomass and LFO plants, compared with  $\approx 4$  M\$/yr in SSP1-2.6.

Once online, these assets reshape the long-term cost structure. Fixed O&M remains anchored by hydro (Bumbuna II and Bekongor at  $\approx 10$ – $13$  M\$/yr each), but the additional fossil units impose a new floor. In effect, SSP5-8.5 carries  $\approx +9$  M\$/yr more fixed charges than SSP1-2.6 simply to maintain adequacy under harsher hydrology. This turns the mid-century system into one with visibly higher standing costs even before accounting for operations.

Variable costs also diverge strongly. Like the other scenarios, SSP5-8.5 experiences early import costs in the 2020s, but unlike SSP1-2.6 these do not fade away. Instead, both imports ( $\approx 14$  M\$/yr by 2050) and LFO dispatch ( $\approx 20$  M\$/yr by 2050) remain significant contributors to operating expenditure, reflecting more frequent dry-season deficits. Biomass dispatch adds only a minor fuel cost ( $\approx 0.7$  M\$/yr), but the system as a whole is far more cost-exposed: annual operating outlays in the late 2040s–2050 are several times larger than in the baseline, and materially higher than in SSP1-2.6.

Results are visually compared across scenarios in .

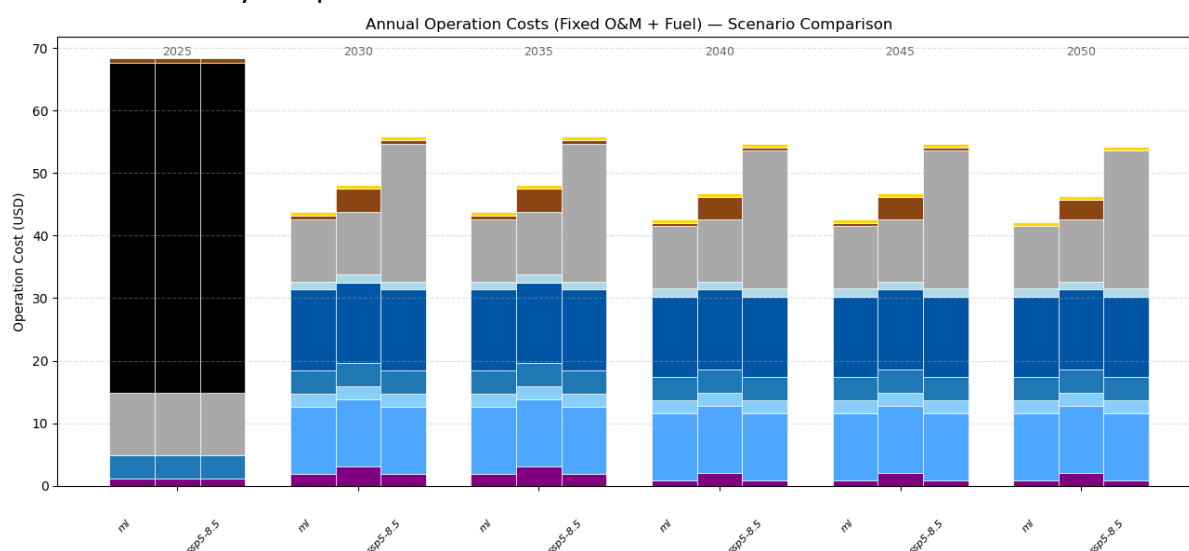


Figure 80 Annual operating costs (fixed O&M plus fuel) for Sierra Leone’s power sector under baseline (ml) and SSP5-8.5 climate scenarios, 2025–2050.

#### 4.4.4 Sustainability assessment

##### ML–ERA5 baseline Results

Emissions are computed on a Scope-1 (), direct basis from modeled fuel use and a single grid factor for imports. Because the ML case dispatches essentially no domestic fossil generation, all CO<sub>2</sub> arises from imports in the early years. For those imports, it has been applied the WAPP operating-margin (OM) grid emission factor (0.578 tCO<sub>2</sub>/MWh) taken from the CDM standardized baseline (UNFCCC, 2021). OM has been used rather than build or combined margin because imports are assumed to displace marginal thermal generation on the regional grid in each year. Multiplying imported MWh by 0.578 tCO<sub>2</sub>/MWh yields a cumulative  $\sim 0.13$  MtCO<sub>2</sub> over 2025–2050. Annual emissions peak around 2025–2026 at  $\sim 0.043$  MtCO<sub>2</sub>, then

decline rapidly toward zero after 2030 as imports fade and hydropower dominates. These figures exclude upstream life-cycle and construction emissions and do not adjust for potential year-to-year changes in the WAPP mix.

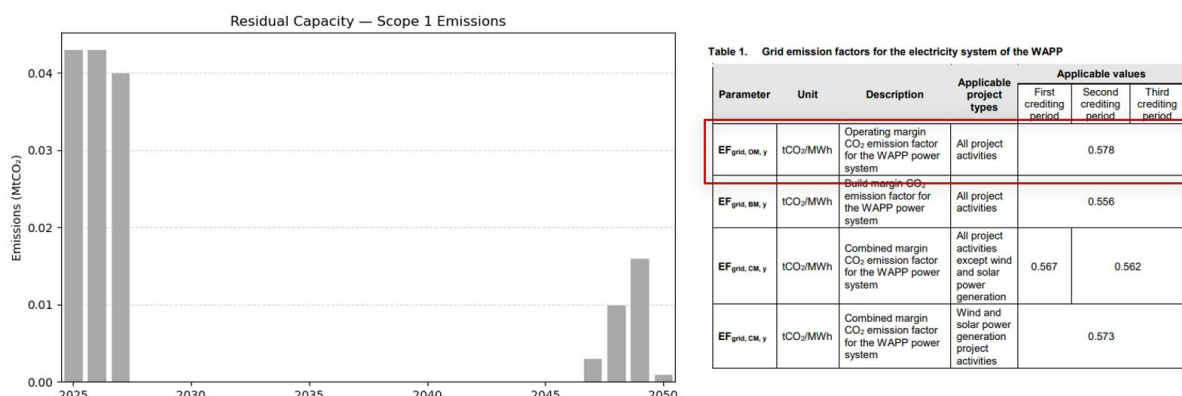


Figure 81 Direct Scope 1 emissions for Sierra Leone's power sector under the ML-ERA5 baseline scenario (2025–2050).

### SSP1-2.6 Scenario Results

Under the SSP1-2.6 climate pathway, emissions remain modest but become structurally higher than in the baseline because the system requires thermal backstop capacity. Cumulative emissions reach  $\approx 0.66$  MtCO<sub>2</sub> over 2025–2050, about five times the baseline value. Imports are still the largest single source, contributing  $\approx 0.56$  MtCO<sub>2</sub>, while the newly built oil units add a small but non-negligible increment:  $\approx 0.02$  MtCO<sub>2</sub> from HFO and  $\approx 0.08$  MtCO<sub>2</sub> from LFO. The temporal profile shows two key phases: an initial peak in the mid-2020s, dominated by imports, and a second rise in the late 2040s as dry years trigger both renewed imports and dispatch of LFO. In most years fossil units remain underutilised, but their occasional operation during hydrological stress is enough to lift cumulative emissions well above the ML-ERA5 baseline ().

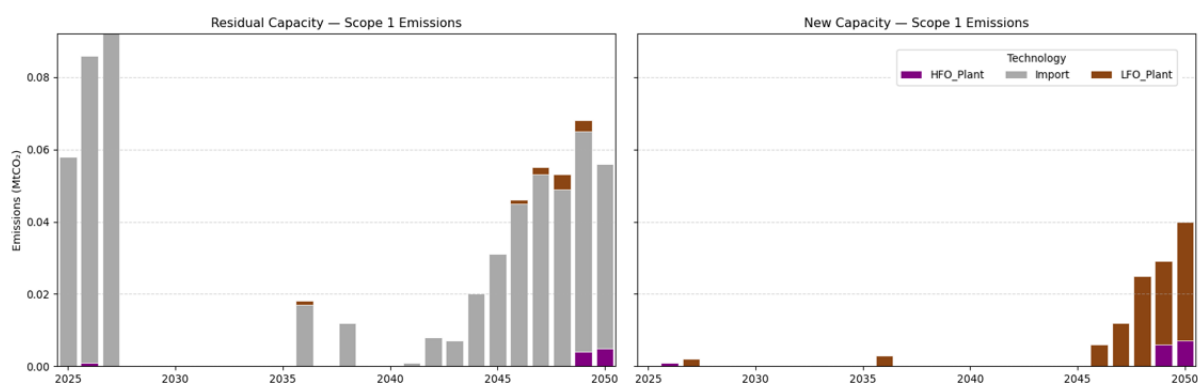


Figure 82 Scope 1 emissions under the MRI-ESM2.0 SSP1-2.6 climate scenario with baseline ETGP demand.

### SSP5-8.5 Scenario Results

The SSP5-8.5 pathway produces the highest emissions burden, reflecting both more severe drying and heavier reliance on fossil expansion. Total emissions over the horizon reach  $\approx 0.95$  MtCO<sub>2</sub>, roughly 50% higher than SSP1-2.6 and seven times the baseline. Imports remain significant at  $\approx 0.48$  MtCO<sub>2</sub>, but now they are joined by substantial contributions from domestic thermal plants:  $\approx 0.36$  MtCO<sub>2</sub> from biomass and  $\approx 0.11$  MtCO<sub>2</sub> from LFO. HFO contributes only marginally ( $\approx 0.01$  MtCO<sub>2</sub> from residual capacity). The emissions trajectory mirrors the cost dynamics: a large early spike from biomass commissioning in 2025–2026,

followed by recurrent fossil dispatch in the 2040s and 2050 as inflows weaken. Compared with SSP1-2.6, therefore, SSP5-8.5 represents not just a costlier pathway but also a materially more carbon-exposed one ( ).

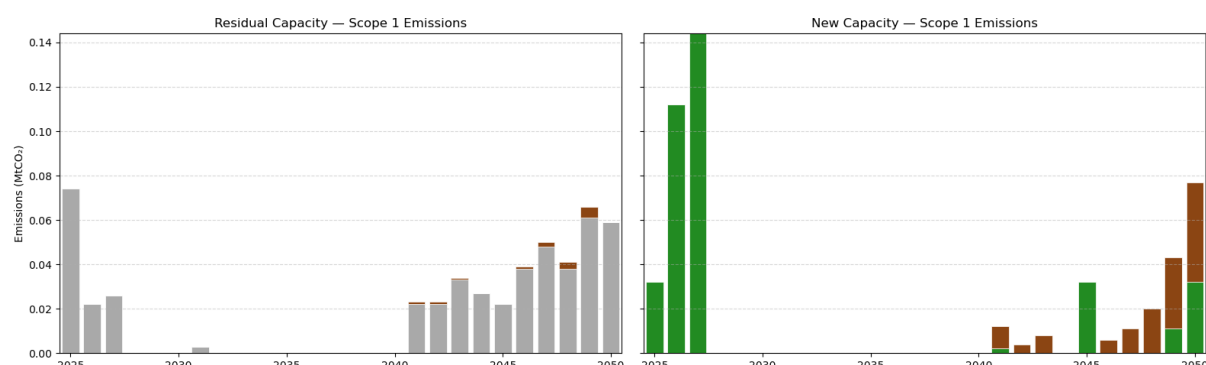


Figure 83 Scope 1 emissions under the MRI-ESM2.0 SSP5-8.5 climate scenario with baseline ETGP demand.

#### 4.4.5 Multi-criteria decision analysis (MCDA)

Access to sustainable electricity production is crucial for energy security especially in a low-income country, particularly in Sierra Leone. Biodigesters and diesel generators are commonly deployed for electricity generation, each with distinct environmental, economic, technical and social implications.

This section uses Multi-Criteria Decision Analysis (MCDA) to compare the sustainability of these systems across several criteria. The objective of this work is to evaluate and compare the sustainability of a biodigester-based system versus a diesel generator-based system for electricity production using MCDA in Sierra Leone, as a testimony of a green path in African development with applying green energy technology in ENERGICA Project.

To achieve that, the Multicriteria Decision Analysis (MCDA) tool developed in the framework of the ENERGICA project will be used. This involves the use of the following steps: Criteria Selection, the weighting Assignment, the scoring of the alternative and the ranking and Sensitivity Analysis.

The following criteria for assessment and their assigned weights are summarized in the Table 5 below:

Table 5 - Criteria for MCDA and assigned weights.

| Category      | Criteria           | Description                                                                      | Weight assignmen |
|---------------|--------------------|----------------------------------------------------------------------------------|------------------|
| Environmental | GHG emissions      | Amount of GHG emissions, expressed in gCO <sub>2</sub> -eq/kWh                   | 0.12             |
|               | Land use           | Land area modified during the lifecycle of the energy system per unit of energy. | 0.11             |
|               | NMVOC              | Non methane volatile organic compounds                                           | 0.10             |
| Economic      | Cost of production | Initial costs for investment in energy infrastructure. It is expressed in €/kW   | 0.09             |

|           |                                |                                                                                                                                                                                                           |      |
|-----------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
|           | NPV                            | The NPV is Also called as net present worth (NPV) and is defined as the total present value of a time series of cash flows.                                                                               | 0.10 |
|           | Operating and maintenance cost | Costs for operation and maintenance of the energy system.                                                                                                                                                 | 0.09 |
| Technical | Plant efficiency               | Ratio between the useful amount of electricity output and the total energy input. It is expressed in %                                                                                                    | 0.06 |
|           | Energy reliability             | Availability and consistency of power supply                                                                                                                                                              | 0.07 |
| Social    | Social Acceptance              | Positive opinions are related to the implementation of the energy system.                                                                                                                                 | 0.06 |
|           | Social benefit                 | Measures the quantity of direct and indirect jobs generated during the startup, operation and maintenance per each MW installed of the power plants, considering the induced future on job opportunities. | 0.1  |
|           | Health damage                  | Life deterioration due to the implementation of the energy system. It is expressed in DALY/TWh                                                                                                            | 0.11 |

Table 5 provides the overall performance scores of MCDA for biodigester and diesel-based electricity production. The biodigester system scores higher overall (0.57 vs. 0.43), mainly due to its strong environmental and social performance. The diesel generator excels in economic viability and reliability but suffers from high emissions and fuel dependency. In summary, the biodigester system is more sustainable overall, particularly in environmentally sensitive and socially engaged communities.

Table 6 - Performance score of MCDA.

| Alternatives     | Scores   | Rank            |
|------------------|----------|-----------------|
| Biodigester      | 0.570245 | 1 <sup>st</sup> |
| Diesel generator | 0.429755 | 2 <sup>nd</sup> |

## 4.5 Discussion

### 4.5.1 Planning Gaps under Climate Drought Scenarios

Under the RF ERA-5 baseline, Sierra Leone's power system appears technically adequate and economically efficient. Existing and committed hydropower plants are sufficient to meet projected demand through mid-century without new generation investments. Imports taper

off after the mid-2020s, fossil units remain idle, and total system costs stay low. In this configuration, the system delivers a near-zero-emission, hydro-dominant pathway, but one whose stability depends entirely on the persistence of historical rainfall patterns.

The results therefore illustrate a fragile equilibrium: while the baseline scenario offers a low-cost trajectory, it assumes hydrological conditions consistent with the recent past. The climate-stress scenarios show how quickly this balance unravels once drought frequency and inflow volatility rise. Under both SSP1-2.6 and SSP5-8.5, reduced precipitation and recurrent short droughts, consistent with the SPEI-6 findings, erode dry-season firm energy from run-of-river plants such as Bumbuna I, Betmai, and Singimi, creating seasonal adequacy gaps that require compensating capacity.

The OSeMOSYS stress tests reveal that under these drier and more variable futures, the least-cost system rebalances toward storage hydropower (notably Bumbuna II and Bekongor) supported by thermal backstops. Even with perfect foresight, these additions increase total system costs, by roughly two to three times under SSP5-8.5 relative to the RF projections highlighting the high economic value of firm energy under uncertainty. This divergence exposes a planning gap: national energy strategies still assume stable hydro yields, yet drought risk is already material. Embedding climate-conditioned hydropower availability profiles into long-term models would enable planners to hedge early against this risk, ensuring sufficient flexible and firm capacity before hydrological shocks materialize.

#### 4.5.2 Implications for Energy Security and Diversification

The analysis shows that hydropower will remain the cornerstone of Sierra Leone's power system, but its reliability declines under increasing hydro-climatic stress. In the RF-ERA5 baseline, hydropower meets nearly all on-grid demand at low cost and with minimal emissions. Under SSP1-2.6 and especially SSP5-8.5, however, declining inflows and recurrent short droughts reduce firm energy from run-of-river plants, forcing greater reliance on imports and new thermal capacity to maintain adequacy.

As the climate becomes drier and more variable, energy security increasingly depends on storage hydropower, notably Bumbuna II and Bekongor, which buffer seasonal variability but cannot fully offset sustained dry-season losses. Least-cost plans under these scenarios introduce limited oil-fired or biomass generation as strategic backstops, raising both system costs and carbon exposure.

These results point to a clear policy implication: sustaining reliability under future climates will require broader diversification of the generation mix. Expanding solar PV with storage, improving interconnection within the WAPP, and retaining limited flexible thermal capacity would strengthen resilience while preserving a predominantly renewable system. Embedding such diversification into the next Integrated Resource Plan would reduce Sierra Leone's vulnerability to hydrological shocks and ensure a climate-robust pathway to energy security.

#### 4.5.3 Limitations

The results presented here should be interpreted as directional stress tests rather than predictive forecasts. Both the OSeMOSYS and hydro-climate modeling frameworks abstract from several layers of real-world complexity.

From an energy-system perspective, OSeMOSYS assumes perfect foresight and cost-optimal behavior, without market constraints, operational reserves, or unplanned outages. Dispatch decisions are deterministic, and market mechanisms such as capacity payments, contract rigidities, or import price volatility are not represented. Consequently, the results highlight the *relative sensitivity* of system composition and costs to hydrological stress; not the absolute magnitude of future investment needs.

At the hydrological interface, the Random Forest (RF) rainfall model provides a statistically consistent, spatially resolved approximation of inflows but remains limited in its ability to capture non-linear feedback, extreme events, and land-use or soil-moisture dynamics. By design, the RF model extrapolates from past relationships; as climate patterns diverge toward mid-century, its skill may degrade. The RF projections to 2050 thus represent a plausible but uncertain upper bound on data-driven accuracy, particularly under the high-emissions SSP5-8.5 scenario, where atmospheric processes evolve beyond the range of the training data.

Regarding climate forcing, both SSP1-2.6 and SSP5-8.5 rely on the same underlying CMIP6 model (MRI-ESM2.0), but their interpretations differ. SSP1-2.6 provides a plausible lower-risk trajectory, consistent with global mitigation efforts that moderate temperature rise and preserve hydrological stability. SSP5-8.5, in contrast, represents a stress-test boundary, a physically consistent but less likely scenario that is useful for exploring system resilience under severe drying and variability. In practice, the most probable future likely lies between these two extremes, suggesting that planning based on ensemble averages or probabilistic blending of scenarios would yield more balanced insights.

Despite these constraints, the combined framework provides a transparent and replicable first-order assessment of how climate variability could reshape Sierra Leone's least-cost energy pathway. The approach is intentionally modular: refinements, such as stochastic inflow generation or integrated market modelling, can be added in future iterations to improve the robustness of planning under deep climate uncertainty.

#### 4.6 Conclusion

This study highlights a fundamental tension at the heart of Sierra Leone's energy transition: the country's future power system appears technically adequate, low-cost, and almost carbon-free if rainfall patterns remain close to the historical record, but becomes increasingly fragile and cost-intensive once climate variability and drought risk are factored in. Under the baseline ML-ERA5 hydrology, Sierra Leone can rely almost entirely on its existing and already committed hydropower assets to meet rising demand through mid-century. In this case, imports taper off after the 2020s, fossil units remain essentially idle, total system costs stay flat at relatively low levels, and cumulative direct emissions are minimal ( $\sim 0.13 \text{ MtCO}_2$ ), limited to imported electricity in the early years. The system thus delivers the kind of low-

cost, low-carbon trajectory that national strategies aspire to, but crucially, it does so on the assumption that past rainfall regimes persist into the future.

When climate-conditioned hydropower availability is introduced, however, the picture changes substantially. In both moderate (SSP1-2.6) and high-emission (SSP5-8.5) scenarios, declining inflows and more frequent short droughts erode dry-season generation from run-of-river plants such as Bumbuna I, Betmai, and Singimi. To preserve adequacy, the least-cost system pivots towards regulated storage plants (notably Bumbuna II and Bekongor) while adding firm backup capacity. Under SSP1-2.6, this translates into modest oil-fired capacity additions that increase fixed costs and lift cumulative emissions to  $\sim 0.66 \text{ MtCO}_2$ . Under SSP5-8.5, the pressures are sharper: earlier and larger expansions (biomass and LFO,  $\sim 273 \text{ MW}$  by the mid-2020s) push annual system costs to two to three times those of the baseline by mid-century, while cumulative emissions rise further to  $\sim 0.95 \text{ MtCO}_2$ . In all cases, the operational burden concentrates on a few large reservoirs, with run-of-river plants increasingly unable to provide reliable dry-season energy. This makes short, recurrent droughts, not just long-term mean drying, the decisive stressor for system stability.

From a planning perspective, the results are clear and actionable. To safeguard reliability under climate uncertainty, future strategies should: (i) systematically integrate climate-conditioned hydro availability into long-term planning rather than assuming historical stability; (ii) diversify the supply mix with utility-scale PV and storage, complemented by limited flexible thermal capacity as strategic insurance; (iii) strengthen CLSG/WAPP interconnections and implement adaptive reservoir operating rules designed around drought conditions; and (iv) promote demand-side flexibility to reduce vulnerability to seasonal adequacy gaps. Such measures can maintain hydropower as the backbone of the system while reducing exposure to climate-driven volatility.

At the same time, it is important to recognize the limitations of this assessment. The analysis represents a set of directional stress tests rather than precise forecasts. OSeMOSYS assumes perfect foresight and cost-optimal behavior, abstracting from market frictions, outage risks, or network constraints. The Random Forest downscaling improves spatial detail but cannot capture all non-linear hydrological feedback or extreme events, and the climate analysis relies on a single CMIP6 model (MRI-ESM2.0) rather than a probabilistic ensemble. Future work should therefore extend the framework by: (1) employing multi-model climate ensembles and basin-level hydrological models with explicit PET and soil-moisture dynamics; (2) adopting stochastic or robust capacity-expansion approaches to capture inflow uncertainty; (3) including market and contractual features such as capacity payments and import price volatility; (4) screening for transmission bottlenecks and congestion; (5) coupling reservoir optimization with environmental flows and drought contingency rules; and (6) widening the system boundary to capture off-grid and distributed energy resources as well as demand-side measures.

Taken together, these improvements would turn today's stress-test insight, that Sierra Leone's system is "hydro-led but climate-sensitive", into a practical, climate-resilient diversification plan. Such a plan would preserve the economic and environmental advantages of hydropower while embedding resilience to hydro-climatic shocks, ensuring that Sierra

Leone's long-term pathway to affordable, secure, and sustainable electricity is robust even under a drier and more variable climate future.

## 5. Madagascar

### 5.1 Case study description

Madagascar is a prime example of the vulnerability of islands to climate change as it has lost much of its forested habitat, and ecosystem services due to climate change (Hannah et al., 2008). Despite being the world's fourth-largest island and the 46th largest country in the world, Madagascar is among the least developed countries with very small greenhouse gas emissions about 2.65 tCO<sub>2</sub>e per capita. Though Madagascar's contribution to global greenhouse gas emissions is relatively small (only around 0.12% of total global GHG emissions) (USAID, 2016), its strongly affected by climate change.

Currently, Madagascar is ranked as the 5th most exposed country in the world and the most exposed in Africa to climate change impacts such as droughts, earthquakes, epidemics, floods, cyclones and extreme temperatures. According to the Global Climate Risk Index 2020, it is among the ten countries most vulnerable to climate risks. Since 1980, climate-related disasters have caused over \$1 billion in economic damage, with the agricultural sector, the backbone of Madagascar's economy, contributing more than one-fourth of GDP, among the hardest hit (WHO, 2016). The country faces development and environmental challenges that may be intensified by climate change.

Demographically, Madagascar's population is growing rapidly, with an estimated annual growth of 2.39% per year (CIA, 2020). The population is predominantly (61.1%) rural and the gross domestic product (GDP) per capita for 2017 was estimated at 1600\$USD (CIA, 2020; UNDP, 2015). Economically, approximately three-quarters of Madagascar's population lives below the national poverty line and faces an annual loss of 9-10% of the GDP due to environmental degradation (WHO, 2016, Rakotondravony et al. 2018). Agriculture makes up 25% of the GDP and 80% of employment (CPGU and BNCCC, 2017). Increased rainfall, floods and droughts cause food insecurity due to drought period, cause fatalities and hamper agricultural productivity.

Projected climate change trends says that these risks are expected to worsen in the future with an increase in temperature from 1.1°C to 2.6°C by 2065, and a varying precipitation patterns in different parts of the country. In addition to this, the sea level rise, 7 to 8 mm per year, leading to coastal erosion and the progression of receding. Climate models predict an increase in the exposure of cropland to drought and as a result Cassava and maize yields, two main food crops in Madagascar, are expected to decline (FAO, 2016, 12]. This low agricultural productivity and incomes lead to high food insecurity, recurring climate shocks, political instability, and household poverty (Rakotondravony et al. 2018, Harvey et al. 2014).

In addition, climate change causes serious damage to the infrastructure sector in Madagascar, especially roads and bridges and threatens the health and sanitation sector. Irregular rainfall patterns, regional drought and deficit has an impact on water supply, causing water stress and increasing the risk of malnutrition, diseases, hunger, and death from famine. According to the World Health Organization, Madagascar recorded around 2.2 million cases of malaria, including 5,350 deaths in 2018 (BMZ, 2020; J]. Many of the public health challenges in Madagascar are expected to worsen with climate change. However, it was found that Madagascar has moderate to low governance capacity to address climate-related vulnerabilities and security risk (Moran and Chesney, 2016).

Climate change will increasingly affect important sectors in Madagascar, including water resources, agriculture, coastal and terrestrial ecosystems, fisheries, and human health (Miklyaev and Olubamiro, 2025). It is a grave injustice that the impacts of climate change are felt by the Malagasy people considering that they contribute the least to the climate crisis. Figure 1 shows projected annual changes in average near-surface air temperature over Madagascar from 1960 to 2100, relative to the 1995–2014 baseline. The projections are based on a multi-model ensemble under different SSP scenarios. The shaded areas (p10–p90) represent the 10th–90th percentile range across models, indicating the spread or uncertainty in the projections. The time series highlights both the long-term warming trend and year-to-year variability in Madagascar’s temperature. While all scenarios show clear warming, the magnitude and rate of increase differ across SSPs. A narrower p10–p90 range indicates stronger model agreement, whereas the widening spread toward the end of the century reflects growing uncertainty. The diverging SSP trajectories illustrate potential avoided warming, showing how different emission pathways shape future climate conditions in the region.

As global temperatures increase, sea levels along Madagascar’s coast are projected to continue rising. Under RCP6.0, sea level is projected to rise by about 11 cm by 2030, 22 cm by 2050, and 43 cm by 2080 relative to the year 2000. These changes pose serious risks for coastal communities, including saline intrusion into waterways and groundwater systems. Future rainfall changes are more uncertain than temperature changes, due to high natural variability. Among the four climate models assessed, two project reduced mean annual precipitation over Madagascar, while two show little change. The median model indicates a decrease of about 114 mm per year by 2080 under RCP6.0, and a smaller decrease of 47 mm under RCP2.6. Overall, higher emissions suggest a drier future for Madagascar. A warmer atmosphere can hold more moisture, leading to more intense rainfall events globally. For Madagascar, models project a modest rise in the number of heavy rainfall days, from about 7.0 days per year in 2000 to 7.5 days under RCP2.6 and 7.2 days under RCP6.0 by 2080.

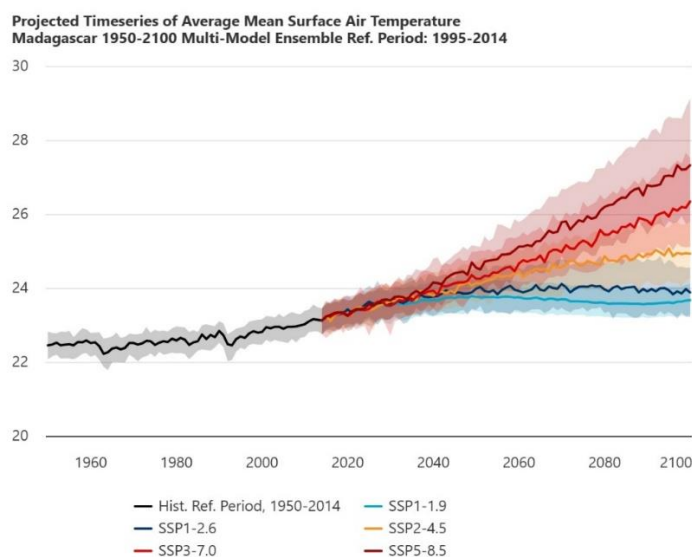


Figure 84 Projected annual mean near-surface air temperature over Madagascar (1960–2100) from CMIP6 multi-model ensembles, shown relative to each model's own 1995–2014 baseline. Shaded areas (p10–p90) indicate inter-model spread, with divergence among SSPs illustrating the range of possible warming pathways. Source: Madagascar - Mean Projections (CMIP6) | Climate Change Knowledge Portal

## 5.2 Background on Carbon Dioxide Removal (CDR)

Global climate policy under the UNFCCC and the Paris Agreement aims to limit warming to 1.5–2 °C. Integrated Assessment Models indicate that large-scale **Carbon Dioxide Removal (CDR)** will be essential to achieve net-zero CO<sub>2</sub> emissions and offset hard-to-abate sectors. CDR strategies reduce atmospheric CO<sub>2</sub> and are key in most IPCC scenarios to limit warming, helping enhance climate resilience in vulnerable regions such as tropical islands.

**Bioenergy with Carbon Capture and Storage (BECCS)** is a land-based CDR method that combines biomass energy production with CO<sub>2</sub> capture and storage in geological reservoirs, achieving net-negative emissions. BECCS uses fast-growing trees, herbaceous crops, or genetically modified sugarcane, and can support electricity, hydrogen, or biofuel production. While BECCS is considered a cost-effective option for long-term mitigation, scaling it up faces challenges including land-use change emissions, water stress, additional GHG emissions from irrigation and fertilization, socio-economic concerns, and limited CCS capacity.

**Ocean Alkalinity Enhancement (OAE)** is a marine-based CDR approach that adds alkaline materials to the ocean surface to increase total alkalinity, enhancing CO<sub>2</sub> uptake. OAE has a large theoretical CDR potential and offers durable carbon storage. ESM studies suggest it could mitigate climate change while supporting Sustainable Development Goals, including reducing ocean acidification. However, the ecological impacts of OAE and its broader Earth system consequences remain uncertain, and governance, monitoring, reporting, and verification frameworks are still under development.

Together, BECCS and OAE represent novel CDR strategies with high potential for negative emissions, linking energy-based interventions to climate mitigation efforts. This study therefore investigates the following question:

### 5.3 Research Question and Objectives

How do different carbon dioxide removal (CDR) strategies differentially impact regional temperature atmospheric CO<sub>2</sub> mixing ratio patterns over Madagascar, and what do these changes imply for climate resilience in tropical island ecosystems?

Our main objectives are to:

1. To trace how global choices about carbon removal ripple into the intimate atmospheric patterns that hold Madagascar.
2. To understand how the island's heat, winds, and seasonal flows shift in response to these interventions.

### 5.4. Methodology

To evaluate how different Carbon Dioxide Removal (CDR) strategies influence regional atmospheric CO<sub>2</sub> and temperature patterns over Madagascar, this study uses a set of controlled Earth system model experiments. Because CDR affects the carbon cycle, land surface processes, ocean chemistry, and climate feedbacks, a fully coupled Earth system model is required to capture the integrated physical and biogeochemical responses.

We therefore employ the **Norwegian Earth System Model version 2, low-resolution configuration (NorESM2-LM)**, which includes interactive atmosphere, ocean, sea-ice, and land components as well as comprehensive carbon-nitrogen and ocean biogeochemistry. The NorESM2 model framework has been shown to reduce known biases in tropical and sub-tropical tropospheric temperature and improve representation of upper-ocean biogeochemical and air-sea flux processes relative to its predecessor, suggesting relatively strong performance in tropical ocean regions (e.g., Seland et al., 2020). While explicit evaluation for the Indian Ocean domain remains limited, these improvements provide confidence for applications such as the present regional study over Madagascar.

#### 5.4.1. The Norwegian Earth System Model

This study uses five idealized simulations performed with the Norwegian Earth System Model (NorESM2-LM; Seland et al., 2020; Tjiputra et al., 2020). NorESM2 is based on CESM2.1 (Danabasoglu et al., 2020) but features its own ocean model and a modified atmospheric component (CAM6-Nor) with an updated aerosol module, improved energy and momentum conservation, and revised air-sea flux and deep convection schemes. The land (CLM5; Lawrence et al., 2019a) and sea-ice (CICE5; Hunke et al., 2015) components are adopted from CESM2.1.

CLM5 simulates coupled carbon-nitrogen dynamics across vegetation, litter, and soil pools, including natural vegetation, crops, and soil biogeochemistry (Lawrence et al., 2019a). The ocean component combines the isopycnic Bergen Layered Ocean Model (BLOM) with the iHAMOCC biogeochemistry module (Tjiputra et al., 2020; Schwinger et al., 2016), which includes a Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) ecosystem and seawater carbonate chemistry following Dickson (2007).

An updated version of BLOM-iHAMOCC with the capability to simulate Ocean Alkalinity Enhancement (OAE) was used. Total alkalinity includes contributions from boric, phosphoric, and silicic acids, among others. NorESM2-LM was run at  $\sim 1^\circ$  ocean and  $\sim 2^\circ$  atmosphere-land horizontal resolution.

#### 5.4.2. Simulation Design

We conducted five idealized, emission-driven simulations using NorESM2-LM: (1) the reference SSP5-3.4 scenario from ScenarioMIP (O'Neill et al., 2016), which includes strong mitigation and net-negative CO<sub>2</sub> emissions after 2070; (2) a bioenergy expansion simulation without CCS ("BE"); (3) a BECCS simulation combining bioenergy expansion with CCS ("BECCS"); (4) an Ocean Alkalinity Enhancement simulation ("OAE"); and (5) a combined BECCS and OAE simulation ("BECCS-OAE"). All modified simulations branch from SSP5-3.4 in 2030 (Table 1).

In the **BE** simulation, land-use data in CLM5 were modified to expand sugarcane area for bioenergy production while keeping food-crop areas fixed at 2015 levels. The additional 5.2 million km<sup>2</sup> of sugarcane mainly replaces fodder grass, rice, wheat, and corn in Sub-Saharan Africa, South America, and North America. Irrigation and fertilization are enabled, and no dynamic biogeography is applied.

The **BECCS** simulation uses the same land-use as BE but couples bioenergy production to carbon capture and storage (CCS) based on a 41% harvesting efficiency (Aguiar et al., 2021) and 90% CCS efficiency (Lisbona et al., 2021; Restrepo-Valencia and Walter, 2023a,b). CO<sub>2</sub> emissions from biofuel production are captured and sequestered, leading to net-negative emissions and partial substitution of fossil fuels in SSP5-3.4.

The **OAE** deployment follows Foteinis et al. (2022), applying CaO over  $\sim 11.1$  million km<sup>2</sup> of ocean surface within the EEZs of the US, Europe, and China, starting in 2030. Annual CaO deployment increases to 2.7 Gt by 2100 (total 82.3 Gt). The added alkalinity is prescribed as a surface flux ( $\text{mol m}^{-2} \text{s}^{-1}$ ) in NorESM2-LM.

Table 7 Description of the emission-driven NorESM2-LM simulations conducted in this study. The simulations were branched off from the standard CMIP6 SSP5-3.4 simulation in 2030.

| Simulation Name  | Description                                                                  | Simulation period |
|------------------|------------------------------------------------------------------------------|-------------------|
| <i>SSP5-3.4</i>  | Standard SSP5-3.4-OS scenario                                                | 2015-2100         |
| <i>BE</i>        | Bioenergy expansion scenario (no CCS for the additional bioenergy expansion) | 2030-2100         |
| <i>BECCS</i>     | BE with CCS scenario                                                         | 2030-2100         |
| <i>OAE</i>       | OAE scenario                                                                 | 2030-2100         |
| <i>BECCS-OAE</i> | BECCS and OAE combined scenario                                              | 2030-2100         |

## 5.5. Results and Discussion

### 5.5.1 Regional CO<sub>2</sub> and Temperature Response over Madagascar

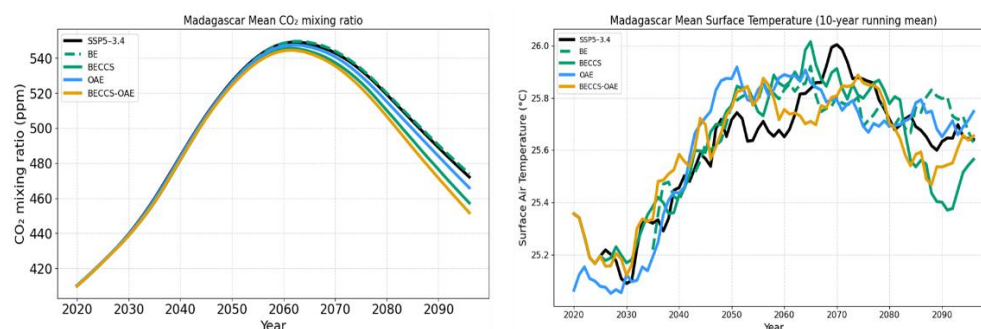


Figure 85 (Left) Annual mean CO<sub>2</sub> mixing ratio over Madagascar from 2020–2100 under SSP5-3.4, BE, BECCS, OAE, and BECCS-OAE scenarios. (Right) Corresponding mean surface air temperature (°C). Both timeseries are plotted as 10 year running mean.

Figure 85 shows that all simulations exhibit a coherent relationship between atmospheric CO<sub>2</sub> decline and regional temperature evolution over Madagascar. CO<sub>2</sub> mixing ratios rise steadily from ~415 ppm in 2020 to a peak of about 545 ppm around 2060, consistent across all scenarios. The subsequent decline in the second half of the century is most pronounced in the BECCS-OAE case, followed by BECCS and OAE, reflecting the cumulative carbon removal potential of these CDR scenarios. The BE case, lacking active CO<sub>2</sub> capture, closely follows the SSP5-3.4 trajectory throughout the century which indicates the necessity of CDR in future climate mitigation plans for Madagascar.

While CO<sub>2</sub> concentrations peak around 2060 and decline thereafter in all CDR simulations, surface air temperature shows a delayed but consistent response, stabilizing and slightly cooling toward the end of the century. Surface temperature exhibits a corresponding warming until mid-century, reaching around 0.6–0.8 °C above the baseline SSP5-3.4 by 2050–2060. This early warming phase mirrors the global and regional trends projected in CMIP6 (Lee et al., 2021) and consistent with regional assessments in IPCC AR6 Chapter 12 (Ranasinghe et al., 2021), where southern Africa, including Madagascar, is expected to experience progressive warming of 0.5–1 °C by mid-century under similar forcing levels. After mid-century, all CDR scenarios show temperature stabilization and weak cooling relative to SSP5-3.4. The BECCS simulation shows the strongest late-century cooling ( $\approx 0.1$ – $0.2$  °C lower than SSP5-3.4 by 2090), followed by BECCS-OAE, indicating an effective temperature response to declining atmospheric CO<sub>2</sub>. In contrast, OAE exhibits a delayed adjustment consistent with the slower equilibration of oceanic carbon dynamics, while BE remains close to SSP5-3.4, underscoring the limited effect of bioenergy cultivation without CCS. By 2100, all CDR simulations yield slightly lower mean surface temperatures ( $\approx 0.1$ – $0.2$  °C cooler) compared to SSP5-3.4. The observed CO<sub>2</sub> decline and temperature response pattern aligns with IPCC AR6 and World Bank Climate Portal regional projections, which suggest moderate but sustained warming under high-forcing scenarios, with potential stabilization under global-scale mitigation and CO<sub>2</sub> removal. This consistency reinforces the model’s credibility in capturing both global and regional-scale climate feedbacks over Madagascar.

### 5.5.2 Spatial patterns

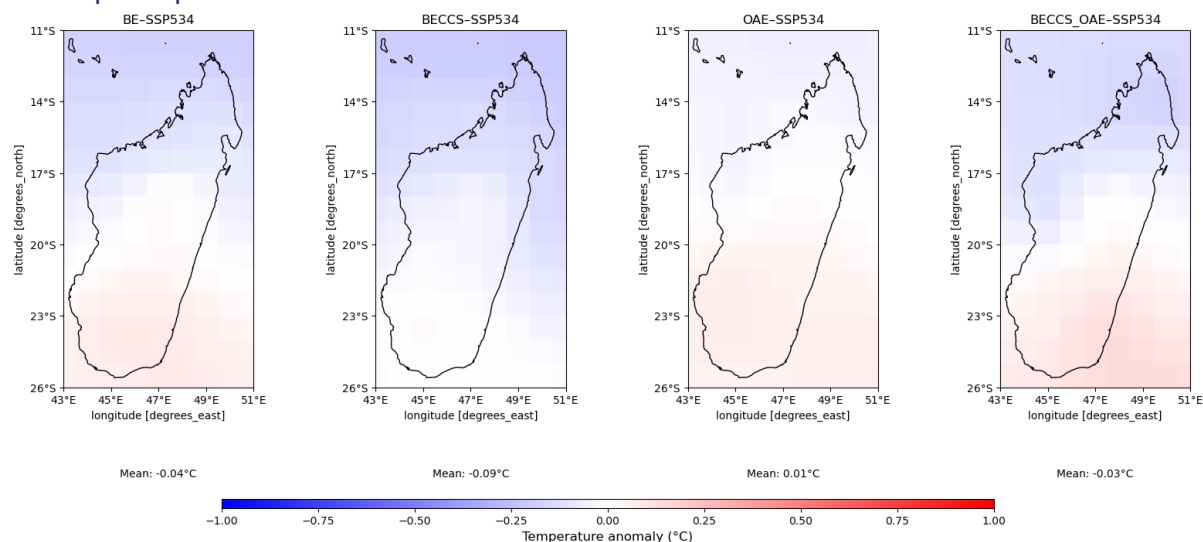


Figure 86 Temperature anomalies (2070–2100 mean) over Madagascar relative to the SSP5-3.4 baseline under different CDR scenarios: (a) BE, (b) BECCS, (c) OAE, and (d) BECCS-OAE. Positive (red) and negative (blue) values represent local warming and cooling, respectively. Mean anomalies for each panel are indicated below the maps.

All scenarios show a north-south temperature gradient, with slight cooling (blue) in the northern highlands and coastal regions, and slight warming (red) toward the southern and southwestern parts. This likely reflects regional circulation and oceanic influences, as southern Madagascar borders the warmer subtropical Indian Ocean. BE and BECCS both show weak cooling overall (mean  $-0.04^{\circ}\text{C}$  and  $-0.09^{\circ}\text{C}$ ). This is consistent with reduced atmospheric  $\text{CO}_2$  and enhanced land carbon uptake, leading to small radiative cooling effects. The stronger cooling in BECCS (compared to BE) is expected since BECCS actively removes  $\text{CO}_2$  via capture and storage. OAE shows a nearly neutral to slightly positive anomaly (mean  $\approx +0.01^{\circ}\text{C}$ ). OAE acts mainly via oceanic  $\text{CO}_2$  drawdown, with minimal local surface forcing over land. The mild warming could be related to regional circulation changes or reduced latent heat fluxes associated with ocean alkalinity perturbations. Combined BECCS-OAE results in a net weak cooling (mean  $\approx -0.03^{\circ}\text{C}$ ), suggesting additive but modest cooling effects when both methods are applied globally. The pattern resembles BECCS, indicating land-driven processes dominate the temperature response over Madagascar.

### 5.5.3 Implications for Climate Resilience

The modest but consistent cooling under BE and BECCS, and the enhanced  $\text{CO}_2$  drawdown in BECCS-OAE, suggest that large-scale CDR deployment could help moderate local warming over Madagascar by the late 21st century. Although the magnitude of regional temperature reduction is small ( $\leq 0.2^{\circ}\text{C}$ ), even limited stabilization could mitigate heat-related stress on agriculture and ecosystems in a warming-prone tropical island setting. The weak or delayed response in OAE highlights the importance of combining land- and ocean-based CDR for near-term climate benefits. These results underscore that, for regions like Madagascar, highly sensitive to temperature and precipitation variability, CDR can complement, but not replace, emission reductions in building long-term climate resilience.

## 5.6 Conclusion

Carbon Dioxide Removal (CDR) is an essential component of all SSP scenarios for climate mitigation, with novel CDRs such as BECCS and OAE offering high carbon removal potential. However, their large-scale deployment remains limited due to low level of readiness and currently deployed at smaller scales. Renewable energy and efficiency remain the most mature, scalable, and cost-effective mitigation options to cut emissions rapidly. CDR approaches such as BECCS and OAE can complement these by enabling net-negative outcomes. Our results show how such CDR pathways could modestly moderate late-century warming over Madagascar.

This study links climate and energy by examining how such CDR strategies influence regional CO<sub>2</sub> and temperature patterns over Madagascar. The findings reveal that even modest reductions in atmospheric CO<sub>2</sub>, achieved through BECCS and BECCS-OAE can lead to measurable, albeit small, cooling effects ( $\leq 0.2$  °C) by the late 21st century. This is particularly significant for Madagascar, a tropical island highly sensitive to climate change.

The projected climate warming trends, combined with changing precipitation patterns and more frequent extreme weather events, place immense stress on Madagascar's agriculture, ecosystems, and human health. The modest but consistent cooling under CDR scenarios could help mitigate some of these impacts, particularly heat-related stress on vulnerable sectors. By connecting energy-based mitigation approaches to local climate responses, the analysis provides insights into how different CDR methods can enhance climate resilience in tropical island ecosystems and inform sustainable energy–climate strategies. The study underscores the importance of integrating CDR with aggressive emission reductions and sustainable land management to build long-term resilience in Madagascar and similar regions.

## VI. REFERENCES

- Abnett, K. (2024). Global CO<sub>2</sub> emissions to hit record high in 2024, report says. Reuters. <https://www.reuters.com/business/environment/global-co2-emissions-hit-record-high-2024-report-says-2024-11-13/#:~:text=The%20Global%20Carbon%20Budget%20report,40.6%20billion%20tons%20last%20year>
- African Union. (2023, September 7). *An overview of agreed commitments and announcements from the Africa Climate Summit, Nairobi, September 4-6, 2023*. African Development Bank. [https://www.afdb.org/sites/default/files/documents/africa\\_climate\\_summit\\_commitments\\_and\\_announcement\\_compilation\\_final\\_sept\\_7\\_2023.docx.pdf](https://www.afdb.org/sites/default/files/documents/africa_climate_summit_commitments_and_announcement_compilation_final_sept_7_2023.docx.pdf)
- Agence Française de Développement. (2023). Coping with climate change in Africa [Infographic]. La Découverte. Retrieved from <https://www.afd.fr/en/ressources/coping-climate-change-africa-numbers>
- Akiwumi, F. A., & Butler, D. R. (2008). Mining and environmental change in Sierra Leone, West Africa: A remote sensing and hydrogeomorphological study. *Environmental Monitoring and Assessment*, 142(1–3), 309–318. <https://doi.org/10.1007/s10661-007-9930-9>
- Aguiar, A., Milessi, T. S., Mulinari, D. R., Lopes, M. S., da Costa, S. M., & Candido, R. G. (2021). Sugarcane straw as a potential second generation feedstock for biorefinery and white biotechnology applications. *Biomass and Bioenergy*, 144(November 2020). <https://doi.org/10.1016/j.biombioe.2020.105896>
- Akinsanola, A. A., Ogunjobi, K. O., Abolude, A. T., & Salack, S. (2021). Projected changes in wind speed and wind energy potential over West Africa in CMIP6 models. *Environmental Research Letters*, 16(4), 044033. <https://doi.org/10.1088/1748-9326/abed7a>
- Al-Breiki, M., & Bicer, Y. (2021). Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization. *Journal of Cleaner Production*, 279, 123481. <https://doi.org/10.1016/j.jclepro.2020.123481>
- Almazroui, M., Saeed, F., Saeed, S., Islam, M. N., Ismail, M., Klutse, N. A. B., & Siddiqui, M. H. (2020). Projected change in temperature and precipitation over Africa from CMIP6. *Earth Systems and Environment*, 4(4), 455–475. <https://doi.org/10.1007/s41748-020-00161-x>
- Andriamifidisoa, M. V., & Andrianaivo, L. (2024). Geothermal status and its potential in Madagascar. *International Journal of Advance Research and Innovative Ideas in Education*, 10(1), 259–266. [https://ijariie.com/AdminUploadPdf/Geothermal Status and its Potential in Madagascar\\_ijariie22378.pdf](https://ijariie.com/AdminUploadPdf/Geothermal Status and its Potential in Madagascar_ijariie22378.pdf)
- Anicaelle, V. M., Wang, T., & Wang, F. (2024). Exploring the capacity of agricultural residue as a sustainable energy resource to enhance Madagascar's energy security. *Indian Journal of Environment Engineering (IJEE)*, 4(1), 8–15. <https://doi.org/10.54105/ijee.A1851.04010524>
- Arivelo, T. A., & Lin, Y.-L. (2016). Climatology of heavy orographic rainfall induced by tropical cyclones over Madagascar: From synoptic to mesoscale perspectives. *Earth Science Research*, 5(2), 132–147. <https://doi.org/10.5539/esr.v5n2p132>
- Attard, M.-C., Reynolds, C., Coetzee, K., Hörsch, J., Welder, L., Tovivo, K., Ramalope, D., Fyson, C., & Hare, B. (2022, February 16). National 1.5 °C compatible emissions pathways and consistent power sector benchmarks in Africa. *Climate Analytics*. <https://climateanalytics.org/publications/national-15c-compatible-emissions-pathways-and-consistent-power-sector-benchmarks-in-africa>

Ayugi, B., Jiang, Z., Iyakaremye, V., Ngoma, H., Babaoousmail, H., Onyutha, C., Dike, V. N., Mumo, R., & Ongoma, V. (2022). East African population exposure to precipitation extremes under 1.5 °C and 2.0 °C warming levels based on CMIP6 models. *Environmental Research Letters*, 17(044051). <https://doi.org/10.1088/1748-9326/ac5d9d>

Barimalala, R., Desbiolles, F., Blamey, R. C., & Reason, C. (2018). Madagascar influence on the South Indian Ocean Convergence Zone, the Mozambique Channel Trough and southern African rainfall. *Geophysical Research Letters*, 45(20), 11,380–11,389. <https://doi.org/10.1029/2018GL079964>

Banze, F., Guo, J., & Shi, X. (2018). Impact of Climate Change on Precipitation in Zambeze River Basin in Southern Africa.

Bazyomo, S. D. Y. B., Lawin, E. A., Coulibaly, O., & Ouedraogo, A. (2016). Forecasted changes in West Africa photovoltaic energy output by 2045. *Climate*, 4(53). <https://doi.org/10.3390/cli4040053>

Bichet, A., Hingray, B., Evin, G., Diedhiou, A., Kebe, C. M. F., & Anquetin, S. (2019). Potential impact of climate change on solar resource in Africa for photovoltaic energy: Analyses from CORDEX-AFRICA climate experiments. *Environmental Research Letters*, 14(12), 124039. <https://doi.org/10.1088/1748-9326/ab500a>

BloombergNEF. (2022). *Sierra Leone. Climatescope 2022*. <https://2022.global-climatescope.org/markets/sl/>

BloombergNEF. (2024). *Africa power transition factbook 2024*. Bloomberg Philanthropies. <https://www.bnef.com/flagships/new-energy-outlook>

BloombergNEF. (2024). *Sierra Leone. Climatescope*. Retrieved March 11, 2025, from <https://global-climatescope.org/markets/sierra-leone>

Bloomfield, H. C., Brayshaw, D. J., Troccoli, A., Goodess, C. M., De Felice, M., Dubus, L., Bett, P. E., & Saint-Drenan, Y.-M. (2021). Quantifying the sensitivity of European power systems to energy scenarios and climate change projections. *Renewable Energy*, 164, 1062–1075. <https://doi.org/10.1016/j.renene.2020.09.065>

Bloomfield, H. C., Wainwright, C. M., & Mitchell, N. (2022). Characterizing the variability and meteorological drivers of wind power and solar power generation over Africa. *Meteorological Applications*, 29(5), e2093. <https://doi.org/10.1002/met.2093>

Bobde, V., Akinsanola, A. A., Folorunsho, A. H., Adebisi, A. A., & Adeyeri, O. E. (2024). Projected regional changes in mean and extreme precipitation over Africa in CMIP6 models. *Environmental Research Letters*, 19(074009). <https://doi.org/10.1088/1748-9326/ad545c>

Boyle, R. (2024, July 16). Greenhouse gas emissions in Madagascar. *Emission Index*. <https://www.emission-index.com/countries/madagascar>

Boyle, R. (2024, July 16). Greenhouse gas emissions in Sierra Leone. *Emission Index*. <https://www.emission-index.com/countries/sierra-leone>

Bullock, E. L., Healey, S. P., Yang, Z., Oduor, P., Gorelick, N., Omondi, S., Ouko, E., & Cohen, W. B. (2021). Three decades of land cover change in East Africa. *Land*, 10(2), 150. <https://doi.org/10.3390/land10020150>

Carlino, A., Wildemeersch, M., Chawanda, C. J., Giuliani, M., Sterl, S., Thiery, W., van Griensven, A., Madani, K., & Castelletti, A. (2023). Doubling down on African hydropower might lock investments in inefficient and risky infrastructure. *United Nations University Institute for Water, Environment and Health (UNU-INWEH)*. <https://doi.org/10.53328/INP23AAC01>

Carvalho, J. -P., Shaw, B. J., Avila, N. I., & Kammen, D. M. (2017). Sustainable low-carbon expansion for the power sector of an emerging economy: The case of Kenya.

*Environmental Science & Technology*, 51(17), 10232–10242.  
<https://doi.org/10.1021/acs.est.7b00711>

Central Intelligence Agency. 2020. The world factbook - Africa: Madagascar. CIA, Washington, D.C., USA. [online] URL: <https://www.cia.gov/the-world-factbook/countries/madagascar/>

Cellule de Prévention et Gestion des Urgences (CPGU), and Bureau National de Coordination des Changements Climatiques (BNCCC). 2017. Strategic program for climate resilience: Madagascar pilot program for climate resilience. Government of Madagascar, Antananarivo, Madagascar. [online] URL: [https://www.primature.gov.mg/cpgu/wp-content/uploads/2017/11/SPCR\\_Madagascar\\_FINAL-10-11-17-1.pdf](https://www.primature.gov.mg/cpgu/wp-content/uploads/2017/11/SPCR_Madagascar_FINAL-10-11-17-1.pdf)

Chen, W., Wang, H., Huang, W., Li, N., & Shi, J. (2017). Shared social-economic pathways (SSPs) modeling: Application of global multi-region energy system model. *Energy Procedia*, 142, 2467–2472. <https://doi.org/10.1016/j.egypro.2017.12.184>

Chukwuemeka, N. S., Ugonna, A. P., Ugochukwu, O. B., Immaculata, E. N., Chiziterem, E. K., & Chukwubikem, O. P. (2023). The challenges and opportunities of energy transition across Africa. *International Journal of Environment and Climate Change*, 13(10), 4312–4339. <https://doi.org/10.9734/IJECC/2023/v13i103109>

Climate Action Tracker. (2024). Kenya's Climate Policies and CO<sub>2</sub> Emissions Scenarios. *Climate Action Tracker*. Retrieved March 16, 2025, from <https://climateactiontracker.org/countries/kenya/policies-action/>

Climate Investment Funds. (2024). Annual report 2023. *The World Bank Group*. Retrieved from <https://www.cif.org>

Conteh, F., Furukakoi, M., Rangarajan, S., Collins, E. R., Conteh, M., Rashwan, A., & Senjyu, T. (2023). Long-term forecast of Sierra Leone's energy supply and demand (2019–2040): A LEAP model application for a sustainable power generation system. *Sustainability*. <https://doi.org/10.3390/su151511838>

countryeconomy.com. (2024). *Madagascar - Electricity generation*. Retrieved February 28, 2025, from <https://countryeconomy.com/energy-and-environment/electricity-generation/madagascar>

Crespo Del Granado, P., Wallace, S. W., & Pang, Z. (2016). The impact of wind uncertainty on the strategic valuation of distributed electricity storage. *Computational Management Science*, 13(1), 5–27. <https://doi.org/10.1007/s10287-015-0231-4>

Ddamulira, R. (2016). Climate change and energy in East Africa. *Development*, 59(3-4), 257–262. <https://doi.org/10.1057/s41301-017-0101-d>

Danabasoglu, G., Lamarque, J. F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., ... Strand, W. G. (2020). The Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, 12(2), 1–35. <https://doi.org/10.1029/2019MS001916>

Dickson, A. G. (2007). Guide to best practices for ocean CO<sub>2</sub> measurements. *PICES Special Publication*, 191.

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., ... Zhang, Q. (2022). The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project

6. *Geoscientific Model Development*, 15(8), 2973–3020. <https://doi.org/10.5194/gmd-15-2973-2022>

Earth System Grid Federation. (2024). *Coupled Model Intercomparison Project Phase 6*. Retrieved May 5, 2024, from <https://esgf-metagrid.cloud.dkrz.de/search/cmip6-dkrz/>

Elsner, P. (2019). Continental-scale assessment of the African offshore wind energy potential: Spatial analysis of an under-appreciated renewable energy resource. *Renewable and Sustainable Energy Reviews*, 104, 394–407. <https://doi.org/10.1016/j.rser.2019.01.034>

Ember. (2024, October 9). Africa. Electricity access remains an urgent problem across the continent. Retrieved February 27, 2025, from <https://ember-energy.org/countries-and-regions/africa/>

Energy and Petroleum Regulatory Authority. (2024). *Energy & petroleum statistics report for the financial year ended 30th June 2024*. <https://doi.org/10.53328/INP23AAC01>

FAO (2016). *Climate-smart agriculture in Madagascar*. <https://www.fao.org/family-farming/detail/en/c/380445/>

Federal Ministry for Economic Cooperation and Development (BMZ) (2020). *Climate Risk Profile: Madagascar*, [https://agricade/wp-content/uploads/2021/01/GIZ\\_Climate-Risk-Profile-Madagascar\\_EN\\_final.pdf](https://agricade/wp-content/uploads/2021/01/GIZ_Climate-Risk-Profile-Madagascar_EN_final.pdf)

Fields, N., Brown, E., & Howells, M. (2025). *Energy modelling research landscape in Kenya: A systematic review*. Cambridge Open Engage. <https://client.prod.orp.cambridge.org/engage/coe/article-details/68403f671a8f9bdab5a4a4a9>

Fields, N., Collier, W., Kiley, F., Caulker, D., Blyth, W., Howells, M., & Brown, E. (2024). Long-term forecasting: A MAED application for Sierra Leone's electricity demand (2023–2050). *Energies*, 17(12), Article 2878. <https://doi.org/10.3390/en17122878>

Formayer, H., Nadeem, I., Leidinger, D., Maier, P., Schöninger, F., Suna, D., Resch, G., Totschnig, G., & Lehner, F. (2023). SECURES-Met: A European meteorological data set suitable for electricity modelling applications. *Scientific Data*, 10(1), Article 590. <https://doi.org/10.1038/s41597-023-02498-8>

Foteinis, S., Andresen, J., Campo, F., Caserini, S., & Renforth, P. (2022). Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. *Journal of Cleaner Production*, 370(July), 133309. <https://doi.org/10.1016/j.jclepro.2022.133309>

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M., Pachauri, S., ... Riahi, K. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, 42, 251–267. <https://doi.org/10.1016/j.gloenvcha.2016.06.004>

Future Climate for Africa. (2020). Improved climate modelling could enhance Kenyan wind energy generation and drought information. *Future Climate for Africa*. Retrieved February 7, 2025, from <https://futureclimateafrica.org/news/improved-climate-modelling-could-enhance-kenyan-wind-energy-generation-and-drought-information/>

Gachanja, J., Muriithi, B., Mwabonje, O., Mugwe, A., Olukuru, J., Da Silva, I. P., Mwangi, F., Strapasson, A., & Sukpanit, P. (2023). Kenya's low carbon futures: An assessment using the KCERT model. *Energies*, 16(21), Article 7459. <https://doi.org/10.3390/en16217459>

Gasser, T. (2024, August 28). *ESM2025 - Earth system models for the future (ESM2025)*. International Institute for Applied Systems Analysis. <https://iiasa.ac.at/projects/esm2025>

Gbanie, S. P., Thornton, A., & Griffin, A. L. (2015). 'The diamond of Western Area is land': Narratives of land use and land cover change in post-conflict Sierra Leone. *The Australasian Review of African Studies*, 36(2), 51–73.

Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2018). Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. *International Journal of Climatology*, 39(2), 955–977. <https://doi.org/10.1002/joc.5777>

Gerasu, T. S., Feyissa, T. A., Gudeta, B. G., Demissie, K., & Tesfahun, M. (2024). An evaluation of the Africa-CORDEX regional climate model's performance in simulating air temperatures and precipitation in the Melka-Wakena catchment, southeast Ethiopia. *Heliyon*, 10(24), e40720. <https://doi.org/10.1016/j.heliyon.2024.e40720>

Giordano, M., & Bassini, E. (2019). Climate change and Africa's future. *Hoover Institution*. Retrieved June 5, 2024, from <https://www.hoover.org/research/climate-change-and-africas-future>

Greiner, C., Vehrs, H.P., & Bollig, M. (2021). Landuse and landcover changes in pastoral drylands: Longterm dynamics, economic change, and shifting socioecological frontiers in Baringo, Kenya. *Human Ecology*, 49(4), 565–577. <https://doi.org/10.1007/s10745021002638>

Haidi, T., & Cheddadi, B. (2022). Wind energy integration in Africa: Development, impacts and barriers. *International Journal of Electrical and Computer Engineering*, 12(5), 4614–4622. <https://doi.org/10.11591/ijece.v12i5.pp4614-4622>

Haile, G. G., Tang, Q., Hosseini-Moghari, S.-M., Liu, X., Gebremicael, T. G., Leng, G., Kebede, A., Xu, X., & Yun, X. (2020). Projected impacts of climate change on drought patterns over East Africa. *Earth's Future*, 8(6), e2020EF001502. <https://doi.org/10.1029/2020EF001502>

Hannah, L., Dave, R., Lowry, P. P., Andelman, S., Andrianarisata, M., Andriamaro, L., ... & Wilmé, L. (2008). Climate change adaptation for conservation in Madagascar. *Biology letters*, 4(5), 590-594.

Haller, T., Adams, T., Gmür, D. R., Käser, F. D., Lanz, K. V., Marfurt, F., Ryser, S., Schubiger, E., von Sury, A. A., & Gerber, J.D. (2019). Largescale land acquisition as commons grabbing: A comparative study on cases from Africa. In L. R. Lozny & T. H. McGovern (Eds.), *Global perspectives on long term community resource management* (Vol. 11, pp. 125–164). Springer International Publishing. [https://doi.org/10.1007/9783030158002\\_6](https://doi.org/10.1007/9783030158002_6)

Harvey, C. A., Z. L. Rakotobe, N. S. Rao, R. Dave, H. Razafimahatratra, R. H. Rabarijohn, H. Rajaofara, and J. L. MacKinnon. 2014. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical Transactions of the Royal Society B: Biological Sciences* 369(1639). <https://doi.org/10.1098/rstb.2013.0089>

Humanitarian Data Exchange. (2023). *COD-EMSle* [Dataset]. <https://data.humdata.org/dataset/cod-em-sle>

Humphries, M., Green, A., Higgs, C., Strachan, K., Hahn, A., Pillay, L., & Zabel, M. (2020). High-resolution geochemical records of extreme drought in southeastern Africa during the past 7000 years. *Quaternary Science Reviews*, 236, 106294. <https://doi.org/10.1016/j.quascirev.2020.106294>

Hunke, E. C., Lipscomb, W. H., Turner, A. K., Jeffery, N., & Elliott, S. (2015). CICE: The Los Alamos Sea ice model documentation and software user's manual version 5.1 LA-CC-06-012. *T-3 Fluid Dynamics Group, Los Alamos National Laboratory*, 675, 15.

Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013: The physical science basis. Summary for policymakers, technical summary and frequently asked questions*. Working Group I Contribution to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge University Press.

<https://www.ipcc.ch/report/ar5/wg1/>

(IPCC), I. P. on C. C. (2014). *Climate Change 2014 – Impacts, Adaptation and Vulnerability: Part B: Regional Aspects: Working Group II Contribution to the IPCC Fifth Assessment Report: Volume 2: Regional Aspects* (Vol. 2). Cambridge University Press.  
<https://doi.org/DOI: 10.1017/CBO9781107415386>

Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2023: Synthesis report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee, & J. Romero (Eds.)]. IPCC. <https://doi.org/10.59327/IPCC/AR6-9789291691647>

International Energy Agency (IEA). (2019). Climate impacts on African hydropower. Retrieved February 27, 2025, from <https://www.iea.org/reports/climate-impacts-on-african-hydropower/climate-impacts-on-african-hydropower>

International Energy Agency (IEA). (2022). Africa energy outlook 2022: World energy outlook special report. <https://www.iea.org/reports/africa-energy-outlook-2022>

International Energy Agency (IEA). (2023). Africa: Energy mix. Retrieved February 27, 2025, from <https://www.iea.org/regions/africa/energy-mix>

International Energy Agency (IEA). (2023). Kenya. IEA. Retrieved February 27, 2025, from <https://www.iea.org/countries/kenya>

International Energy Agency (IEA). (2023). Kenya: Emissions. IEA. <https://www.iea.org/countries/kenya/emissions>

International Energy Agency (IEA). (2023). Keeping cool in a hotter world is using more energy, making efficiency more important than ever. IEA. Retrieved February 27, 2025, from <https://www.iea.org/commentaries/keeping-cool-in-a-hotter-world-is-using-more-energy-making-efficiency-more-important-than-ever>

International Energy Agency (IEA). (2023). Madagascar. IEA. <https://www.iea.org/countries/madagascar>

International Energy Agency (IEA). (2024). CO<sub>2</sub> emissions in 2023: A new record high, but is there light at the end of the tunnel? *International Energy Agency*. Retrieved from <https://www.iea.org/reports/co2-emissions-in-2023>

International Energy Agency (IEA). (2025). Kenya Electricity Generating Company. Geothermal. Retrieved February 27, 2025, from <https://www.kengen.co.ke/index.php/business/power-generation/geothermal.html>

International Hydropower Association. (2022). Africa. Retrieved February 27, 2025, from <https://www.hydropower.org/region-profiles/africa>

International Institute for Applied Systems Analysis (IIASA). (2024). *SSP database*. Retrieved March 5, 2024, from <https://tntcat.iiasa.ac.at/SspDb/>

International Renewable Energy Agency (IRENA). (2021). The renewable energy transition in Africa: Powering access, resilience and prosperity. *IRENA*. Retrieved from [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/March/Renewable\\_Energy\\_Transition\\_Africa\\_2021.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/March/Renewable_Energy_Transition_Africa_2021.pdf)

International Renewable Energy Agency (IRENA). (2023). Energy profile: Kenya. Retrieved from <https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/StatisticalProfiles/Africa/KenyaAfricaRESP.pdf>

- International Renewable Energy Agency (IRENA). (2024). Renewable capacity statistics 2024. IRENA. [https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA\\_RE\\_Capacity\\_Statistics\\_2024.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Mar/IRENA_RE_Capacity_Statistics_2024.pdf)
- International Renewable Energy Agency (IRENA). (2024). Sierra Leone: Africa Renewable Energy Statistics and Policies. Abu Dhabi: IRENA.
- International Renewable Energy Agency (IRENA). (2024). Sierra Leone: Africa Renewable Energy Statistics Profile. [https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical\\_Profiles/Africa/Sierra-Leone\\_Africa\\_RE\\_SP.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Sierra-Leone_Africa_RE_SP.pdf)
- International Trade Administration. (2024). *Kenya - energy-electrical power systems*. U.S. Department of Commerce. Retrieved February 27, 2025, from <https://www.trade.gov/country-commercial-guides/kenya-energy-electrical-power-systems>
- Isaac, M., & van Vuuren, D. P. (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 37(2), 507–511. <https://doi.org/10.1016/j.enpol.2008.09.051>
- James, R., Washington, R., Abiodun, B., Kay, G., Mutemi, J., Pokam, W., Hart, N., Artan, G., & Senior, C. (2018). Evaluating climate models with an African lens. *Bulletin of the American Meteorological Society*, 99(2), 313–336. <https://doi.org/10.1175/BAMS-D-16-0090.1>
- Jiang, L. (2014). Internal consistency of demographic assumptions in the shared socioeconomic pathways. *Population and Environment*, 35(3), 261–285. <https://doi.org/10.1007/s11111-014-0206-3>
- Kara, T., & Şahin, A. D. (2023). Implications of climate change on wind energy potential. *Sustainability*, 15, 14822. <https://doi.org/10.3390/su152014822>
- Kariuki, B. W., & Sato, T. (2018). Interannual and spatial variability of solar radiation energy potential in Kenya using Meteosat satellite. *Renewable Energy*, 116, 88–96. <https://doi.org/10.1016/j.renene.2017.09.069>
- Kazmierczuk, A. H. (2019). Wind energy in Kenya: A status and policy framework review. *Renewable and Sustainable Energy Reviews*, 107, 434–445. <https://doi.org/10.1016/j.rser.2018.12.061>
- Kenya News Agency. (2024, October 18). KenGen aims to add 1500 MW of green energy to national grid. Retrieved February 27, 2025, from <https://www.kenyanews.go.ke/kengen-aims-to-add-1500-mw-of-green-energy-to-national-grid/>
- Kiley, F., Caulker, D., Collier, W., Fields, N., Blyth, W., Quirós-Tortós, J., & Howells, M. (2024). A dataset for energy demand and supply modelling in Sierra Leone. *Data in Brief*, 55, 110715. <https://doi.org/10.1016/j.dib.2024.110715>
- Kolstad, E. W., Parker, D. J., MacLeod, D. A., Wainwright, C. M., & Hirons, L. C. (2024). Beyond the regional average: Drivers of geographical rainfall variability during East Africa's short rains. *Quarterly Journal of the Royal Meteorological Society*, 150(764), 4550–4566. <https://doi.org/10.1002/qj.4829>
- Langat, P. K., Kumar, L., & Koech, R. (2017). Temporal variability and trends of rainfall and streamflow in Tana River Basin, Kenya. *Sustainability*, 9(11), 1963. <https://doi.org/10.3390/su9111963>
- Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., & Ghimire, B. (2019). *The Community Land Model Version 5 : Description of New*

*Features , Benchmarking , and Impact of Forcing Uncertainty Journal of Advances in Modeling Earth Systems.* 5, 4245–4287. <https://doi.org/10.1029/2018MS001583>

Lee, J. Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., ... & Christensen, H. M. (2021). Future global climate: scenario-based projections and near-term information.

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A. C., Mutemi, J., Ndiaye, O., Panickal, S., & Zhou, T. (2021). Future global climate: Scenario-based projections and near-term information. In V. Masson-Delmotte et al. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 553–672). Cambridge University Press.

Lemba, I. T., Dias, M. F., & Robaina, M. (2019). Challenges and planning in the energy sector in Africa. *WSEAS Transactions on Environment and Development*, 15, 544–556.

Lim Kam Sian, K. T. C., Wang, J., Ayugi, B. O., Nooni, I. K., & Ongoma, V. (2021). Multi-decadal variability and future changes in precipitation over Southern Africa. *Atmosphere*, 12(6), 742. <https://doi.org/10.3390/atmos12060742>

Løken, E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews*, 11(7), 1584–1595. <https://doi.org/10.1016/j.rser.2005.11.005>

Lisbona, P., Pascual, S., & Pérez, V. (2021). Evaluation of synergies of a biomass power plant and a biogas station with a carbon capture system. *Energies*, 14(4), 1–23. <https://doi.org/10.3390/en14040908>

Marthews, T. R., Jones, R. G., Dadson, S. J., Otto, F. E. L., Mitchell, D., Guillod, B. P., & Allen, M. R. (2019). The impact of human-induced climate change on regional drought in the Horn of Africa. *Journal of Geophysical Research: Atmospheres*, 124(8), 4549–4566. <https://doi.org/10.1029/2018JD030085>

Massetti, E., Ricci, E. C., & Valente, D. (2019). The impact of climate change on photovoltaic power potential in Europe. *Climatic Change*, 162(4), 2431–2447. <https://doi.org/10.1007/s10584-019-02405-w>

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Peán, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (Eds.). (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>

Martinez, A., & Iglesias, G. (2024). Global wind energy resources decline under climate change. *Energy*, 288, 129765. <https://doi.org/10.1016/j.energy.2023.129765>

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., & Zhao, Z.-C. (2007). Global climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 747–845). Cambridge University Press.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., ... Wang, R. H. J. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their

extensions to 2500. *Geoscientific Model Development*, 13(13), 3571–3605. <https://doi.org/10.5194/gmd-13-3571-2020>

Meyer, I., Davies, G., Vogt, C., Kuhlmann, H., & Stuut, J. (2013). Changing rainfall patterns in NW Africa since the Younger Dryas. *Aeolian Research*, 10, 111–123. <https://doi.org/10.1016/j.AEOLIA.2013.03.003>

Miklyaev, M., & Olubamiro, O. C. (2025). *Impacts of Climate Change and Hazards on Key Sectors in Madagascar*. Queen's University Dunning Hall, Department of Economics.

Ministry of Energy. (2023). *Small hydropower development in Kenya*. Retrieved February 27, 2025, from <https://www.energy.go.ke/small-hydropower-development-kenya>

Ministry of Energy Kenya. (2022). *KCERT 2050 carbon calculator*. Strathmore University. <https://kcert.ilabafrica.ac.ke>

Molua, E. L., Mendelsohn, R. O., & Akamin, A. (2020). Economic vulnerability to tropical storms on the southeastern coast of Africa. *Jàmbá: Journal of Disaster Risk Studies*, 12(1), a676. <https://doi.org/10.4102/jamba.v12i1.676>

Moran, A. and Chesney, R., 2016. *Climate Change, State Stability, and Political Risk in Africa* (No. 55870LSMRI274).

Muis, S., Aerts, J. C. J. H., Á. Antolínez, J. A., Dullaart, J. C., Duong, T. M., Erikson, L., et al. (2023). Global projections of storm surges using high-resolution CMIP6 climate models. *Earth's Future*, 11, e2023EF003479. <https://doi.org/10.1029/2023EF003479>

Munene, M. B. (2021). Impact of climate change on energy developments in Kenya. *London School of Economics and Political Science*. Retrieved from <https://www.researchgate.net/publication/375258292>

Munro, P. G., Samarakoon, S., & van der Horst, G. (2020). African energy poverty: A moving target. *Environmental Research Letters*, 15(10), 104059. <https://doi.org/10.1088/1748-9326/abaf1a>

Musonye, X. S., Davíðsdóttir, B., Kristjánsson, R., Ásgeirsson, E. I., & Stefánsson, H. (2020). Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review. *Renewable and Sustainable Energy Reviews*, 128, 109915. <https://doi.org/10.1016/j.rser.2020.109915>

Muthuwatta, L., Sood, A., McCartney, M., Silva, N. S., & Opere, A. (2018). Understanding the impacts of climate change in the Tana River Basin, Kenya. *Proceedings of the International Association of Hydrological Sciences*, 379, 37–42. <https://doi.org/10.5194/piahs-379-37-2018>

NASA Global Precipitation Measurement. (n.d.). How does climate change affect precipitation? NASA. Retrieved February 14, 2025, from <https://gpm.nasa.gov/resources/faq/how-does-climate-change-affect-precipitation>

NASA Goddard Institute for Space Studies. (2021, April). *CMIP6: Model data for climate projections*. NASA. [https://www.giss.nasa.gov/research/features/202104\\_cmip6/](https://www.giss.nasa.gov/research/features/202104_cmip6/)

Nazarenko, L. S., Tausnev, N., Russell, G. L., Rind, D., Miller, R. L., Schmidt, G. A., Bauer, S. E., Kelley, M., Ruedy, R., Ackerman, A. S., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Cesana, G., Cheng, Y., Clune, T. L., Cook, B. I., Cruz, C. A., ... Yao, M.-S. (2022). Future climate change under SSP emission scenarios with GISS-E2.1. *Journal of Advances in Modeling Earth Systems*, 14(7), e2021MS002871. <https://doi.org/10.1029/2021MS002871>

Ndehedehe, C., Usman, M., Okwuashi, O., & Ferreira, V. (2021). Modelling impacts of climate change on coastal West African rainfall. *Modeling Earth Systems and Environment*. <https://doi.org/10.1007/s40808-021-01302-5>

Ndaye, A., Moussa, M. S., Dione, C., Sawadogo, W., Bliefernicht, J., Dungall, L., & Kunstmann, H. (2022). Projected changes in solar PV and wind energy potential over West Africa: An analysis of CORDEX-CORE simulations. *Energies*, 15(9602). <https://doi.org/10.3390/en15249602>

Nematchoua, M. K. (2021). Analysis and comparison of potential resources and new energy policy of Madagascar island: A review. *Renewable Energy*, 171, 747–763. <https://doi.org/10.1016/j.renene.2021.02.080>

Nikolulin, G., Jones, C., Samuelsson, P., Giorgi, F., Sylla, M. B., Asrar, G., Büchner, M., Cerezo-Mota, R., Christensen, O. B., Déqué, M., Fernández, J., Hänsler, A., Meijgaard, E. van, & Sushama, L. (2012). Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. *Journal of Climate*, 25(18), 6057–6078. <https://doi.org/10.1175/JCLI-D-11-00375.1>

Nicholson, S. E., Funk, C., & Fink, A. H. (2018). Rainfall over the African continent from the 19th through the 21st century. *Global and Planetary Change*, 165, 114–127. <https://doi.org/10.1016/j.gloplacha.2017.12.014>

Nogueira, L. P., Dalla Longa, F., & van der Zwaan, B. (2020). A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar. *Climate Policy*, 20(10), 1257–1273. <https://doi.org/10.1080/14693062.2020.1791030>

Ochieng, W. O., Oludhe, C., Dulo, S., & Olaka, L. (2021). An analytical assessment of climate change trends and their impacts on hydropower in Sondu Miriu River Basin, Kenya. *African Journal of Environmental Science and Technology*, 15(12), 519–528. <https://doi.org/10.5897/AJEST2021.3064>

O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400. <https://doi.org/10.1007/s1058401309052>

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>

Obahoundje, S., Diedhiou, A., Troccoli, A., Boorman, P., Alabi, T. A. F., Anquetin, S., Crochemore, L., Fassinou, W. F., Hingray, B., Koné, D., Mamadou, C., & Sorho, F. (2024). Teal-WCA: A climate services platform for planning solar photovoltaic and wind energy resources in West and Central Africa in the context of climate change. *Data*, 9(148). <https://doi.org/10.3390/data9120148>

Obahoundje, S., & Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: A review. *Environmental Research Letters*, 17(4), 043005. <https://doi.org/10.1088/1748-9326/ac5b3b>

Odwori, E. O. (2022). Effect of rainfall and temperature variability on streamflow in Nzoia River Basin, Kenya. *Asian Journal of Advanced Research and Reports*, 16(5), 33–61. <https://doi.org/10.9734/AJARR/2022/v16i530473>

Ouedraogo, W. A. A., Gathenya, J. M., & Raude, J. M. (2019). Projecting wet season rainfall extremes using regional climate models ensemble and the advanced delta change model: Impact on the streamflow peaks in Mkurumudzi Catchment, Kenya. *Hydrology*, 6(3), 76. <https://doi.org/10.3390/hydrology6030076>

Parkes, B., Cronin, J., Dessens, O., & Sultan, B. (2019). Climate change in Africa: Costs of mitigating heat stress. *Climatic Change*, 154(3–4), 461–476.

Parzen, M., Abdel-Khalek, H., Fedotova, E., Mahmood, M., Frysztacki, M. M., Hampp, J., Franken, L., Schumm, L., Neumann, F., & Poli, D. (2023). PyPSA-Earth. A new global open energy system optimization model demonstrated in Africa. *Applied Energy*, 341, Article 121096. <https://doi.org/10.1016/j.apenergy.2023.121096>

Pappis, I., Howells, M., Sridharan, V., Usher, W., Shivakumar, A., Gardumi, F., & Ramos, E. (2019). Energy projections for African countries. In I. Hidalgo González, H. Medarac, R. González Sánchez, & I. Kougias (Eds.), *EUR 29904 EN*. Publications Office of the European Union. doi:10.2760/678700

Pietroiusti, R., Vanderkelen, I., Otto, F. E. L., Barnes, C., Temple, L., Akurut, M., Bally, P., van Lipzig, N. P. M., & Thiery, W. (2024). Possible role of anthropogenic climate change in the record-breaking 2020 Lake Victoria levels and floods. *Earth System Dynamics*, 15, 225–264. <https://doi.org/10.5194/esd-15-225-2024>

PreventionWeb. (2024). Catching the sun: Adapting solar power to the challenges of climate change. Retrieved February 7, 2025, from <https://www.preventionweb.net/quick/87813>

Rabazanahary Tanteliniaina, M. F., Rahaman, M. H., & Zhai, J. (2021). Assessment of the future impact of climate change on the hydrology of the Mangoky River, Madagascar using ANN and SWAT. *Water*, 13(1239). <https://doi.org/10.3390/w13091239>

Rajaobelison, M., Raymond, J., Malo, M., & Dezayes, C. (2020). Classification of geothermal systems in Madagascar. *Geothermal Energy*, 8(22). <https://doi.org/10.1186/s40517-020-00176-7>

Rakotondravony, H. A., Abdallah, I., Andrianaivo, H., Andrianarison, L. N., Hetz, K., Mahatante, P. T., ... & Rasamison, A. A. (2018). État des lieux des études de la vulnérabilité à Madagascar: revue bibliographique. *Antananarivo, Madagascar. GIZ, Bonn*.

Restrepo-Valencia, S., & Walter, A. (2023a). BECCS opportunities in Brazil: Comparison of pre and post-combustion capture in a typical sugarcane mill. *International Journal of Greenhouse Gas Control*, 124(June 2021), 103859. <https://doi.org/10.1016/j.ijggc.2023.103859>

Restrepo-Valencia, S., & Walter, A. (2023b). CO<sub>2</sub> Capture in a Thermal Power Plant Using Sugarcane Residual Biomass. *Energies*, 16(12), 1–19. <https://doi.org/10.3390/en16124570>

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Crespo Cuaresma, J., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., ... Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, 42, 153–168. <https://doi.org/10.1016/j.gloenvcha.2016.05.009>

Ritchie, H., & Roser, M. (n.d.). Kenya: CO<sub>2</sub> country profile. *Our World in Data*. Retrieved February 27, 2025, from <https://ourworldindata.org/co2/country/kenya>

Russo, M., Carvalho, D., Martins, N., & Monteiro, A. (2022). Forecasting the inevitable: A review on the impacts of climate change on renewable energy resources. *Sustainable Energy Technologies and Assessments*, 52(Part C), 102283. <https://doi.org/10.1016/j.seta.2022.102283>

Sackey, C. V. H., Levin, T., & Nock, D. (2022). Latent demand for electricity in sub-Saharan Africa: A review. *Environmental Research: Infrastructure and Sustainability*, 2(2), 025004. <https://doi.org/10.1088/2634-4505/ac5fb2>

Sam, M., Simwela, A., & Mekondjo, S. S. (2018). Availability, accessibility and the road map for clean, affordable, effective and efficient energy for Sierra Leone: A six years analysis from 2006 to 2011. *International Journal of Scientific and Research Publications*, 8(5). <http://www.ijsrp.org/research-paper-0518.php?rp=P777433>

Samson, T. K., & Aweda, F. O. (2024). Wind speed prediction in some major cities in Africa using Linear Regression and Random Forest algorithms. *Journal of the Nigerian Society of Physical Sciences*, 6(2024), 2079. DOI:10.46481/jnsps.2024.2079

Sankoh, M., Diarra, B., Samikannu, R., & Ladu, N. S. D. (2022). Techno-economic feasibility analysis of a solar photovoltaic hybrid system for rural electrification in Sierra Leone for zero carbon emission. *International Transactions on Electrical Energy Systems*. <https://doi.org/10.1155/2022/6349229>

Sawadogo, W., Reboita, M. S., Faye, A., da Rocha, R. P., Odoulami, R. C., Olusegun, C. F., Adeniyi, M. O., Abiodun, B. J., Sylla, M. B., Diallo, I., Coppola, E., & Giorgi, F. (2021). Current and future potential of solar and wind energy over Africa using the RegCM4 CORDEX-CORE ensemble. *Climate Dynamics*, 57, 1647–1672. <https://doi.org/10.1007/s00382-020-05377-1>

Schmutz, W. K. (2021). Changes in the total solar irradiance and climatic effects. *Journal of Space Weather and Space Climate*, 11, 40. <https://doi.org/10.1051/swsc/2021016>

Schwinger, J., Goris, N., Tjiputra, J. F., Kriest, I., Bentsen, M., Bethke, I., Ilicak, M., Assmann, K. M., & Heinze, C. (2016). Evaluation of NorESM-OC (versions 1 and 1.2), the ocean carbon-cycle stand-alone configuration of the Norwegian Earth System Model (NorESM1). *Geoscientific Model Development*, 9(8), 2589–2622.

Seland, Ø., Bentsen, M., Olivié, D. J. L., Toniazzo, T., Gjermundsen, A., Heinze, C., Ilicak, M., & Schulz, M. (2020). Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geoscientific Model Development*, 13(12), 6165–6200. <https://doi.org/10.5194/gmd-13-6165-2020>

Singh, A., Lund, H. G., & Barr, J. (2018). Challenges in building climate-resilient quality energy infrastructure in Africa. In Z. Zommers & K. Alverson (Eds.), *Resilience* (pp. 181–189). Elsevier. <https://doi.org/10.1016/B978-0-12-811891-7.00014-1>

Soares, P. M. M., Brito, M. C., & Careto, J. A. M. (2019). Persistence of the high solar potential in Africa in a changing climate. *Environmental Research Letters*, 14(12), 124036. <https://doi.org/10.1088/1748-9326/ab51a1>

Souverijns, N., Thiery, W., Demuzere, M., & van Lipzig, N. (2016). Drivers of future changes in East African precipitation. *Environmental Research Letters*, 11(11), 114011. <https://doi.org/10.1088/17489326/11/11/114011>

Sterl, S., & Chawanda, C. J. (2024). *Online repository of materials for an all-Africa hydropower atlas* (v2.3). HydroShare. <https://www.hydroshare.org/resource/197eab83ae424be3804ee154ed98aea8/>

Sylla, M. B., Giorgi, F., Coppola, E., & Mariotti, L. (2013). Uncertainties in daily rainfall over Africa: Assessment of observation products and evaluation of a regional climate model simulation. *International Journal of Climatology*, 33(8), 1805–1817. <https://doi.org/10.1002/joc.3551>

Taylor, E. T., Kamara, I. S., & Bockarie, A. (2014). Rainfall Pattern in Freetown, Sierra Leone: From a Retrospective Viewpoint. Institute of Environmental Management and Quality Control, School of Environmental Sciences, Njala University, Sierra Leone.

Tesfamichael, M., & Fuchs, J. (2024). Navigating complexity: Integrating political realities into energy system modelling for effective policy in Sub-Saharan Africa. *Progress in Energy*, 6(043001). <https://doi.org/10.1088/2516-1083/ad5cbf>

The Energy and Petroleum Regulatory Authority. (EPRA). (2024). *Energy & petroleum statistics report for the financial year ended 30th June 2024*. [https://www.epra.go.ke/sites/default/files/2024-10/EPRA%20Energy%20and%20Petroleum%20Statistics%20Report%20FY%202023-2024\\_2.pdf](https://www.epra.go.ke/sites/default/files/2024-10/EPRA%20Energy%20and%20Petroleum%20Statistics%20Report%20FY%202023-2024_2.pdf)

TheGlobalEconomy.com. (2025). *Madagascar: Geothermal electricity capacity*. Retrieved March 11, 2025, from [https://www.theglobaleconomy.com/Madagascar/geothermal\\_electricity\\_capacity/](https://www.theglobaleconomy.com/Madagascar/geothermal_electricity_capacity/)

Tiger, B. H., Burns, S., Dawson, R. R., Scropton, N., Godfrey, L. R., Ranivoharimanana, L., Faina, P., & McGee, D. (2023). Zonal Indian Ocean variability drives millennial-scale precipitation changes in northern Madagascar. *Paleoceanography and Paleoclimatology*, 38, e2023PA004626. <https://doi.org/10.1029/2023PA004626>

Tiandraza, F., Qu, S., Hu, S., Mkono, C. N., Tikhomirova, A., & Randrialahamady, S. N. (2023). Response of ecosystem services to land use change in Madagascar Island, Africa: A multi-scale perspective. *International Journal of Environmental Research and Public Health*, 20(4), 3060. <https://doi.org/10.3390/ijerph20043060>

Tjiputra, J. F., Schwinger, J., Bentsen, M., L. Morée, A., Gao, S., Bethke, I., Heinze, C., Goris, N., Gupta, A., He, Y. C., Olivié, D., Seland, O., & Schulz, M. (2020). Ocean biogeochemistry in the Norwegian Earth System Model version 2 (NorESM2). *Geoscientific Model Development*, 13(5), 2393–2431. <https://doi.org/10.5194/gmd-13-2393-2020>

Tokpa, M., Lobanov, V., Mhanna, A., Morozova, S., & Alimpieva, M. (2023). Estimation of modern changes in atmospheric precipitation in Central Africa. *Bulletin of Udmurt University. Series Biology. Earth Sciences*. <https://doi.org/10.35634/2412-9518-2023-33-2-217-232>

Trisos, C. H., Adelekan, I. O., Totin, E., Ayanlade, A., Efitre, J., Gemed, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., Ngaruiya, G., Olago, D., Simpson, N. P., & Zakielde, S. (2022). Africa. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1285–1455). Cambridge University Press. <https://doi.org/10.1017/9781009325844.011> [USAID \(2016\). Greenhouse Gas Emissions in Madagascar.](https://www.usaid.gov/press-releases/2016/01/11/usaids-greenhouse-gas-emissions-in-madagascar)

Veron, S., Mouchet, M., Govaerts, R., Haevermans, T., & Pellens, R. (2019). Vulnerability to climate change of islands worldwide and its impact on the tree of life. *Scientific Reports*, 9(1), 14471. <https://doi.org/10.1038/s41598-019-51107-x>

Vision 2030 Delivery Secretariat. (2022, August). Kenya Vision 2030 flagship programmes and projects progress report (FY 2020/2021). *Republic of Kenya*. <https://vision2030.go.ke>

Wadsworth, R., Jalloh, A., & Lebbie, A. (2019). Changes in rainfall in Sierra Leone: 1981–2018. *Climate*, 7(12), 144. <https://doi.org/10.3390/cli7120144>

Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V., & Tsvetkov, A. (2005). From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science*, 308(5723), 847–850. <https://www.jstor.org/stable/3841939>

Willkomm, M., Vierneisel, B., & Dannenberg, P. (2016). Land use change dynamics in the Mt. Kenya region – A remotely sensed analysis using RapidEye satellite images. *Zeitschrift für Geologische Wissenschaften, Paläontologie, Teil I*, 2016(1), 23–40. <https://doi.org/10.1127/zgpl/2016/0023-0040>

Wilson, C., Liang, B., Wilson, S., & Akiwumi, F. (2018). Land use, microclimate, and surface runoff linkages: Space-time modeling from Rokel-Seli River Basin, Sierra Leone. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-4/W8*, 225–230. <https://doi.org/10.5194/isprs-archives-XLII-4-W8-225-2018>

Wind energy data for Switzerland. (2024). *Wind profile calculator*. Retrieved May 15, 2024, from <https://wind-data.ch/tools/profile.php>

World Health Organization (WHO). 2016. Climate and health country profile-2015 Madagascar. World Health Organization, Geneva, Switzerland. [online] URL: <https://apps.who.int/iris/handle/10665/246140s>

World Bank. (2021). Kenya – Climate data & projections. *World Bank Climate Knowledge Portal*. Retrieved February 5, 2025, from <https://climateknowledgeportal.worldbank.org/country/kenya/climate-data-projections>

World Bank. (2021). Madagascar – Climate data & projections. *World Bank Climate Knowledge Portal*. Retrieved February 5, 2025, from <https://climateknowledgeportal.worldbank.org/country/madagascar/climate-data-projections>

World Bank. (2021). Sierra Leone – Climate data & projections. *World Bank Climate Knowledge Portal*. Retrieved February 5, 2025, from <https://climateknowledgeportal.worldbank.org/country/sierra-leone/climate-data-projections>

World Meteorological Organization (WMO). (2023). *State of the Climate in Africa 2022* (WMO-No. 1330). World Meteorological Organization. ISBN: 978-92-63-11330-6. Retrieved from <https://library.wmo.int/viewer/67761/?offset=#page=1&viewer=picture&o=bookmark&n=0&q=>

World Resources Institute. (2025). Historical GHG emissions: Energy sector CO<sub>2</sub> (2000–2021) – Kenya, Madagascar, Sierra Leone. *Climate Watch*. [https://www.climatewatchdata.org/data-explorer/historical-emissions?historical-emissions-data-sources=climate-watch&historical-emissions-end\\_year=2021&historical-emissions-gases=co2&historical-emissions-regions=KEN%2CMDG%2CSLE&historical-emissions-sectors=energy&historical-emissions-start\\_year=2000&page=1](https://www.climatewatchdata.org/data-explorer/historical-emissions?historical-emissions-data-sources=climate-watch&historical-emissions-end_year=2021&historical-emissions-gases=co2&historical-emissions-regions=KEN%2CMDG%2CSLE&historical-emissions-sectors=energy&historical-emissions-start_year=2000&page=1)

World Resources Institute. (2025). Kenya: GHG emissions. *Climate Watch*. [https://www.climatewatchdata.org/countries/KEN?end\\_year=2022&start\\_year=1990#ghg-emissions](https://www.climatewatchdata.org/countries/KEN?end_year=2022&start_year=1990#ghg-emissions)

Millennium Challenge Corporation, Sierra Leone Threshold Program Evaluation Report v.5-Social Impact. 2022. Available online: [http://designreport-sle-water-si-oct1920\(5\).pdf/](http://designreport-sle-water-si-oct1920(5).pdf/)

Africa Energy Portal (AEP), Tracking Sustainable Development Goal 7 (SDG7)/World Bank Group. 2020. Available online: <http://africa-energy-portal.org/fr/country/sierra-leone/>

Hirmer, S.; George-Williams, H.; Rhys, J.; McNicholl, D.; McCulloch, M. Stakeholder decision-making: Understanding Sierra Leone's energy sector. *Renew. Sustain. Energy Rev.* 2021, 145, 111093.

Millennium Challenge Coordinating Unit (MCCU), Millennium Challenge Coordinating Unit Monitoring and Evaluation Plan. 2020. Available online:

<http://assets.mcc.gov/content/uploads/ME-Plan-SLE-Th-V5-Dec20.pdf/>

World Bank. (2025, June). *Sierra Leone Country Climate and Development Report* (Western and Central Africa). Washington, DC: World Bank Group.

<https://documents1.worldbank.org/curated/en/099061025134515861/pdf/P180420-3b8a8f03-2cbc-4a24-a58e-700ecde830be.pdf>

Kiley, F., Caulker, D., Collier, W., Fields, N., Blyth, W., Quirós-Tortós, J., & Howells, M. (2024). A dataset for energy demand and supply modelling in Sierra Leone. *Data in Brief*, 55, 110715.

<https://doi.org/10.1016/j.dib.2024.110715>

International Renewable Energy Agency (IRENA). (2023). *IRENASTAT power capacity and generation*. Abu Dhabi: IRENA. Retrieved February 8, 2024, from

<https://www.irena.org/Data/Downloads/IRENASTAT>

Government of Sierra Leone. (2016, May). *Renewable Energy Policy of Sierra Leone*.

Freetown: Ministry of Energy, Government of Sierra Leone. Retrieved from

[https://cdn.climatepolicyradar.org/navigator/SLE/2016/renewable-energy-policy-of-sierra-leone\\_adf5ee8365fd42216c72d81ece767f9a.pdf#:~:text=to%20the%20Power%20Sector%20Master,Hydropower](https://cdn.climatepolicyradar.org/navigator/SLE/2016/renewable-energy-policy-of-sierra-leone_adf5ee8365fd42216c72d81ece767f9a.pdf#:~:text=to%20the%20Power%20Sector%20Master,Hydropower)

Karim, S., & Bah, C. J. (2022). An analysis of the impacts of climate change on green economy of Sierra Leone. *Journal of Green Economy*, 3(2), 61–66.

<https://doi.org/10.5281/zenodo.6396231>

Obahoundje, S., & Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: A review. *Environmental Research Letters*, 17(4), 043005. <https://doi.org/10.1088/1748-9326/ac5b3b>

Strobl, E., & Strobl, R. O. (2011). The distributional impact of large dams: Evidence from cropland productivity in Africa. *Journal of Development Economics*, 96(2), 432–450.

<https://doi.org/10.1016/j.jdeveco.2010.08.005>

Sustainable Energy for All (SEforALL). (n.d.). *Sierra Leone Energy Transition and Green Growth Plan*. Retrieved October 16, 2025, from <https://www.seforall.org/our-work/initiatives-projects/energy-transition-plans/sierra-leone>

ERM; Joule Africa; Government of Sierra Leone; EDG; CEMMATS. (2017, February). *Bumbuna II Hydroelectric Project: Non-Technical Summary (NTS) of Environmental, Social & Health*

*Impact Assessment (ESHIA)*. Freetown. Retrieved from

<https://www.selihydropower.sl/Content/documents/1.%20Bumbuna%20NTS.pdf>

World Climate Research Programme (WCRP). (n.d.). *CMIP Phase 6 (CMIP6)*. Coupled Model Intercomparison Project. Retrieved October 16, 2025, from <https://wcrp-cmip.org/cmip-phases/cmip6/>

Romanovska, P., Gleixner, S., & Gornott, C. (2023). Climate data uncertainty for agricultural impact assessments in West Africa. *Theoretical and Applied Climatology*, 152(3–4), 933–950. <https://doi.org/10.1007/s00704-023-04430-3>

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>

John, A., Douville, H., Ribes, A., & Yiou, P. (2022). Quantifying CMIP6 model uncertainties in extreme precipitation projections. *Weather and Climate Extremes*, 38, 100435. <https://doi.org/10.1016/j.wace.2022.100435>

Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5–32. <https://doi.org/10.1023/A:1010933404324>

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscale drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23(7), 1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>

Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, 1(2), 96–99. <https://doi.org/10.13031/2013.26773>

Barnes, T., Shivakumar, A., Brinkerink, M. et al. OSeMOSYS Global, an open-source, open data global electricity system model generator. *Sci Data* 9, 623 (2022). <https://doi.org/10.1038/s41597-022-01737-0>

NDC Partnership. (n.d.). *Integrated MARKAL-EFOM System (TIMES) Model*. Climate Toolbox, Knowledge Portal. Retrieved October 16, 2025, from <https://ndcpartnership.org/knowledge-portal/climate-toolbox/integrated-markal-efom-system-times-model>

International Institute for Applied Systems Analysis (IIASA). (n.d.). *The MESSAGEix framework*. Retrieved October 16, 2025, from <https://docs.messageix.org/en/latest/>

Maximilian Parzen, Hazem Abdel-Khalek, Ekaterina Fedotova, Matin Mahmood, Martha Maria Frysztacki, Johannes Hampf, Lukas Franken, Leon Schumm, Fabian Neumann, Davide Poli, Aristides Kiprakis, Davide Fioriti,

PyPSA-Earth. A new global open energy system optimization model demonstrated in Africa, *Applied Energy*, Volume 341, 2023, 121096, ISSN 0306-2619, <https://doi.org/10.1016/j.apenergy.2023.121096>.

Pfenniger, S., & Pickering, B. (2018). Calliope: A multi-scale energy systems modelling framework. *Journal of Open Source Software*, 3(29), 825. <https://doi.org/10.21105/joss.00825>

Allan, R. P., Boucher, O., & Collins, M. (2020). Climate variability and change: Understanding precipitation responses. *Nature Reviews Earth & Environment*, 1(7), 329–345.

Haensler, A., Saeed, F., & Jacob, D. (2013). Assessing the robustness of projected precipitation changes over West Africa in CMIP5 simulations. *Environmental Research Letters*, 8(4), 044022.

Quagraine, K. A., Nkrumah, F., Klein, C., Klutse, N. A. B., & Quagraine, K. T. (2020). West African summer monsoon precipitation variability as represented by reanalysis datasets. *Climate*, 8(10), 111. <https://doi.org/10.3390/cli8100111>

World Bank. (2021). Climate risk profile: Sierra Leone. Washington, DC: World Bank Group.

Sylla, M.B., Pal, J.S., Faye, A. et al. Climate change to severely impact West African basin scale irrigation in 2 °C and 1.5 °C global warming scenarios. *Sci Rep* 8, 14395 (2018). <https://doi.org/10.1038/s41598-018-32736-0>

United Nations Framework Convention on Climate Change (UNFCCC). (2021). Standardized baseline: Grid emission factor for the West African Power Pool (ASB0034-2021, Version 01.0). Clean Development Mechanism. Retrieved from <https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20210325112041972/ASB0034-2021.pdf>

## VII. APPENDICES

### A.1 Climate projection of other variables by EC-Earth3-Veg model

#### A1.1 Kenya

1). Projection on the Surface Shortwave Radiation: slightly decline towards 2050

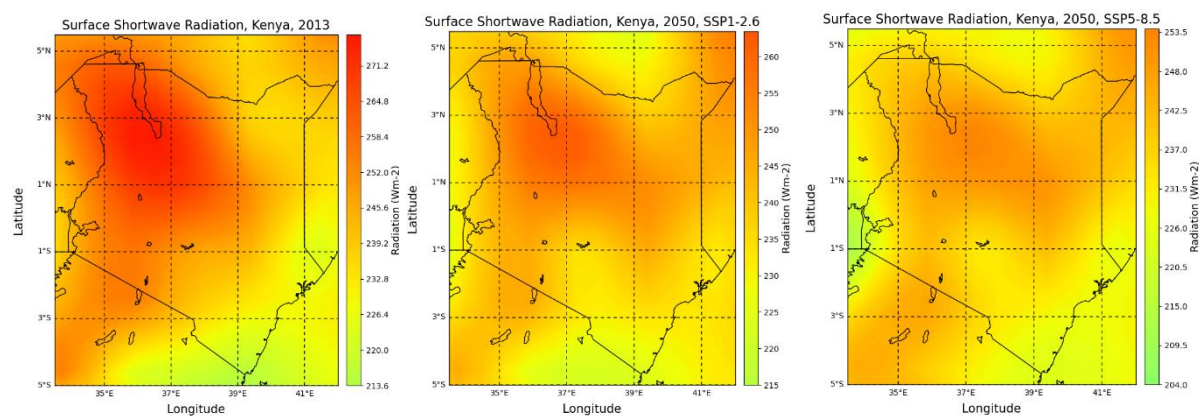


Figure A1.1 The projected and the historical Surface Shortwave Radiation in Kenya

2). Runoff: No significant change towards 2050

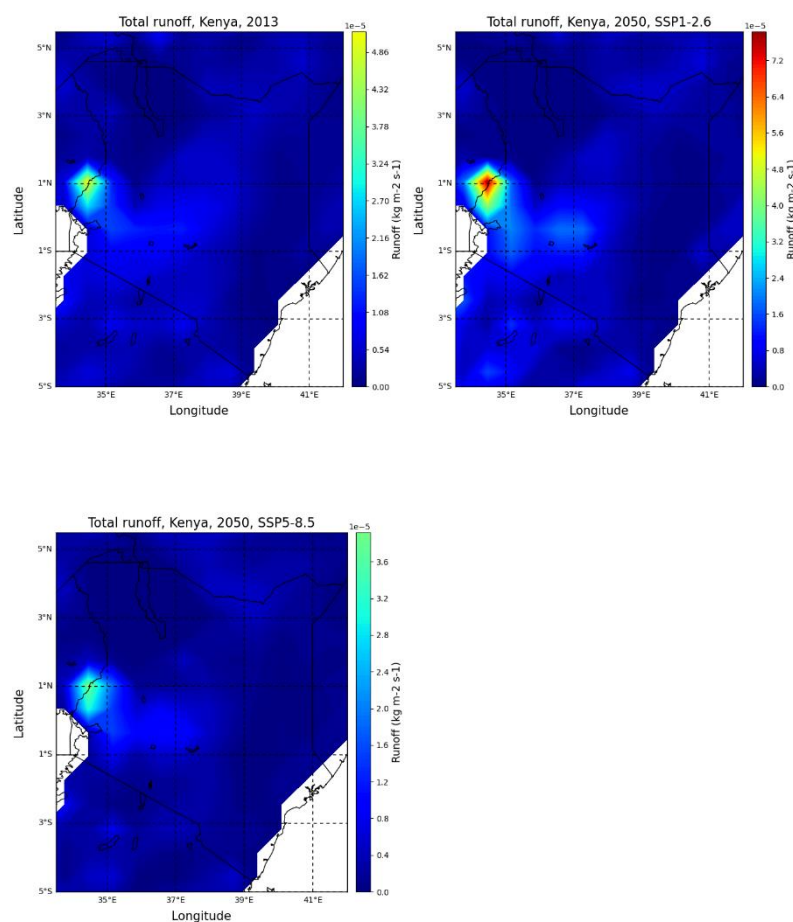


Figure A1.2 The projected and the historical Runoff in Kenya

## A1.2 Sierra Leone

### 1). Temperature: significantly increase towards 2050

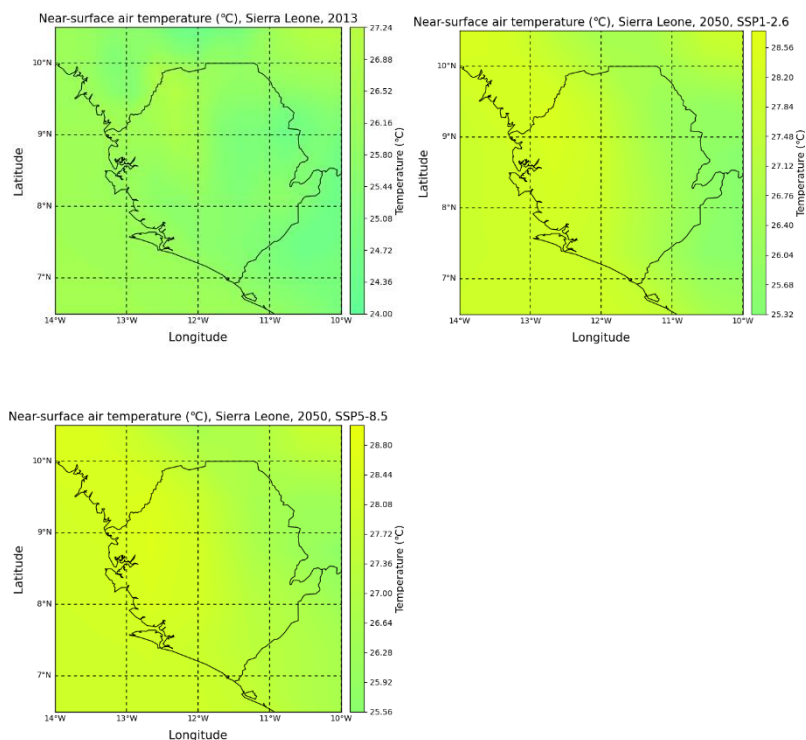


Figure A1.3 The projected and the historical Temperature in Sierra Leone

### 2). Surface Shortwave Radiation: slight decrease towards 2050

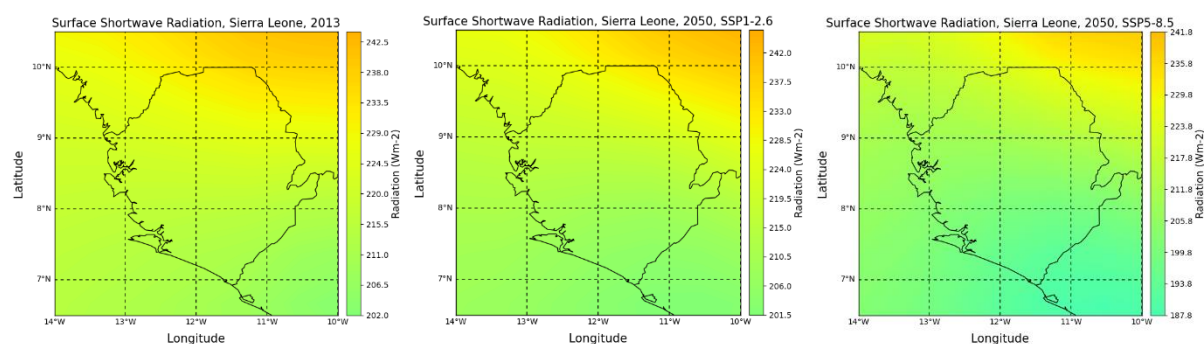


Figure A1.4 The projected and the historical Surface Shortwave Radiation in Sierra Leone

## A1.3 Madagascar

### 1). Temperature: significantly increase towards 2050

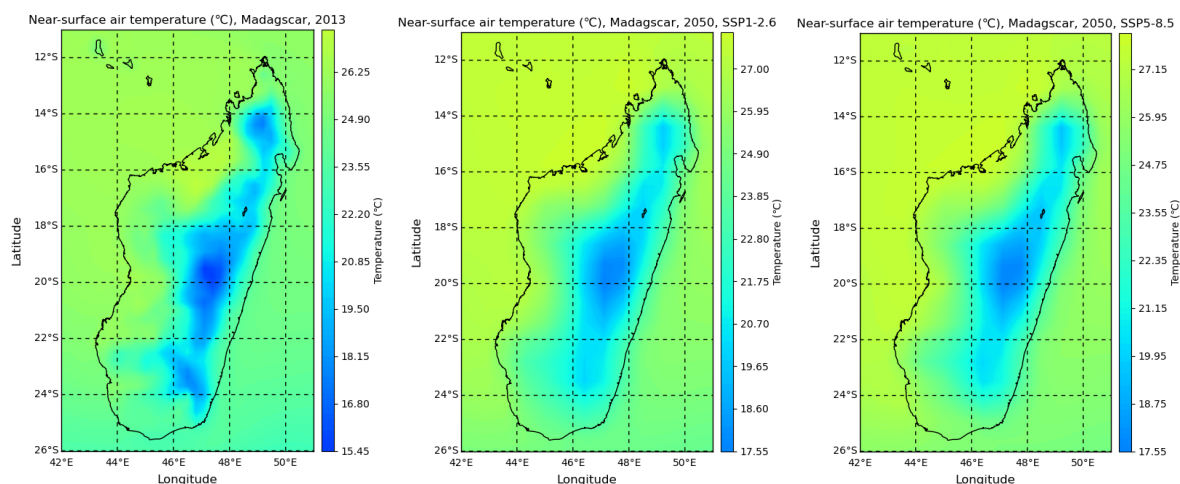


Figure A1.5 The projected and the historical Temperature in Madagascar

## 2). Surface Shortwave Radiation: slightly increase

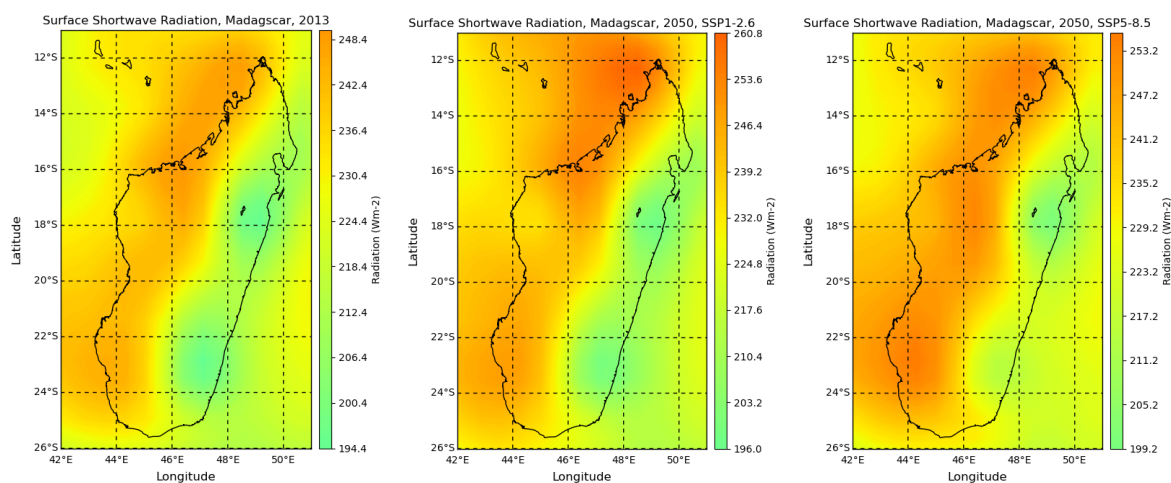


Figure A1.6 The projected and the historical Surface Shortwave Radiation in Madagascar

## 3). Runoff

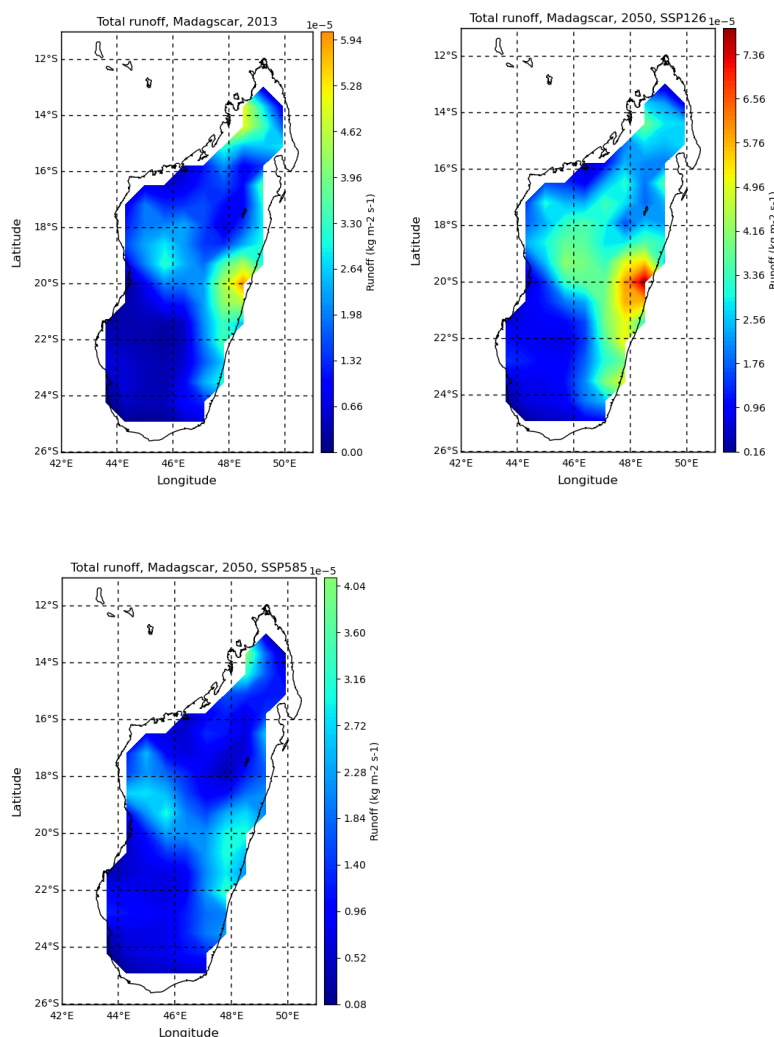


Figure A1.7 The projected and the historical Runoff in Madagascar

## A.2 Cooling demand

### A2.1 Sierra Leone

To estimate future cooling demand in Sierra Leone, this study relies on projected cooling degree days (CDDs) combined with a coefficient indicating the change in electricity demand for each unit change in CDDs. These calculations are further adjusted based on anticipated electricity access rates relative to the 2013 baseline, assuming that 75% of cooling demand represents served cooling use under both the SSP1-2.6 and SSP5-8.5 scenarios (Charting the Globe, 2023; Fields et al., 2024; Ministry of Environment, Climate Change and Forestry, 2023; World Bank, 2023).

Figure A2.1, shown below, depicts the projected electricity demand for cooling in Sierra Leone from 2014 to 2050 under the SSP1-2.6 and SSP5-8.5 scenarios. The projections show a steady rise in cooling demand across both scenarios, with values reaching about 548 GWh under SSP1-2.6 and approximately 577 GWh under SSP5-8.5 by 2050. This reflects a roughly 5.3% higher demand in the SSP5-8.5 scenario compared to SSP1-2.6, highlighting the greater cooling requirements driven by higher temperatures and less stringent climate action in SSP5-

8.5. These results underscore how differing climate policy pathways can significantly shape future electricity infrastructure needs.

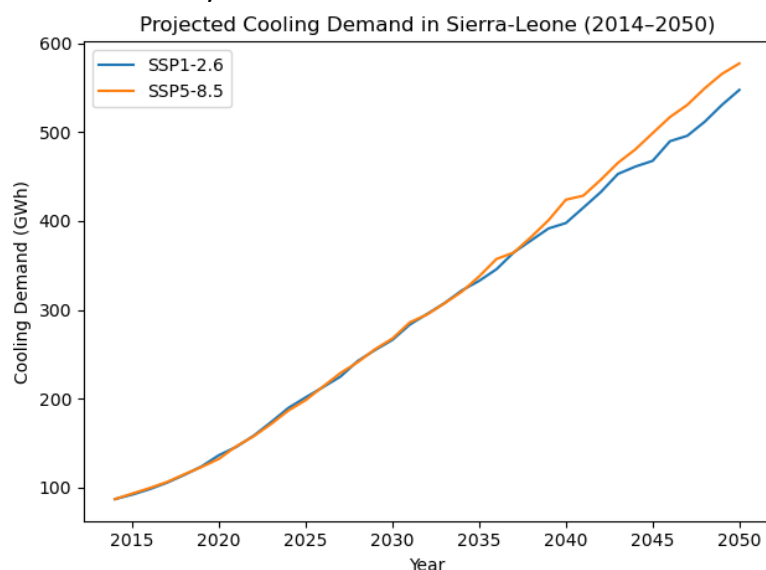


Figure A2.1. Comparison of Predicted Cooling Demand for SSP1-2.6 and SSP5-8.5 for Sierra Leone.

## A2.2 Madagascar

To estimate cooling demand in Madagascar, this study uses projected cooling degree days (CDDs) along with a coefficient representing the change in electricity demand per unit change in CDDs, adjusted for future electricity access rates relative to the 2013 baseline, and assuming that 75% of cooling demand corresponds to served cooling usage under both the SSP1-2.6 and SSP5-8.5 scenarios (IEA, 2023; Ministry of Environment, Climate Change and Forestry, 2023; World Bank, 2023).

Figure A2.2, shown below, presents the projected electricity demand for cooling in Madagascar from 2014 to 2050 under the SSP1-2.6 and SSP5-8.5 scenarios. As illustrated, cooling demand steadily increases in both scenarios, reaching approximately 1,151 GWh under SSP1-2.6 and 1,258 GWh under SSP5-8.5 by 2050. This represents about a 9.3% higher demand in the SSP5-8.5 scenario compared to SSP1-2.6 in 2050, reflecting the additional cooling needs driven by higher temperatures and reduced climate mitigation efforts in SSP5-8.5. This contrast highlights the significant influence of climate policy choices on Madagascar's long-term energy planning and infrastructure development.

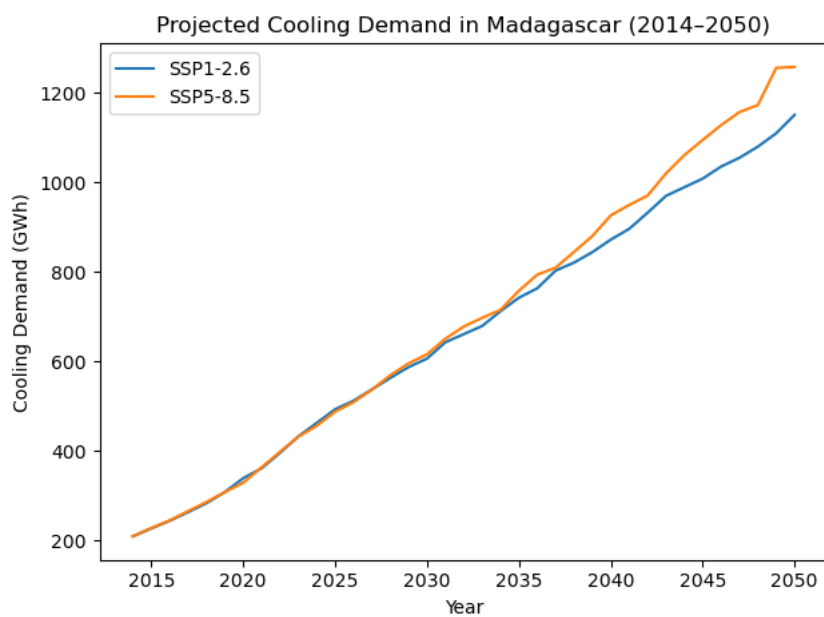
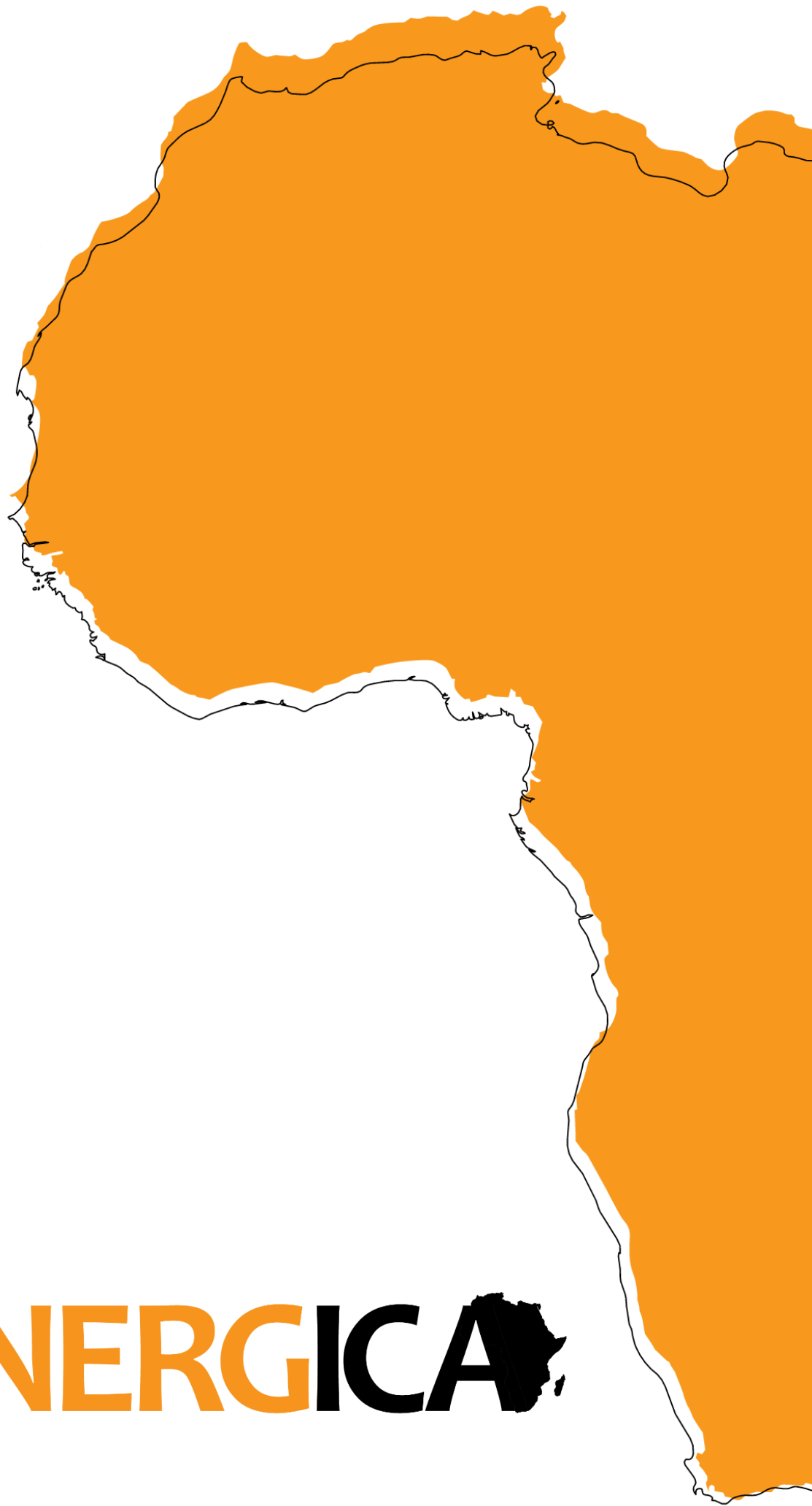


Figure A2.2 Comparison of Predicted Cooling Demand for SSP1-2.6 and SSP5-8.5 for Madagascar.

Subchapters: Kenya, Madagascar, Sierra-Leone  
Kenya, Madagascar, Sierra-Leone map plots



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