INTEGRATED SCENARIO ANALYSIS UNDER ENERGY, WATER AND DECARBONIZATION STRESS: THE CASE OF RWANDA

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Abstract: Crises such as rapid population and demand growth, droughts, resource availability fluctuations, and supply-chain disruptions increasingly expose hidden fragilities in socio-technical systems. At the same time, they generate political momentum and practical urgency for institutional and governance innovation, as emergency measures often become prototypes for routine practice. This paper develops a national-scale, multi-sector water–energy–emissions (W–E–E) scenario model for Rwanda and uses it to test how demand growth, hydrological stress, and supply-side choices jointly shape future energy security and emissions trajectories through 2050. The analysis shows that, under SSP2 and especially SSP5 growth conditions, emissions remain strongly demand-driven; therefore, even ambitious demand-side and supply-side measures are best interpreted as pathways that moderate, rather than fully reverse, emissions growth. The contribution of the study is to identify which combinations of efficiency, electrification, renewable deployment, thermal retirement, and hydrological risk management most effectively reduce system stress and improve resilience under compound crises.

Keywords: Water-energy-emissions nexus; Multi-crisis scenario analysis; LEAP; Hydropower; Energy system resilience; Droughts; Rwanda

1. Introduction: Multi-sector crises and integrated thinking

The global energy transition is unfolding in what has increasingly been described as an era of "permanent crises", characterized by overlapping pressures on water, energy, infrastructure, and climate systems (Alamanos & Koundouri, 2022). Rapid population growth, rising energy demand, intensifying droughts, and the accumulation of greenhouse gas (GHG) emissions interact with one another, reinforcing systemic vulnerabilities rather than appearing as isolated shocks (Sinha et al., 2023). These pressures are particularly acute in low- and middle-income countries, where energy systems are expanding rapidly while remaining highly exposed to climatic and economic disruptions (Iyiola et al., 2024). Crises rarely respect sectoral or institutional silos. A severe drought, for instance, reduces river flows and reservoir inflows, directly constraining hydropower generation. Lower hydropower availability can trigger increased reliance on thermal generation or electricity imports, raising fuel costs and emissions (Englezos et al., 2023). Conversely, such effects propagate through the economy as households face higher risks of outages, water utilities struggle to secure reliable energy for pumping and treatment, industrial production may be disrupted by supply intermittency, and electrified transport systems become more vulnerable to grid instability (Koundouri et al., 2024; Xu et al., 2024).

In low- and middle-income countries, however, rising emissions are often linked to legitimate development needs rather than discretionary consumption. Population growth, electrification, industrialization, and the expansion of water and transport services all require more energy, and these needs cannot be treated as a failure of policy in the same way as wasteful high-income consumption patterns. A just transition therefore requires that mitigation in lower-income settings be coupled with finance, technology transfer, and institutional support that make low-carbon development feasible rather than punitive. Planning approaches that treat water, energy, and emissions independently systematically underestimate these interactions and, as a result, misjudge system resilience (Grubler et al., 2018; McCollum et al., 2018). An expanding strand of the literature has focused on integrated and cross-sectoral energy system modelling, particularly where interactions between electricity, fuels, and emissions are important (Bataille et al., 2020; Koundouri et al., 2025). Also, the joint consideration of water-energy interactions has received increasing attention in recent years, particularly in systems with significant hydropower dependence. Studies by van Vliet et al. (2016) and Turner et al. (2017) quantified how climate-induced hydrological changes can constrain electricity generation and increase reliance on thermal backup, with implications for both emissions and energy security. More recent work has stressed that droughts and water scarcity act as systemic stressors rather than isolated shocks, propagating across power systems, trade, and end-use sectors (Byers et al., 2018). In the context of multi-crises, holistic approaches are necessary, but they need also to be tested under various potential future conditions. Thus, scenario analysis has long been used as a core tool for exploring uncertainty in energy and climate systems, particularly where long-term dynamics, structural change, and policy trade-offs are central concerns (van der Heijden, 1996). At the global and regional scale, the Shared Socioeconomic Pathways (SSPs) framework has become a widely adopted reference for linking socio-economic development trajectories with energy use and emissions outcomes (O'Neill et al., 2017; Riahi et al., 2017). Building on this framework, van Vuuren et al. (2014) demonstrated how alternative development pathways strongly condition mitigation potential, highlighting the importance of demand-side dynamics alongside supply-side transitions. Furthermore, Pfenninger et al. (2014) and Trutnevyte et al. (2016) emphasized that scenario analysis is most valuable not as a predictive or optimization exercise, but as a means of stress-testing systems and revealing vulnerabilities under uncertainty.

Particularly for Rwanda, the literature so far has been focused on electricity generation planning, access expansion, and renewable energy potential. Several studies assess Rwanda’s hydropower resources and vulnerability to climate variability, often focusing on individual plants or basin-level impacts (Uwisengeyimana et al., 2017; Eustache et al., 2023). Others evaluate least-cost power system expansion pathways, emphasizing the role of domestic hydropower, methane extraction from Lake Kivu, and regional electricity trade (Bolson et al., 2021). Electrification-focused analyses examine progress toward universal access and the challenges of integrating variable renewables into a small and rapidly growing power system (Niyonteze et al., 2020; Gasore et al., 2021). While these studies provide valuable insights, they tend to remain sector-specific and electricity-centric. Most do not capture the full energy system, including non-electric fuels used in transport, industry, residential cooking, and services, nor do they explicitly link demand growth, hydropower availability, electricity trade, and economy-wide emissions trajectories within a single integrated framework. Moreover, scenario analyses for Rwanda rarely explore compound or multi-crisis conditions, such as the simultaneous occurrence of rapid demand growth, constrained regional imports, or droughts, that are increasingly relevant under climate change and geopolitical uncertainty.

The aim of this work is to address these gaps by developing a national-scale, multi-sector water-energy-emissions modelling framework for Rwanda. The scenario-based approach tests conditions of multi-crises and mitigation measures, integrating demand-side dynamics, supply-side options, water-sensitive hydropower constraints, and GHG emissions accounting, for the first time to our knowledge, in Rwanda. In doing so, it contributes a holistic and policy-relevant perspective on resilience and decarbonization that complements and extends the existing literature.

2. Study area

We examine Rwanda’s energy system as a single, integrated national system while explicitly representing the primary end-use sectors, namely Residential, Transportation, Industry, Services, Water supply, Wastewater, and Other. Rwanda’s power system is compact in geographic extent and modest in absolute capacity, yet rapidly evolving in response to strong population and economic growth (Bimenyimana et al., 2018). Over the past decade Rwanda has expanded electricity access and generation capacity, with a large portion of generation supplied by domestic hydropower complemented by thermal units (diesel/oil and peat) and growing contributions from lake-methane and solar PV (REG, 2022). These characteristics of rapid demand growth, strong hydropower component, nascent utility-scale solar, emerging methane generation (Lake Kivu), and routine cross-border trading and interconnections, make the country a representative of many low- and middle-income countries and a tractable case for national-scale water-energy-emissions (W-E-E) analysis. Also, Rwanda’s compact grid and clearly identifiable major plants make it feasible to represent both demand- and supply-side measures (growth, retirements, new renewables, methane development) together with cross-sectoral demand responses (residential cooking electrification, transport electrification, water-utility pumping) within a unified energy-balance framework.

For the purposes of the electricity supply analysis in this paper, the system is represented by the major system-relevant plants, which together account for the vast majority of grid capacity and annual generation (Figure 1). The principal existing plants included (REG, 2017, 2022) are: Nyabarongo I (run-of-river hydropower, 28 MW), Mukungwa (hydropower, 12 MW), Ntaruka (hydropower, 11.25 MW), Rukarara I (run-of-river hydropower, 9.5 MW) and Rukarara II (run-of-river hydropower, 5 MW); KivuWatt Phase I (Lake Kivu methane, ~26.4 MW); oil/HFO units at Jabana I & II (~27.8 MW); SoEnergy (diesel) in Kigali (~30 MW); Gishoma (peat, 15 MW); and the on-grid Rwamagana solar PV plant (8.5 MW). In addition to these commissioned units, our model considered candidate processes for utility-scale PV, utility wind, battery storage (4-hour), and combined-cycle gas turbines based on methane (CCGT_Methane_New), which represent the main plausible near-term expansion options for the national system (Bolson & Patzek, 2022).

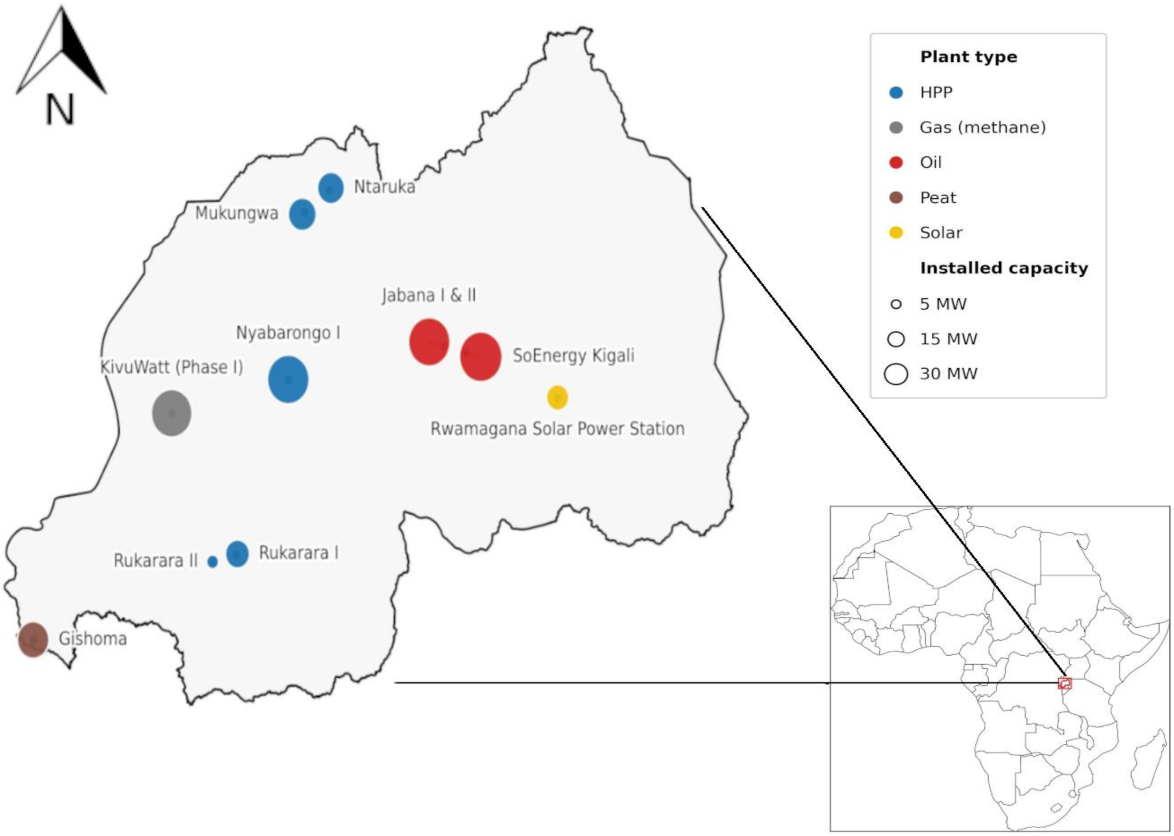

Figure 1. Rwanda's location within Africa, and the main plants used for the electricity generation analysis, per type and capacity. These represent Rwanda's largest and most system-influential generation units, while other smaller units have been aggregated for the purpose of the national scale, yet detailed model (Byers et al., 2018; Resource Watch, 2026; Rura, 2026).

Plant capacities, commissioning years and ownership were compiled from regulator/utility reports and open inventories, cross-checked against the Global Power Plant Database and national publications (Byers et al., 2018; Resource Watch, 2026; Rura, 2026; World Resources Institute, 2026). For hydropower plants we combine these nameplate capacities with hydrological-driven monthly availability constraints (derived separately; see Methods) so that both installed size and water-dependent firm energy are represented. For Lake Kivu methane generation, we use the documented capacities and public reporting for KivuWatt Phase I and other developments; the distinctive nature of Kivu methane projects (floating extraction platforms and gas-to-power units) is modelled as dedicated methane-fired processes with observed capacity and operating characteristics. Cross-border trade capacity and recent interconnection projects (for example the 220/110 kV Shango substation linking Rwanda with neighboring systems) are included to represent realistic import/export options and to test exposure to regional hydropower availability and geopolitical supply constraints.

This level of plant-specific representation is also important in relation to the existing literature focusing on the energy system of Rwanda. Previous studies have generated valuable but partial insights into the country's energy transition. Uwisengeyimana et al. (2017) provide a broad review of Rwanda's renewable energy resources, electrification targets, and key sectoral constraints, while Bisaga et al. (2019) focus on off-grid electrification, examining how the *imihigo* framework (i.e., Rwanda's performance-based local governance system) can support participation, awareness, and private-sector provision in rural areas. Mudaheranwa et al. (2021) extend the discussion toward long-term electricity planning by developing future energy scenarios to 2050, with emphasis on capacity expansion, low-carbon technologies, and regional integration, whereas Hakizimana and Umukunzi (2021) assess the implications of Rwanda's electricity plan for power-sector carbon emissions. At a broader systems level, Bolson and Patzek (2022) reconstruct Rwanda's national power flows and resource base, highlighting the centrality of biomass, the importance of electricity supply constraints, and the mismatch between domestic resource availability and long-term development ambitions.

Taken together, however, these studies remain either electricity-centric, resource-diagnostic, or access-focused. They do not examine how national shocks, such as drought-induced hydropower shortfalls or fuel price spikes, can rapidly expose trade-offs between reliability, cost, and emissions, nor do they represent all major end-use sectors within a single national energy-balance framework. To our knowledge, no previous Rwanda-focused study has jointly analyzed the residential, transportation, industry, services, water supply, wastewater, and other sectors while simultaneously tracking supply-side fuels and resources, final energy use, emissions, and the cross-sectoral consequences of policy change. Likewise, the existing literature has not combined such a whole-system perspective with a sufficiently detailed representation of existing and planned power plants to evaluate realistic future policies, or with explicit testing of green policy choices (such as electric cooking, aggressive efficiency improvements, and large renewable builds) and their system-wide effects. The present study is designed to address these gaps.

3. Methods

We apply an integrated, scenario-based modelling framework to examine the long-term interactions between energy demand, energy supply, water availability, and greenhouse gas (GHG) emissions in Rwanda at the national scale. The objective is not to identify an optimal or prescriptive pathway, nor predict the future, but to stress-test the energy system and decarbonization trajectory under alternative, internally consistent futures that reflect plausible socio-economic development, policy choices, and multi-sector crises.

3.1. Energy-system model

The modelling framework couples: i) sectoral energy demand projections; ii) a detailed representation of energy supply technologies and trade, including hydropower availability; and (iii) associated GHG emissions accounting. All components are implemented within the Low Emissions Analysis Platform

(LEAP), a widely used, transparent demand-driven scenario analysis tool for integrated energy and climate planning (Heaps, 2022). In our case, LEAP simulates sectoral final energy consumption, the supply/transformation system (power plants, storage, imports/exports), and associated GHG emissions (Table 1). Energy demand in each sector is modelled using LEAP's Final Energy Demand Analysis method (Heaps, 2022), where demand is expressed as the product of an activity level and an energy intensity (unit of energy used per typical unit of activity level). Activity levels are driven by exogenous socio-economic projections (population, GDP, sectoral output), while energy intensities and fuel shares evolve according to scenario-specific assumptions on efficiency improvements and/or electrification. This formulation allows explicit representation of demand-side policies while maintaining internal consistency across scenarios.

On the supply side, the energy system is represented through existing and candidate generation technologies, including hydropower, methane gas, oil-based thermal plants, peat, solar photovoltaics, wind, and battery storage. Existing plants are modelled as exogenous capacities based on observed inventories, such as the Global Power Plant Database, a comprehensive, open-source database of power plants around the world (Byers et al., 2018), while candidate technologies are available for endogenous expansion subject to scenario constraints. Electricity imports from regional grids are represented explicitly, allowing assessment of trade-offs between domestic generation, imports, and emissions. Next, GHG emissions are calculated endogenously within LEAP using IPCC (AR6) default emission factors, applied consistently across fuels, sectors, and transformation processes (Tian et al., 2016; Heaps, 2022). Emissions are reported both from final energy consumption and from electricity generation, enabling decomposition of demand-driven versus supply-side effects (Zou et al., 2022). Hydropower generation is treated as the primary water-dependent component of the energy system. Monthly availability constraints are imposed on hydropower plants based on historical river discharge patterns, translated into energy availability factors. This is an approach commonly used as it is straightforward, allowing hydrological variability and drought stress to propagate directly into electricity supply outcomes, without requiring a fully coupled hydrological optimization model (Carvajal et al., 2019; Stevanato et al., 2021).

Table 1. Key features, inputs, outputs, assumptions and uncertainties of the Rwanda energy model.

Primary purpose	Long-term, scenario-based integrated assessment of energy demand, supply and trade, water-sensitive hydropower availability, and GHG emissions for Rwanda. Emphasis on comparative scenario testing (what-if), governance lessons and multi-crisis resilience.
Key inputs	**Demand-side:** Sectors (Residential, Transportation, Industry, Services, Water supply, Wastewater, Other/non-specified). LEAP's Final Energy Demand method was used for each sector, calculated with the Final Energy Demand Analysis method (consumption = *activity level* × *energy intensity*) (Koundouri et al., 2025) + Demand anchors (national): World Bank/OWID energy indicators (access %, generation, consumption) (World Bank, 2023; Ritchie & Rosado, 2025) **Supply-side:** Plant inventory (nameplate MW, fuel type, commissioning year), candidate technologies (PV, wind, CCGT, battery), fuel prices, CAPEX/OPEX, storage/dispatch constraints, while monthly hydropower availability (imposed in LEAP as process max-capacity factors) derived from observed discharge timeseries (GloFAS/ERA5 reanalysis) (Heaps, 2022).

	GHG emissions are computed using standard IPCC AR6 emission factors (provided in LEAP), reported at sectoral and system levels (consumption and production basis) (IPCC, 2023).
Main outputs	Sectoral final energy by fuel and end-use, energy and electricity generation by technology, imports/exports, annual and cumulative GHG emissions (consumption & production basis), energy balances, and other cross-scenario comparable metrics (e.g., avoided emissions, avoided energy, import exposure).
Assumptions & Uncertainties	Main uncertainties: socio-economic growth (SSP variants), hydrological variability, electrification adoption rates, technology adoption rates, and policy implementation speed. These have been addressed by exploring different scenarios spanning different possible values for each uncertainty driver.

3.2. Scenario ensemble

This modelling setup was explored under different scenarios. The scenario analysis follows an exploratory, "what-if" logic rather than forecasting or optimization. Scenarios are designed to answer the question of how would Rwanda's energy-water-emissions system respond under alternative policy choices and (multi-)crisis conditions, given the same underlying socio-economic trajectory. This approach is consistent with the use of scenarios as tools for learning, robustness testing, and governance insight, rather than prediction (Börjeson et al., 2006).

All scenarios tested are anchored to Shared Socioeconomic Pathways (SSPs), which provide internally consistent projections of population and economic growth commonly used in climate and energy system analysis (Riahi et al., 2017). The baseline reference case adopts SSP2 ("Middle of the Road"), reflecting a continuation of historical development trends with moderate population growth, steady economic expansion, and incremental improvements in technology and institutions (Fricko et al., 2017). SSP2 is widely used as a neutral benchmark in policy analysis, particularly for low- and middle-income countries. Under SSP2, Rwanda's population and GDP trajectories drive substantial growth in energy demand across all sectors, reflecting ongoing electrification, urbanization, industrialization, and rising service provision (Dagnachew et al., 2023). This baseline (business-as-usual - BAU) scenario includes the existing energy generation assets and policies, but no additional demand- or supply-side interventions. Thus, the BAU serves as a counterfactual against which all alternative scenarios are evaluated. The other scenarios refer to efficiency improvements, electrification rates, renewable build-out, hydrological stress and combinations, representing structured perturbations around the baseline, spanning a plausible range of outcomes often reported in the literature, or implied by national policy discussions (Mudaheranwa et al., 2021). In total, 27 scenarios were tested (Table 2). To facilitate communication, we present them in groups (scenario families with same context):

- *BAU scenario*

This is based on SSP2 projections, with no energy system interventions.

- *Demand-side transformation scenarios*

Demand-side scenarios explore reductions in energy intensity and shifts in fuel mix through electrification of end-uses. Energy intensity improvements of 10–20% by 2030 and 25–40% by 2050 are applied across sectors in moderate and ambitious variants, respectively. These ranges are consistent with historical efficiency gains observed in developing economies undergoing structural change, as well as with international energy efficiency scenarios reported by IEA and other global assessments (IEA, 2021). Importantly, these improvements are applied relative to the SSP-driven baseline demand, meaning that absolute energy use may still increase due to economic and population growth.

Electrification scenarios for residential cooking and transportation are implemented through gradual shifts in fuel shares from oil-based fuels toward electricity. The selected shares (10–20% by 2030 and 20–40% by 2050) are not intended to represent full technology diffusion pathways, but rather to test system sensitivity to partial electrification under realistic adoption constraints, including affordability, infrastructure, and institutional capacity. These scenarios reveal how electrification can reduce direct emissions while increasing pressure on the power system, particularly under hydrological stress.

- *Supply-side transformation scenarios*

Supply-side scenarios focus on the expansion of renewable generation (solar and wind), retirement of high-emission thermal plants, and increased reliance on regional electricity trade. Annual build rates for solar and wind (10–15MW per year) reflect Rwanda's system scale and recent regional deployment experience, avoiding unrealistic step changes while still testing meaningful capacity growth.

Thermal retirement scenarios explore the implications of phasing out oil and peat generation by mid-century on emissions, while retaining a limited amount of methane-fired capacity for system security. These scenarios isolate the contribution of supply decarbonization, independent of demand growth.

Electricity import scenarios examine increased access to regional hydropower, reflecting ongoing and planned cross-border interconnections. These scenarios highlight trade-offs between domestic generation, exposure to hydrological and geopolitical risks, and emissions displacement beyond national boundaries.

- *Hydrological stress and water-energy interactions*

Hydrological scenarios are central to the water–energy nexus explored in this study. A "DrySpell" scenario is constructed by imposing multi-year reductions in hydropower availability, implemented as percentage reductions in maximum monthly generation. The magnitude of these reductions (on the order of 20–25% during stress periods) is chosen to approximate severe historical drought conditions observed in regional discharge reanalysis datasets, such as GloFAS-ERA5, while remaining conservative relative to worst-case climate projections (Harrigan et al., 2020). Rather than modelling detailed reservoir operations, this approach translates hydrological stress directly into reduced firm energy availability, allowing its system-wide consequences to be traced transparently. The hydrological representation is intentionally simplified to capture the first-order effect of drought on firm electricity supply. Complementary scenarios test alternative operating rules (environmental flow constraints) and modest efficiency improvements, illustrating how governance and technology choices can partially offset water scarcity without increasing abstraction.

- *Compound and multi-crises scenarios*

To examine sensitivity to higher development pressure and compounding crises, we also considered our scenarios under SSP5 assumptions, following the multi-crisis narrative we explore here. SSP5 represents a high-growth, energy-intensive pathway characterized by faster GDP growth and higher demand levels, providing an upper-bound stress test for infrastructure, emissions, and resource dependence (Kriegler et al., 2017). The kind of multi-crisis considered here combines multiple stressors (e.g., high population and demand growth, drought, reduced regional hydropower availability, and absence of proactive policy) to represent worst-case multi-crisis futures. These scenarios are not predictions, but deliberately pessimistic stress tests designed to expose system fragilities (Brett et al., 2025).

A corresponding “resilient net-zero under stress” scenario applies ambitious demand-side measures, rapid renewable expansion, and supply decarbonization under the same adverse conditions. Comparing these outcomes quantifies the extent to which proactive, integrated policies can mitigate the impacts of compound crises.

Table 2. Detailed description of the scenarios explored.

Code	**Family**	**Short name**	**SSP**	**Key parameter changes (concise, implementable)**
BAU	A — Baseline	BAU	SSP2	SSP2 pop & GDP; includes existing & planned plants; no additional measures
SC01	B — Intensity	Intensity_Mod	SSP2	Energy intensity −10% by 2030, −25% by 2050 (relative to BAU)
SC02	B — Intensity	Intensity_Amb	SSP2	Energy intensity −20% by 2030, −40% by 2050
SC03	C — Residential mix	Residential_Mod	SSP2	Residential oil share −10% (2030), −20% (2050); electricity share +10%/ +20%
SC04	C — Residential mix	Residential_Amb	SSP2	Residential oil share −20% (2030), −40% (2050); electricity share +20%/ +40%
SC05	C — Transport mix	Transport_Mod	SSP2	Transport oil share −10% (2030), −20% (2050); electricity share +10%/+20%
SC06	C — Transport mix	Transport_Amb	SSP2	Transport oil share −20% (2030), −40% (2050); electricity share +20%/+40%
SC07	D — Renewables	WindPV_Mod	SSP2	Add 10 MW/year wind + 10 MW/year PV from 2027 (steady annual deployments)
SC08	D — Renewables	WindPV_Amb	SSP2	Add 15 MW/year wind + 15 MW/year PV from 2027 (steady annual deployments)
SC9	D — Thermal policy	Thermal_Retire	SSP2	Retire oil & peat by 2050; cap NG (methane) at 50 MW by 2050; replace capacity with renewables
SC10	D — Imports	Hydro_Imports_Mod	SSP2	Increase regional shared hydropower imports by +5 MW/year from 2027
SC11	D — Imports	Hydro_Imports_Amb	SSP2	Increase regional shared hydropower imports by +10 MW/year from 2027

Code	Family	Short name	SSP	Key parameter changes (concise, implementable)
SC12	E — Hydrology	DrySpell	SSP2	Multi-year hydropower availability reduction: severe sequence*. Implement by reducing monthly max-availability by 5% in each year during stress years (example: −5% in the first year, -10% in the second year, …, -20% in the fourth year). We assume that “Dry spells” occur one time per decade.
SC13	E — Hydrology	Operating_Rule	SSP2	Environmental flow / operating rule: reduce hydro effective capacity by 10% from 2027 onwards (operational constraint)
SC14	E — Hydrology	Hydro_Efficiency	SSP2	Small turbine/system efficiency gains: increase Hydro_MaxAvail by +5% annual baseline (represents equipment/upgrades)
SC15	F — Combined (moderate)	All_Mod_NegHydro	SSP2	Combination: SC01 + SC03 + SC05 + SC07 + SC10 + SC09 + DrySpell (SC12)
SC16	F — Combined (ambitious)	All_Amb_NegHydro	SSP2	Combination: SC02 + SC04 + SC06 + SC10 + SC11 + SC12 + DrySpell (SC13)
SC17	F — Combined (moderate, positive hydro)	All_Mod_PosHydro	SSP2	Combination: SC01 + SC03 + SC05 + SC07 + SC10 + SC09 + Hydro_Efficiency (SC14)
SC18	F — Combined (ambitious, best case)	All_Amb_PosHydro (Best)	SSP2	Combination: SC02 + SC04 + SC06 + SC08 + SC11 + SC09 + Hydro_Efficiency (SC14)
SC19	G — High-growth variant	Intensity_Mod	SSP5	Energy intensity −10% (2030), −25% (2050). Mirrors SC01 under SSP5 drivers
SC20	G — High-growth variant	Intensity_Amb	SSP5	Energy intensity −20% (2030), −40% (2050). Mirrors SC02 under SSP5 drivers
SC21	G — High-growth variant	Residential_Mod	SSP5	Residential electrification moderate (as SC03) under SSP5 drivers
SC22	G — High-growth variant	Residential_Amb	SSP5	Residential electrification ambitious (as SC04) under SSP5 drivers
SC23	G — High-growth variant	Transport_Mod	SSP5	Transport electrification moderate (as SC05) under SSP5 drivers
SC24	G — High-growth variant	Transport_Amb	SSP5	Transport electrification ambitious (as SC06) under SSP5 drivers
SC25	G — High-growth / crisis	Hydrodiplomacy_crisis	SSP5	Reduce capacity of regional shared HPP by 50% from 2030 (sudden import constraint).
SC26	G — Worst multi-crisis	Worst_multi_crisis	SSP5	Compound worst case: SSP5 drivers + DrySpell (SC12) + Hydrodiplomacy_crisis (SC25) + no demand/supply interventions (BAU). Used to stress system limits, imports and security

Code	Family	Short name	SSP	Key parameter changes (concise, implementable)
SC27	G — Worst multi-crisis mitigated	Worst_multi_crisis_measures	SSP5	(This is the SC26 mitigated variant in your plan): SSP5 drivers + DrySpell + ambitious mitigation bundle (All_Amb_PosHydro/SC18 approaches + regional imports (SC11) maintained).

*** Note:** the DrySpell parameter (SC12) was constructed by analyzing historical discharge variability from Copernicus GloFAS/ERA5 reanalysis (Harrigan et al., 2020; Zsótér et al., 2020; Copernicus, 2024) for the major Rwanda river basins and selecting a conservative yet severe percentile-based stress signal (for example, the 5th percentile multi-year low flow translated into monthly energy reductions). In practice this is implemented in LEAP by reducing monthly hydro process max availability by a specified percent for periods of four contiguous stress years.

Model credibility was assessed through structural consistency checks and comparison with publicly available national statistics and sectoral energy indicators. Existing generation assets and plant capacities were cross-checked against public inventories and utility/regulatory sources, while national electricity access and energy trend indicators were used to verify that the baseline trajectory is within plausible bounds. The objective of this validation step is not to calibrate the model to a single historical year, but to ensure that the system representation, orders of magnitude, and relative scenario responses are consistent with observed national conditions. Across all scenarios, numerical values and percentages should be interpreted as illustrative rather than precise (they are not forecasting, but what-if exploration). Their purpose is to establish orders of magnitude, relative differences, and directional insights, rather than point estimates. By holding socio-economic drivers constant within each SSP family and varying only policy and stress parameters, the analysis isolates causal relationships and trade-offs that are directly relevant for planning and governance.

4. Results and Discussion

Given the large number of scenarios examined, Figures 1-3 present only four selected scenarios, representing the most indicative boundary cases for the analysis. Specifically, BAU is shown as the reference case under SSP2, representing continuation of current trends without additional interventions; SC18 represents the most ambitious integrated intervention package under SSP2 assumptions; SC26 represents the worst multi-crisis case under SSP5 assumptions, combining high growth, hydrological stress, and hydrodiplomacy constraints without mitigation; and SC27 represents the corresponding mitigated multi-crisis case, i.e., SC26 combined with ambitious interventions. These four scenarios therefore provide a compact but representative view of the range of outcomes identified in the wider scenario ensemble, from baseline evolution to best-case integrated transition, and from worst-case systemic stress to mitigated crisis response. Their comparison should thus be read as an illustration of the system's outer bounds under different development and policy conditions (comparative scenario outcomes), rather than as forecasts or policy prescriptions. Their main value lies in showing which levers reduce emissions growth, which levers improve resilience, and where vulnerabilities remain under stronger demand pressure and hydrological stress. In particular, the analysis indicates that demand growth dominates the long-term emissions trajectory, so no single measure is sufficient to deliver deep decarbonization on its own.

Figure 1 shows that total energy consumption increases over time in all four scenarios, despite the implementation of decarbonization and efficiency measures in the intervention cases. This reflects the strength of the underlying socio-economic drivers built into the SSP pathways. Under SSP2, GDP is assumed to grow by 398% and population by 65.5% between 2023 and 2050, while under SSP5 the corresponding increases are 788.6% and 80.6%, respectively. These growth rates place strong upward pressure on energy demand across all sectors and explain why even ambitious policy packages do not produce an absolute decline in total energy use over the full horizon. Instead, the role of interventions is to moderate the pace of growth and alter its composition. In this respect, SC18 performs substantially better than BAU, highlighting the importance of demand-side measures, especially energy efficiency improvements, in reducing total system demand under otherwise similar SSP2 conditions. Likewise, SC27 remains clearly below SC26, even though both are driven by the much more expansionary SSP5 assumptions, again demonstrating the strong moderating role of efficiency-oriented interventions.

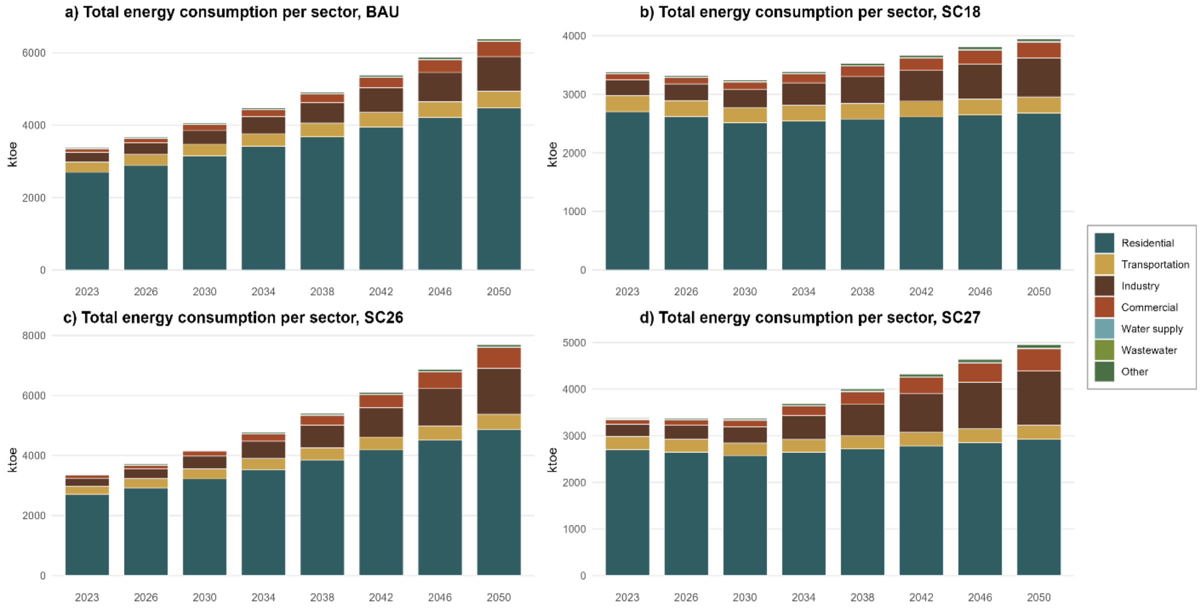

Figure 1. Total energy consumption per sector (ktoe) of BAU, SC18, SC26, SC27.

Across all cases, the residential sector remains the largest energy consumer throughout the modelling horizon, followed by transportation and industry. However, industry grows markedly over time, reflecting Rwanda's structural transformation and rising productive activity, while the services/commercial sector also expands significantly, consistent with the very strong GDP growth embedded in both SSP families. By contrast, water supply, wastewater, and the remaining minor sectors account for only a small fraction of total final energy demand in all scenarios and years. Overall, Figure 1 suggests that the central challenge for Rwanda is not whether energy demand will rise, but how rapidly it will rise, how efficiently that growth can be managed, and how the associated pressures can be absorbed without creating new vulnerabilities in supply, trade dependence, and emissions.

Figure 2 highlights substantial differences in electricity-sector evolution across the four selected cases. Under BAU, electricity generation remains broadly stable over time, consistent with the assumption that the power sector does not undergo major structural change beyond existing and already-committed assets. By contrast, under SC18 electricity generation increases strongly and approaches a near tripling by 2050, reflecting the combined effects of rising demand and accelerated electrification in key end-use sectors, especially residential cooking and transportation. A large share of this increase appears to come from solar deployment, complemented by additional hydropower and other low-carbon options. As a result, the electricity mix becomes markedly cleaner over time, with a near phase-out of the most carbon-intensive fossil technologies and a much stronger reliance on renewable sources. At the same time, this transition also introduces new system-management challenges, including greater sensitivity to renewable intermittency and continued exposure to hydrological uncertainty where hydropower remains important.

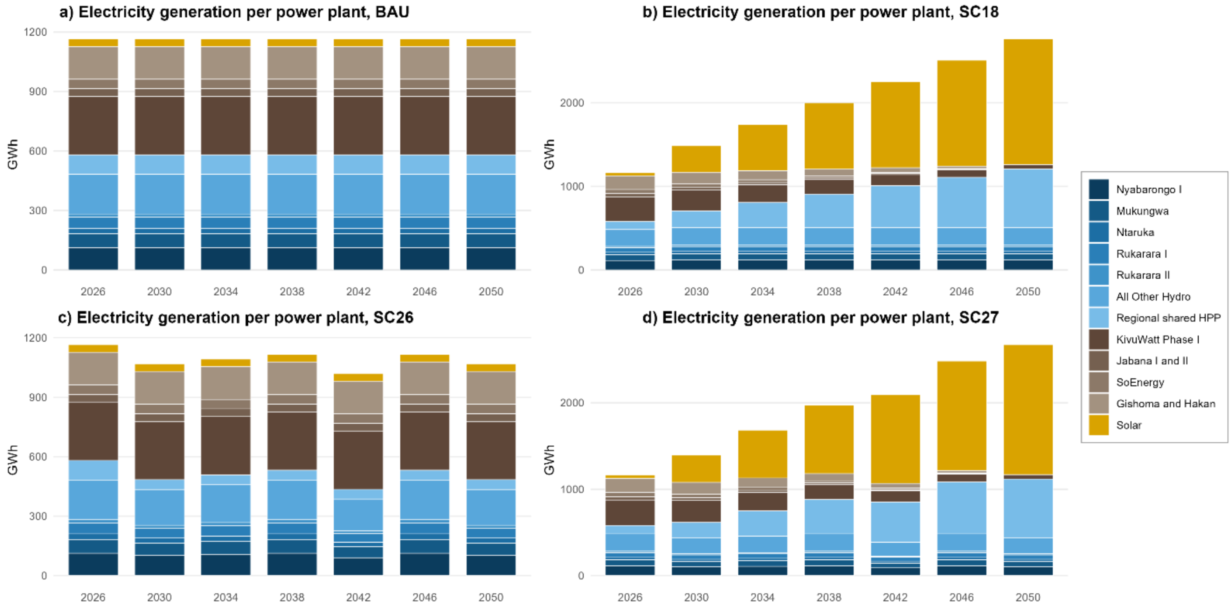

Figure 2. Total electricity generation per power plant (GWh) of BAU, SC18, SC26, SC27

The crisis scenarios further underline the role of water and regional interdependence in shaping electricity security. Under SC26, total electricity generation exhibits a more unstable trajectory, with visible fluctuations linked to reduced hydropower availability and constrained regional electricity access. This is precisely the type of compounded stress that the scenario framework was designed to reveal. Extreme weather and geopolitical or hydrodiplomatic constraints do not simply reduce one source of supply, but they destabilize the wider electricity balance and expose the system to higher import dependence and tighter security margins. Under SC27, this vulnerability is only partly mitigated, but the combined intervention package clearly improves the system's ability to cope with the same adverse context. The figure therefore suggests that decarbonization cannot be evaluated only in terms of plant additions or fuel switching, but it must also be assessed in terms of resilience to hydrological and regional shocks.

Figure 3 broadly mirrors the demand patterns described above. Total GHG emissions increase over time in all scenarios, indicating that the growth effects associated with economic expansion, demographic pressure, and structural change remain dominant over the modelling horizon. Nevertheless, the intervention scenarios achieve important relative improvements. SC18 produces substantially lower emissions than BAU, while SC27 remains well below SC26, showing that integrated policy packages can significantly slow emissions growth even under highly adverse development conditions. The key point is therefore not that Rwanda can fully decouple emissions from development under the assumptions tested here, but that the scale of the increase is highly sensitive to policy choice. Decarbonization measures matter, yet they operate against a very strong background of rising demand.

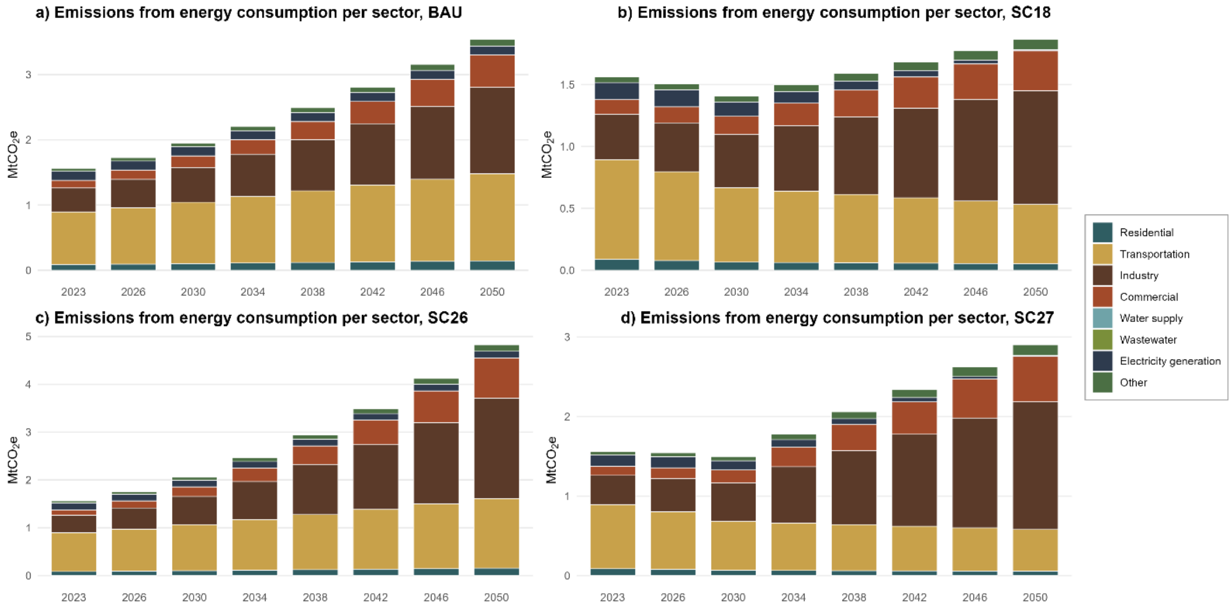

Figure 3. Total GHG emissions per sector (MtCO2) of BAU, SC18, SC26, SC27.

The sectoral composition of emissions also changes over time. While the residential sector remains a major contributor in earlier years, the industrial sector's emissions rise sharply and by 2050 overtake residential emissions, reflecting the growing weight of industrial activity in the economy and its associated fuel requirements. The services/commercial sector also records substantial emissions growth, although it remains below residential and industry over most of the time horizon. This pattern is consistent with a developing economy undergoing rapid expansion of both productive and service activities. It also implies that future mitigation strategies cannot focus only on households or electricity generation, but they must increasingly engage with industrial energy use and the energy needs of a modernizing service economy.

Under the assumptions tested here, none of the scenarios achieves net-zero emissions by 2050; instead, the strongest packages substantially reduce the rate of emissions growth and system vulnerability, but remain insufficient to fully offset the demand-driven increase in energy services.

Table 3 confirms these patterns across the full scenario ensemble. Among the standalone interventions, the energy-intensity scenarios deliver the strongest reductions in both cumulative energy consumption and cumulative GHG emissions. Under SSP2, SC02 reduces cumulative energy consumption to 98,841 ktoe and cumulative emissions to 52.4 MtCO2, compared with 134,337 ktoe and 68.4 MtCO2 in BAU. Under SSP5, SC20 also performs strongly, reducing cumulative emissions to 64.9 MtCO2 despite the much more expansionary socio-economic context. By contrast, residential electrification alone (SC03–SC04 and SC21–SC22) changes aggregate energy use only marginally and delivers only modest emissions reductions. Transport electrification has a more visible effect on emissions, especially in its ambitious form (SC06 and SC24), but on its own it does not reduce total final energy consumption. Supply-side-only scenarios mainly reshape the electricity mix and trade balance. Renewable expansion and greater imports increase cumulative electricity generation markedly, but have limited influence on total final energy demand and only modest economy-wide emissions benefits unless combined with demand-side measures. Hydrology-only scenarios (SC12–SC14) leave cumulative energy consumption and GHG emissions essentially unchanged, but they do alter domestic generation and trade requirements. The best overall outcomes are achieved in the combined scenarios, especially SC16, SC18, and SC27, which clearly outperform isolated interventions.

Table 3. KPIs per scenario

Scenarios	Total Cumulated Energy Consumption (ktoe)	Total Cumulated Energy Generation (GWh)	Total Cumulated GHG Emissions (MtCO2)
BAU	134337	32608	68.4
SC1	118142	32592	62.6
SC2	98841	32517	52.4
SC3	134338	32615	68.0
SC4	134338	32615	67.5
SC5	134338	32632	64.3
SC6	134338	32632	60.3
SC7	134338	59707	67.9
SC8	134338	51804	68.4
SC9	134338	29280	66.8
SC10	134338	36377	68.4
SC11	134338	40146	68.4
SC12	134338	31686	68.4
SC13	134338	31215	68.4
SC14	134338	33305	68.4
SC15	118141	43420	57.3
SC16	98841	51994	44.9
SC17	118141	44771	57.3
SC18	98841	53345	44.9
SC19	134112	32610	79.0
SC20	111080	32583	64.9
SC21	148314	32615	81.0
SC22	148314	32615	80.5
SC23	148308	32632	77.2
SC24	148308	32632	72.9
SC25	148271	31580	81.5
SC26	148271	30816	81.5
SC27	111081	51727	57.0

An important nuance emerges when comparing SC15/SC16 with SC17/SC18. The difference between these pairs lies primarily in electricity imports rather than in total energy consumption or GHG emissions.

SC15 and SC16 assume a negative hydrological setting (dry spell), whereas SC17 and SC18 assume a positive hydrological setting associated with improved hydropower operating conditions. Because all other power plants are already operating near full capacity throughout the period, the hydrological change mainly affects how much electricity can be produced domestically by hydropower plants. As a result, the negative hydrological cases exhibit a larger electricity trade deficit than the positive hydrological cases, even though their total energy demand and economy-wide emissions remain essentially the same. This is an important result as hydrological conditions in Rwanda do not primarily change the aggregate energy or emissions trajectory, but they do materially affect electricity security and import dependence.

Figure 4, read together with Table 3, synthesizes the main policy message of the study. The boxplots indicate that the largest and most robust reductions in both total energy consumption and total GHG emissions come from demand-side management, especially energy-efficiency improvements. Electrification measures also contribute, particularly in transportation, but on their own they tend to shift pressure onto the electricity system and can increase import requirements if not accompanied by sufficient domestic low-carbon generation. Purely supply-side measures, including renewable build-out, thermal retirement, or additional electricity imports, are valuable for decarbonizing the power mix and improving some security indicators, but they do not address the root driver of long-term pressure, namely rapidly rising final energy demand. The strongest overall performance is achieved by the combined scenarios, which integrate demand-side moderation with supply-side transformation.

From a governance perspective, such a cross-sectoral scenario analysis framework provides an invaluable tool to support decision-makers in the sustainable management of their natural resources. Model results provide an evidence-base to anchor strategic discussions amongst key stakeholders (Kalinauskaite, et. al., 2021; Akinsete et. al., 2025) the proposed framework has the potential to fundamentally support more transparent and participatory policy-making in the global south (Ackerman, 2004; UNDP, 2025). Considering the temporal sequencing of the interventions, model outputs suggests that the most rational sequencing is to begin with demand management before pursuing large-scale supply expansion. In many developing economies, policy tends to focus first on exploiting still-available natural resources or expanding installed capacity, partly because there is a perception that development requires an almost unrestricted supply response. The present results caution against that logic. A strategy centered first on consumption management and efficiency is more sustainable because it reduces the size of the system that must later be financed, built, imported, and protected against shocks. It also lowers the risk of locking the country into costly, resource-intensive, or climate-vulnerable infrastructure. Supply expansion remains necessary, especially under the strong growth assumptions considered here, but it is most effective when it follows, rather than substitutes for, demand-side discipline. In that sense, Figure 4 conveys a broader lesson beyond Rwanda: resilient decarbonization in rapidly developing countries should start from managing demand, and only then scale supply in a way that is consistent with long-term resource, climate, and security constraints.

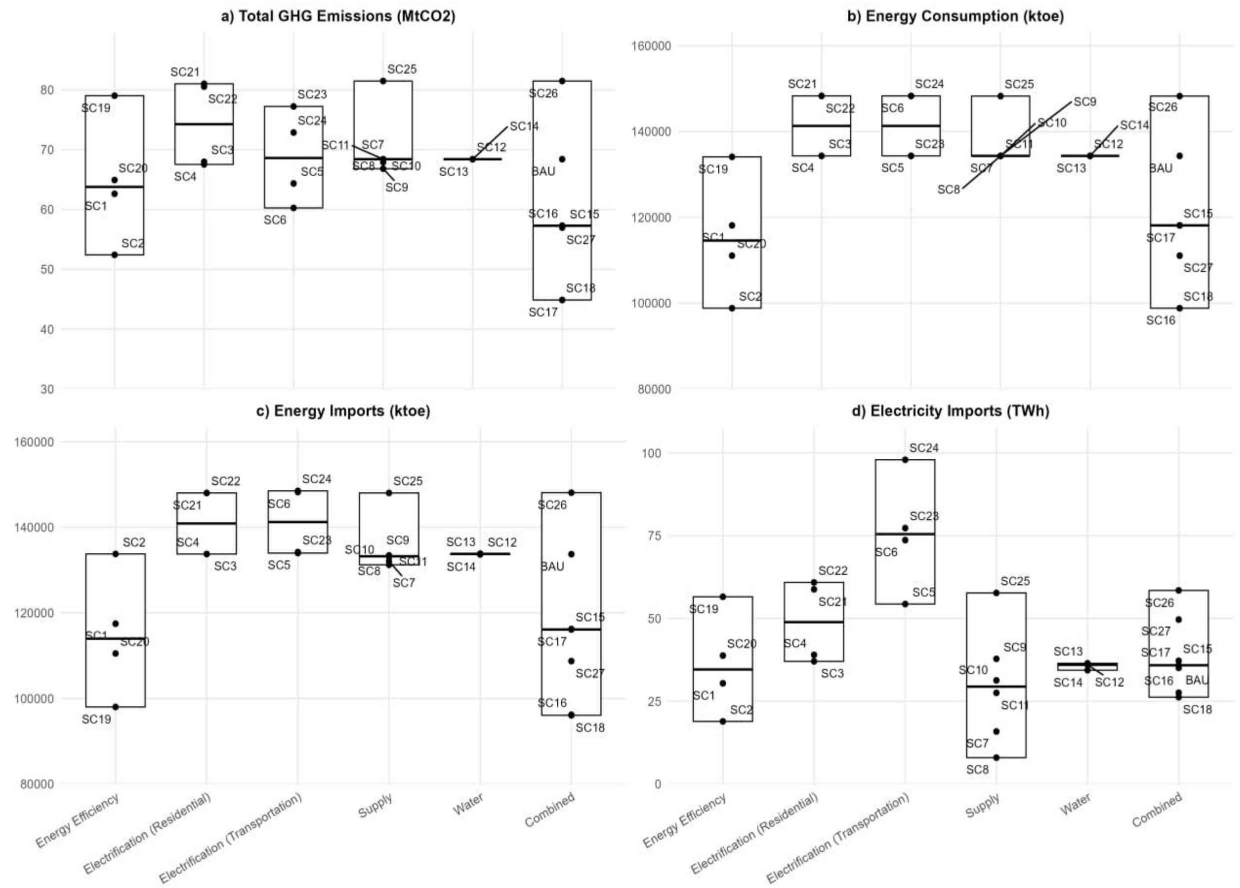

Figure 4. a) Total GHG emissions (MtCO2); b) Energy consumption (ktoe); c) Energy imports (ktoe); d) electricity imports (TWh) under all scenarios defined in Table 2. These scenarios are grouped into broader categories characterizing the type of intervention, namely interventions targeting energy efficiency, electrification in residential/transportation sector, supply side, water sector, or combinations.

The analysis presented has a few unavoidable limitations: It uses scenario-based assumptions rather than endogenous optimization; so, as mentioned, the results should be read as structured what-if comparisons rather than point forecasts. Hydropower stress is represented through availability constraints rather than detailed reservoir operations, and the treatment of candidate technologies reflects current planning knowledge rather than future market learning. However, these limitations are offset by the model's transparency, its full-sector coverage, and the breadth of scenarios tested, which together provide robust comparative insights for planning.

Conclusion

This paper presented a cross-sectoral scenario-analysis framework for water–energy–emissions (W–E–E) modelling, applied to Rwanda, with the explicit aim of stress-testing energy system performance and decarbonization pathways under compound and multi-crises conditions through 2050. By integrating sectoral energy demand, a detailed representation of supply and trade, water-constrained hydropower availability, and GHG emissions accounting, the analysis provides a holistic perspective on system resilience and climate mitigation.

The analyzed trade-offs are broadly consistent with findings from the wider energy and climate literature, particularly in highlighting the dominant role of demand growth in driving long-term emissions and the limited effectiveness of supply-side measures when implemented in isolation (Kyle & Kim, 2011; Golfam et al., 2024). Moreover, this study fills an important gap in the Rwanda-focused literature by explicitly linking demand-side dynamics, hydrological variability, electricity trade, and economy-wide emissions within a single framework that allowed us to quantify their trade-offs, especially under compound crisis scenarios rather than isolated shocks. Across all scenarios, emissions growth remains largely demand-driven, reflecting increases due to rapid population and economic expansion. Even under ambitious supply-side interventions (such as accelerated renewable deployment, thermal plant retirements, or increased regional electricity imports), emissions continue to rise relative to current levels. Demand-side measures, particularly energy efficiency improvements and partial electrification of end-uses, consistently deliver larger emissions reductions than supply-only strategies. However, the strongest mitigation and resilience outcomes emerge only when demand-side and supply-side measures are combined, underscoring the importance of integrated policy packages rather than single-instrument approaches. Overall, the results suggest that the pathway ahead is unlikely to be optimistic without substantially stronger action. Under rapid economic and population growth, reducing emissions without creating unintended pressures on affordability, reliability, and broader development systems will be extremely difficult, particularly in lower-income countries with limited fiscal and technological capacity. In this context, slower progress toward emissions-control in developing countries should not be interpreted as a failure of development, but as a reflection of unequal starting points, unequal capacities, and the structural need for international support in order to pursue decarbonization without undermining other development priorities. If net-zero is pursued as a global commons objective, then high-income countries must contribute practical support (through concessional finance, technology transfer, and institutional capacity building) such that mitigation can proceed in a manner that is both effective and equitable (Fujimori et al., 2026).

Hydrological variability emerges as a critical factor that should be considered in the future energy mix. To avoid systemic risks, we should avoid over-reliance on a main source of energy. Instead, a flexible mix should be sought. This conclusion is supported by the finding that hydrological stress remains a binding vulnerability even under combined intervention scenarios that might improve system performance, but they do not eliminate exposure to drought-related reductions in hydropower generation, continued emissions growth under rising demand, or a larger electricity trade deficit when domestic hydro availability falls. While changes in hydropower availability do not substantially alter total energy consumption or economy-wide emissions (since other generation technologies compensate, and that should be a goal to maintain and further strengthen in the future), they have a pronounced effect on electricity trade balances and import dependence. Under dry or constrained hydrological conditions, Rwanda becomes significantly more reliant on electricity imports, increasing exposure to regional supply risks and geopolitical uncertainty. Conversely, positive hydrological conditions or modest efficiency improvements in hydropower operations can substantially reduce import needs, even without changing overall emissions trajectories. These findings highlight water not merely as an environmental constraint, but as a central determinant of energy security and system resilience.

Unavoidably, the study comes with certain (and necessary) limitations, which we acknowledge, along with the ways to overcome each one. First, the analysis relies on scenario-based assumptions, testing the basic cross-system responses. Therefore, the results should be interpreted as relative insights rather than precise forecasts. Second, hydrological impacts are represented through reduced production capacity factors rather than fully coupled reservoir optimization models, trading operational detail for transparency and tractability. However, as mentioned, this was a preliminary assessment, and the goal was to understand these trade-offs. Our ongoing and future research includes more solutions-oriented approaches, such as optimization and more explicit hydrological modelling. At the moment these limitations have been addressed by exploring a quite wide range of consistent scenarios, capturing different measures and effects, and emphasizing comparative results rather than point estimates.

Beyond the Rwanda case, the framework is designed to be transferable. By combining explicit demand modelling, water-sensitive hydropower constraints, and integrated emissions accounting within a transparent scenario structure, the approach can be readily adapted to other countries facing similar development pressures and climate risks. While parameters and system characteristics will vary, the governance lessons are also broadly applicable: prioritization of demand management and flexibility, institutionalization of crisis-aware planning rules, and explicit integration of water constraints into long-term energy strategies, are insightful lessons learned from this exercise. Furthermore, the framework is well-suited to participatory frameworks which encourage stakeholder discourse, negotiation and transparency. This proves that the findings of this work point to a challenging but instructive reality: In rapidly developing economies, emissions are likely to rise in the near to medium term despite ambitious policy efforts, particularly under crisis conditions. Water scarcity and climate variability further constrain options and amplify trade-offs. Yet crises also act as stress tests and laboratories for innovation. When planners adopt integrated W–E–E scenario analysis, they can move from reactive responses toward proactive governance, building energy systems that are both lower-carbon and more resilient to the complex crises of the future.

References

Ackerman, J. (2004), Social Accountability in the public sector: A conceptual framework. Social Development Papers, 82, 1-32.

Akinsete, E., Papadaki, L., Koundouri, P. Black Sea Blue Transitions: Multi-actor Forums to Promote a Sustainable Blue Economy. *In: Amer, M., El Kaftangui, M., Maarouf, I.ES., Khalid, N., Dol, S.S.B. (eds) Territorial Landscapes Solutions for Sustainable Energy and Food Security. ICASF 2023. Sustainable Landscape Planning and Natural Resources Management. Springer, Cham. 2025* https://doi.org/10.1007/978-3-031-82419-7_6

Alamanos, A., & Koundouri, P. (2022). Emerging Challenges and the Future of Water Resources Management. *Hydrolink 2022-4, Citizen Science*. https://www.iahr.org/library/infor?pid=22131

Bataille, C., Waisman, H., Briand, Y., Svensson, J., Vogt-Schilb, A., Jaramillo, M., Delgado, R., Arguello, R., Clarke, L., Wild, T., Lallana, F., Bravo, G., Nadal, G., Le Treut, G., Godinez, G., Quiros-Tortos, J., Pereira, E., Howells, M., Buira, D., … Imperio, M. (2020). Net-zero deep decarbonization pathways in Latin America: Challenges and opportunities. *Energy Strategy Reviews*, *30*, 100510. https://doi.org/10.1016/j.esr.2020.100510

Bimenyimana, S., Asemota, G. N. O., & Li, L. (2018). The State of the Power Sector in Rwanda: A Progressive Sector With Ambitious Targets. *Frontiers in Energy Research*, *6*. https://doi.org/10.3389/fenrg.2018.00068

Bisaga, I., Parikh, P., Mulugetta, Y., & Hailu, Y. (2019). The potential of performance targets (imihigo) as drivers of energy planning and extending access to off-grid energy in rural Rwanda. *WIREs Energy and Environment*, *8*(1), e310. https://doi.org/10.1002/wene.310

Bolson, N., & Patzek, T. (2022). Evaluation of Rwanda's Energy Resources. *Sustainability*, *14*(11), 6440. https://doi.org/10.3390/su14116440

Bolson, N., Yutkin, M., & Patzek, T. (2021). Energy efficiency and sustainability assessment for methane harvesting from Lake Kivu. *Energy*, *225*, 120215. https://doi.org/10.1016/j.energy.2021.120215

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, *38*(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Brett, L., White, C. J., Domeisen, D. I. V., van den Hurk, B., Ward, P., & Zscheischler, J. (2025). Review article: The growth in compound weather and climate event research in the decade since SREX. *Natural Hazards and Earth System Sciences*, *25*(8), 2591–2611. https://doi.org/10.5194/nhess-25-2591-2025

Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., … Riahi, K. (2018). Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*, *13*(5), 055012. https://doi.org/10.1088/1748-9326/aabf45

Byers, L., Friedrich, J., Hennig, R., Kressig, A., Li, X., Valeri, L. M., & McCormick, C. (2018). *A Global Database of Power Plants*. https://www.wri.org/research/global-database-power-plants

Carvajal, P. E., Li, F. G. N., Soria, R., Cronin, J., Anandarajah, G., & Mulugetta, Y. (2019). Large hydropower, decarbonisation and climate change uncertainty: Modelling power sector pathways for Ecuador. *Energy Strategy Reviews*, *23*, 86–99. https://doi.org/10.1016/j.esr.2018.12.008

Copernicus. (2024). *River discharge and related historical data from the Global Flood Awareness System*. https://ewds.climate.copernicus.eu/datasets/cems-glofas-historical?tab=overview

Dagnachew, A. G., Choi, S.-M., & Falchetta, G. (2023). Energy planning in Sub-Saharan African countries needs to explicitly consider productive uses of electricity. *Scientific Reports*, *13*(1), 13007. https://doi.org/10.1038/s41598-023-40021-y

Englezos, N., Kartala, X., Koundouri, P., Tsionas, M., & Alamanos, A. (2023). A Novel HydroEconomic—Econometric Approach for Integrated Transboundary Water Management Under Uncertainty. *Environmental and Resource Economics*, *84*(4), 975–1030. https://doi.org/10.1007/s10640-022-00744-4

Eustache, H., Wali, U. G., & Venant, K. (2023). Understanding the Potential Impact of Climate Change on Hydropower Generation in Rwanda. *Green and Low-Carbon Economy*, *1*(3), 138–146. https://doi.org/10.47852/bonviewGLCE3202762

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

Fujimori, S., Fan, L., Zhao, S., Asayama, S., Hasegawa, T., Nishiura, O., Shiraki, H., & Takahashi, K. (2026). International financial support to achieve the net-zero emissions goal could help resolve equity trade-off between developing and developed countries. *Communications Earth & Environment*, *7*(1), 118. https://doi.org/10.1038/s43247-026-03208-5

Gasore, G., Ahlborg, H., Ntagwirumugara, E., & Zimmerle, D. (2021). Progress for On-Grid Renewable Energy Systems: Identification of Sustainability Factors for Small-Scale Hydropower in Rwanda. *Energies*, *14*(4), 826. https://doi.org/10.3390/en14040826

Golfam, P., Ashofteh, P.-S., & Loáiciga, H. A. (2024). Forecasting long-term energy demand and reductions in GHG emissions. *Energy Efficiency*, *17*(3), 19. https://doi.org/10.1007/s12053-024-10203-2

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Hakizimana, A. K., & Umukunzi, C. (2021). Potential Impact of Rwanda Energy Plan on Carbon Emissions from Electricity Generation. *Journal of Economics and Sustainable Development*, *12*(6). https://doi.org/10.7176/JESD/12-6-01

Harrigan, S., Zsoter, E., Alfieri, L., Prudhomme, C., Salamon, P., Wetterhall, F., Barnard, C., Cloke, H., & Pappenberger, F. (2020). GloFAS-ERA5 operational global river discharge reanalysis 1979–present. *Earth System Science Data*, *12*(3), 2043–2060. https://doi.org/10.5194/essd-12-2043-2020

Heaps, C. G. (2022). *LEAP: The Low Emissions Analysis Platform* (Version 2024.1.1.15) [Computer software]. Stockholm Environment Institute. https://leap.sei.org

IEA. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. IEA. https://www.iea.org/reports/net-zero-by-2050

IPCC (Ed.). (2023). Energy Systems. In *Climate Change 2022—Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 613–746). Cambridge University Press. https://doi.org/10.1017/9781009157926.008

Iyiola, A. O., Afolabi, O. A., Alimi, S. K., Akingba, O. O., Izah, S. C., & Ogwu, M. C. (2024). Climate Change and Water Crisis in the Global South. In S. C. Izah, M. C. Ogwu, A. Loukas, & H. Hamidifar (Eds), *Water Crises and Sustainable Management in the Global South* (pp. 111–140). Springer Nature. https://doi.org/10.1007/978-981-97-4966-9_4

Kalinauskaite, I., Brankaert, R., Lu, Y., Bekker, T., Brombacher, A., & Vos, S. Facing Societal Challenges in Living Labs: Towards a Conceptual Framework to Facilitate Transdisciplinary Collaborations. Sustainability. 2021, 13(2), 614. https://doi.org/10.3390/su13020614

Koundouri, P., Alamanos, A., Arampatzidis, I., Devves, S., Dellis, K., & Deranian, C. (2025). Assessing national climate-neutrality plans through a modelling nexus lens: The case of Greece. *Npj Climate Action*, *4*(1), 113. https://doi.org/10.1038/s44168-025-00318-2

Koundouri, P., Alamanos, A., Devves, S., Landis, C., & Dellis, K. (2024). Innovations for Holistic and Sustainable Transitions. *Energies*, *17*(20), 5184. https://doi.org/10.3390/en17205184

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., … Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Kyle, P., & Kim, S. H. (2011). Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. *Energy Policy*, *39*(5), 3012–3024. https://doi.org/10.1016/j.enpol.2011.03.016

McCollum, D. L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., … Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, *3*(7), 589–599. https://doi.org/10.1038/s41560-018-0179-z

Mudaheranwa, E., Masengo, G., Odoakah, Y. O., Cipcigan, L., & Ugalde-Loo, C. E. (2021). *Development of Rwanda's Future Energy Scenarios for Long-Term Investment and Planning*. 1124–1129. https://doi.org/10.1109/AEEES51875.2021.9403043

Niyonteze, J. D. D., Zou, F., Norense Osarumwense Asemota, G., Bimenyimana, S., & Shyirambere, G. (2020). Key technology development needs and applicability analysis of renewable energy hybrid technologies in off-grid areas for the Rwanda power sector. *Heliyon*, *6*(1), e03300. https://doi.org/10.1016/j.heliyon.2020.e03300

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews*, *33*, 74–86. https://doi.org/10.1016/j.rser.2014.02.003

REG. (2017). *Gishoma 15 MW Peat to Power Project*. Rwanda Energy Group. https://www.reg.rw/what-we-do/projects/project-details/view/gishoma-15-mw-peat-to-power-project/category/peat/

REG. (2022). *Annual Report for Rwanda Energy Group for the Year 2021-2022*. Rwanda Energy Group. https://www.reg.rw/fileadmin/user_upload/REG_Annual_report_2021-2022.pdf

Resource Watch. (2026). *Global Power Plant Database*. https://resourcewatch.org/data/explore/Powerwatch

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., Cuaresma, J. C., 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., & Rosado, P. (2025). Energy. *Our World in Data*. https://ourworldindata.org/profile/profile/energy/rwanda

Rura. (2026). *Rwanda Utilities Regulatory Authority*. https://www.rura.rw/

Sinha, S. K., Davis, C., Gardoni, P., Babbar-Sebens, M., Stuhr, M., Huston, D., Cauffman, S., Williams, W. D., Alanis, L. G., Anand, H., & Vishwakarma, A. (2023). Water sector infrastructure systems resilience: A social–ecological–technical system-of-systems and whole-life approach. *Cambridge Prisms: Water*, *1*, e4. https://doi.org/10.1017/wat.2023.3

Stevanato, N., Rocco, M. V., Giuliani, M., Castelletti, A., & Colombo, E. (2021). Advancing the representation of reservoir hydropower in energy systems modelling: The case of Zambesi River Basin. *PLOS ONE*, *16*(12), e0259876. https://doi.org/10.1371/journal.pone.0259876

Tian, L., Ding, Z., Wang, Y., Duan, H., Wang, S., Tang, J., & Wang, X. (2016). Analysis of the Driving Factors and Contributions to Carbon Emissions of Energy Consumption from the Perspective of the Peak Volume and Time Based on LEAP. *Sustainability*, *8*(6), 513. https://doi.org/10.3390/su8060513

Trutnevyte, E., McDowall, W., Tomei, J., & Keppo, I. (2016). Energy scenario choices: Insights from a retrospective review of UK energy futures. *Renewable and Sustainable Energy Reviews*, *55*, 326–337. https://doi.org/10.1016/j.rser.2015.10.067

Turner, S. W. D., Hejazi, M., Kim, S. H., Clarke, L., & Edmonds, J. (2017). Climate impacts on hydropower and consequences for global electricity supply investment needs. *Energy*, *141*, 2081–2090. https://doi.org/10.1016/j.energy.2017.11.089

UNDP (2025) Why strong institutions, transparency and inclusive leadership are key to delivering climate solutions at COP30 and beyond. [Online] Available: https://www.undp.org/blog/why-strong-institutions-transparency-and-inclusive-eadership-are-key-to-delivering-climate-solutions-at-COP30-and-beyond

Uwisengeyimana, J. de D., Teke, A., & Ibrikci, T. (2017). Current Overview of Renewable Energy Resources in Rwanda. *Journal of Energy and Natural Resources*, *5*(6), 92–97. https://doi.org/10.11648/j.jenr.20160506.13

van der Heijden, K. (1996). *Scenarios: The art of strategic conversation*. Chichester, UK: Wiley.

van Vliet, M. T. H., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, *6*(4), 375–380. https://doi.org/10.1038/nclimate2903

van Vuuren, D. P., Kriegler, E., O’Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., & Winkler, H. (2014). A new scenario framework for Climate Change Research: Scenario matrix architecture. *Climatic Change*, *122*(3), 373–386. https://doi.org/10.1007/s10584-013-0906-1

World Bank. (2023). *Access to electricity (% of population)—Rwanda*. World Bank Open Data. https://data.worldbank.org

World Resources Institute. (2026). *Global Power Plants Dataset*. https://datasette.io/global-power-plants?p0=Rwanda&sql=select+rowid%2C+country%2C+country_long%2C+name%2C+gppd_idnr%2C+capacity_mw%2C+latitude%2C+longitude%2C+primary_fuel%2C+other_fuel1%2C+other_fuel2%2C+other_fuel3%2C+commissioning_year%2C+owner%2C+source%2C+url%2C+geolocation_source%2C+wepp_id%2C+year_of_capacity_data%2C+generation_gwh_2013%2C+generation_gwh_2014%2C+generation_gwh_2015%2C+generation_gwh_2016%2C+generation_gwh_2017%2C+generation_data_source%2C+estimated_generation_gwh+from+%5Bglobal-power-plants%5D+where+%22country_long%22+%3D+%3Ap0+order+by+latitude+limit+101

Xu, L., Feng, K., Lin, N., Perera, A. T. D., Poor, H. V., Xie, L., Ji, C., Sun, X. A., Guo, Q., & O'Malley, M. (2024). Resilience of renewable power systems under climate risks. *Nature Reviews Electrical Engineering*, *1*(1), 53–66. https://doi.org/10.1038/s44287-023-00003-8

Zou, X., Wang, R., Hu, G., Rong, Z., & Li, J. (2022). CO2 Emissions Forecast and Emissions Peak Analysis in Shanxi Province, China: An Application of the LEAP Model. *Sustainability*, *14*(2), 637. https://doi.org/10.3390/su14020637

Zsótér, E., Cloke, H. L., Prudhomme, C., Harrigan, S., de Rosnay, P., Munoz-Sabater, J., & Stephens, E. (2020). *Trends in the GloFAS-ERA5 river discharge reanalysis* (Technical Report No. 871). ECMWF Technical Memoranda. 10.21957/p9jrh0xp