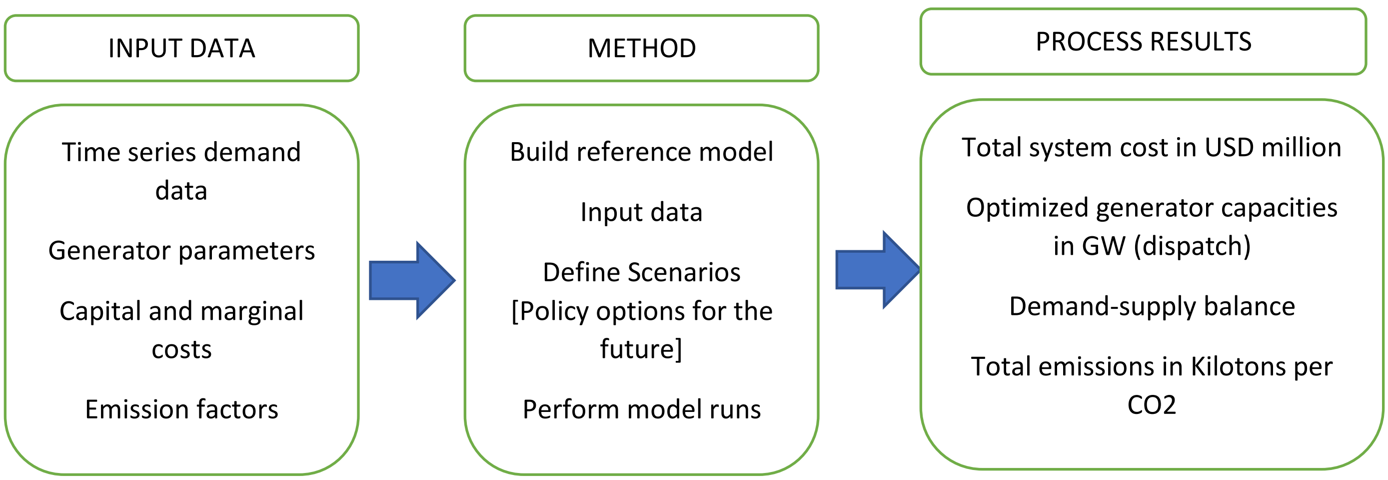
Evaluating policy options for decarbonizing future energy systems in Ghana

Background

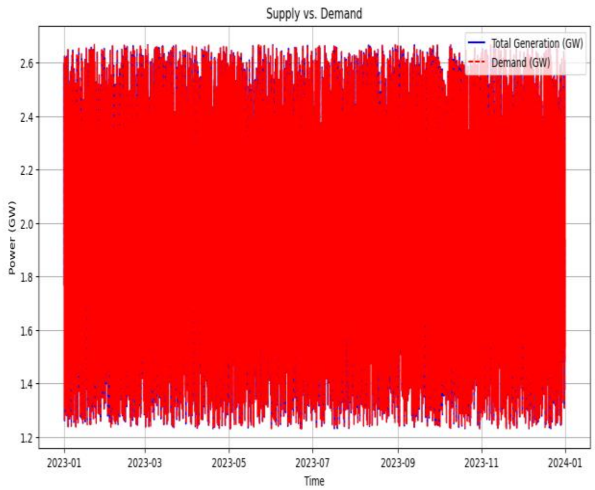
In this study, I used a bottom-up energy system-modelling tool – PYPSA to evaluate policy options for future energy systems in Ghana. A reference energy system was modelled and compared to 3 different policy options under different key indicators. This includes the total system cost in USD million, optimized generator capacities in GW (dispatch), demand-supply balance, total emissions in Kilotons per CO2. The figure below shows an overview of the method used in the study.

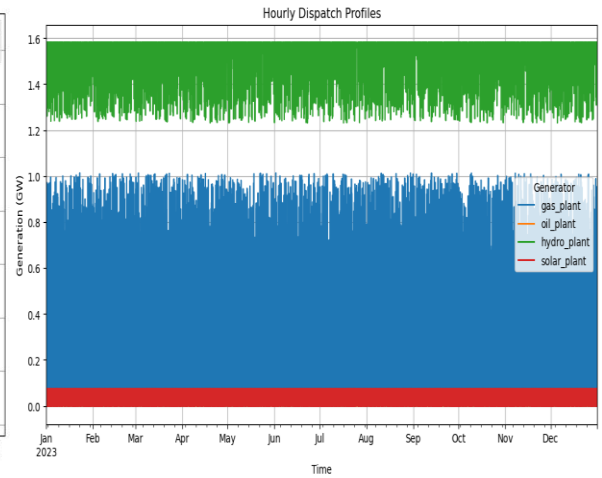


Baseline Model

For the baseline model, I started by inputting the data into the network. This comprised of electricity demand data in hourly resolutions. The demand data was aggregated for the whole country, with an average peak demand of 3469 MW, off peak demand of 1500 MW and annual demand of 17 TWh. Other components such as the Bus, load and generator parameters was added. For this model, only one bus was considered – the electricity bus. The load [demand data] was connected to this bus. Based on Ghana power plant portfolios as of 2023, four types of generators were considered in this scenario. These are oil, gas, hydro and solar. For each, their nominal capacity, capital costs, marginal costs, emission factors and efficiencies were inputted. After building the model, I optimized the networks operation aiming to minimize the total system cost (generation + investment + operational costs) while meeting hourly electricity demand.

Results showed that the total system cost of the electricity network operation and infrastructure was 153.4 million dollars. This is the minimum total cost required to meet hourly electricity demand in relation to the demand data. This could increase if the scenario included additional network costs such as transmission and storage. The model produced hourly generation profiles for four types of generators: gas plants, oil plants, hydro plants, and solar plants. The total annual generation and individual contributions from each generator are as follows (dispatch): Gas Plant: 3.071698 GW, Oil Plant: 0.000000 GW (inactive), Hydro Plant: 13.441900 GW & Solar Plant: 0.486402 GW. Hydro plants dominated the generation mix, accounting for a significant share of the total generation. Gas plants provided supplementary generation, while solar plants made a minimal contribution. Oil plants were not utilized, likely due to the high costs of operation. The system effectively met demand under the base scenario and the total (CO_2) emissions produced by all generators in the PyPSA network over the simulation period was 614.3 kt per CO2.



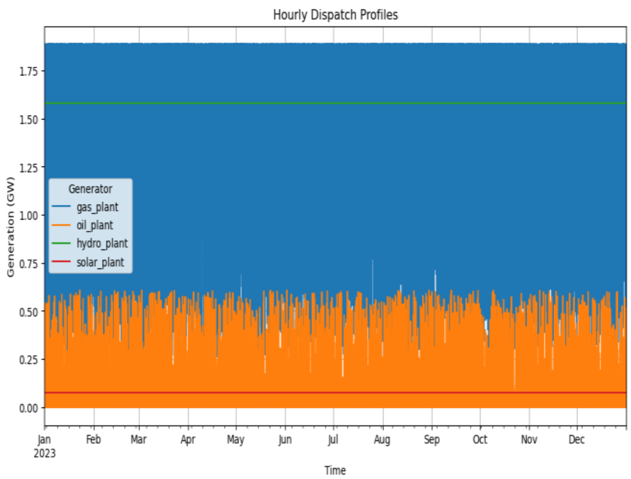


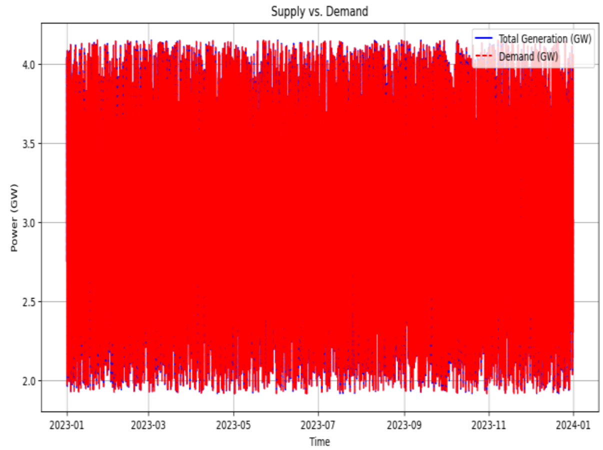
Scenario 1 – [Using Natural gas as a transition fuel for electricity production, industrial heating, and transport].

Natural gas has been identified as a transition fuel as it is cleaner than other hydrocarbons. The government of Ghana aims to invest in the sustainable use and development of natural gas infrastructure. Hence, I explore how it will affect Ghana's future energy system. In this scenario, due to challenges in getting time variable demand for the industrial heating and transport sectors, I used an average value for their demands that remained constant. The constant demand throughout the year for each hour in the industrial heating sector was 500MW and for the transport sector was 200 MW. The demand for all sectors in 2030 was 26.5 TWh. This is based on projections from the Energy Commission in Ghana. The idea was to find out if the gas plants in the baseline model would be sufficient or if there is a need to develop more natural gas power plants by 2030 to serve as a transition fuel.

The total system cost rose significantly from \$153.58M to \$632.79M due to higher utilization of the gas plant for industrial heating and transport demands. This reflects the increased operational costs associated with natural gas. Total CO_2 emissions jumped from 614.33 kt to 2,432.50 kt. This increase is a direct result of greater reliance on the gas plant, which has a higher carbon intensity than hydro and solar. I noticed a generation mix shift. Gas plant generation increased dramatically from 3.07 TWh to 11.25 TWh, making it the dominant source in the natural gas scenario. Hydro generation increased slightly (+0.40 TWh), while solar's contribution increased by a marginal 0.16 TWh due to its smaller installed capacity. Oil plants, which were inactive in the baseline scenario, contributed 0.70 TWh due to the additional load demand. The contributions of hydro and solar remained relatively stable as their capacities did not change. Hydro plants retained a significant role in meeting base demand due to their low marginal cost.

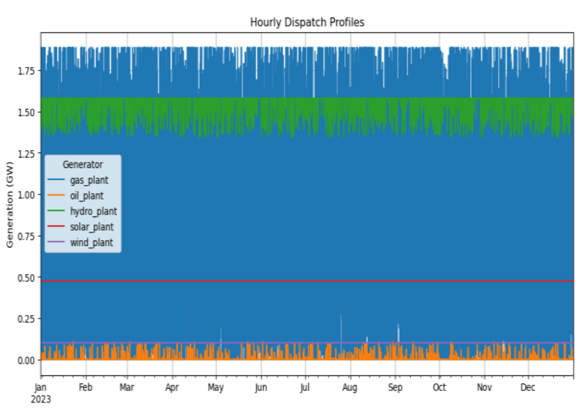
While natural gas increased generation, and met industrial, and transport demand, it significantly raised system costs and emissions. This showed the trade-off between using natural gas as a transitional energy source and meeting climate goals. The natural gas scenario highlights the carbon intensity of relying on fossil fuels, emphasizing the need for carbon capture or transitioning to renewables to minimize emissions. The rise in costs indicates that a transition strategy involving natural gas requires careful consideration of long-term financial and environmental impacts.

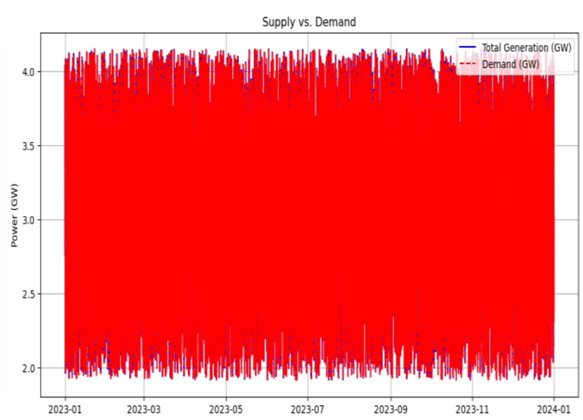




Scenario 2 – [Increase the share of renewables in the energy generation mix + Natural Gas].

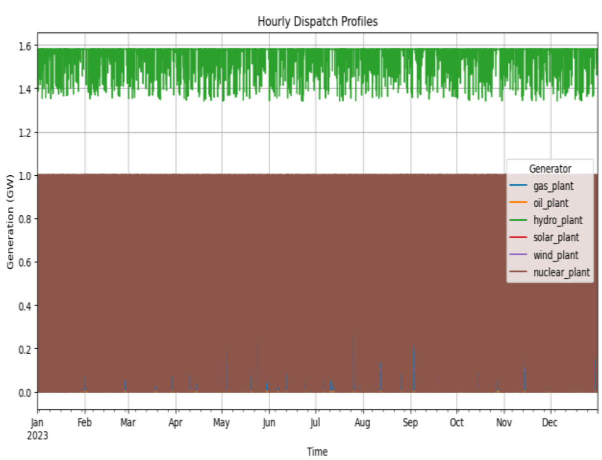
Ghana aims to diversify its energy mix by increasing the share of renewables, to curb carbon emissions. Several projects are set to be completed in 2030. Ghana aims to add an installed capacity of 400MW from solar and 100MW from wind in the year 2030. This is modelled as a scenario. Increasing renewables to the Natural Gas reduces emissions compared to the Natural Gas Scenario in Isolation (from 2,432.50 kt to 1,538.43 kt), but the costs remain higher than the Baseline scenario. This shows that integrating renewables lowers reliance on fossil fuels but requires higher upfront investments. The gas plant generation reduced with the increase of RE compared to the Natural Gas Scenario (11.25 TWh to 7.66 TWh), indicating a shift to renewable sources. Solar and wind plants play a more significant role in meeting demand in the Renewables Scenario, contributing a combined 5.03 TWh (29.4% of total generation). This contrasts with the Baseline, where solar contributed only 0.49 TWh, and wind was absent from the model. Hydro's contribution remains stable across scenarios, showing its role as a reliable renewable baseload source. Compared to the Natural Gas Scenario, emissions reduced significantly (-894.07 kt), emphasizing the environmental benefits of renewable integration. While renewable integration increases costs compared to the Baseline, it is significantly cheaper than relying heavily on natural gas.

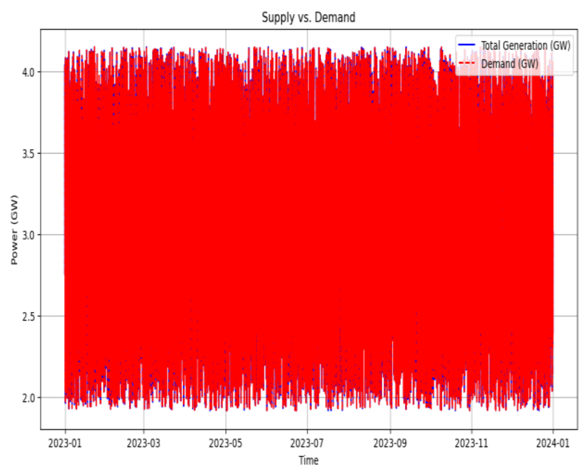




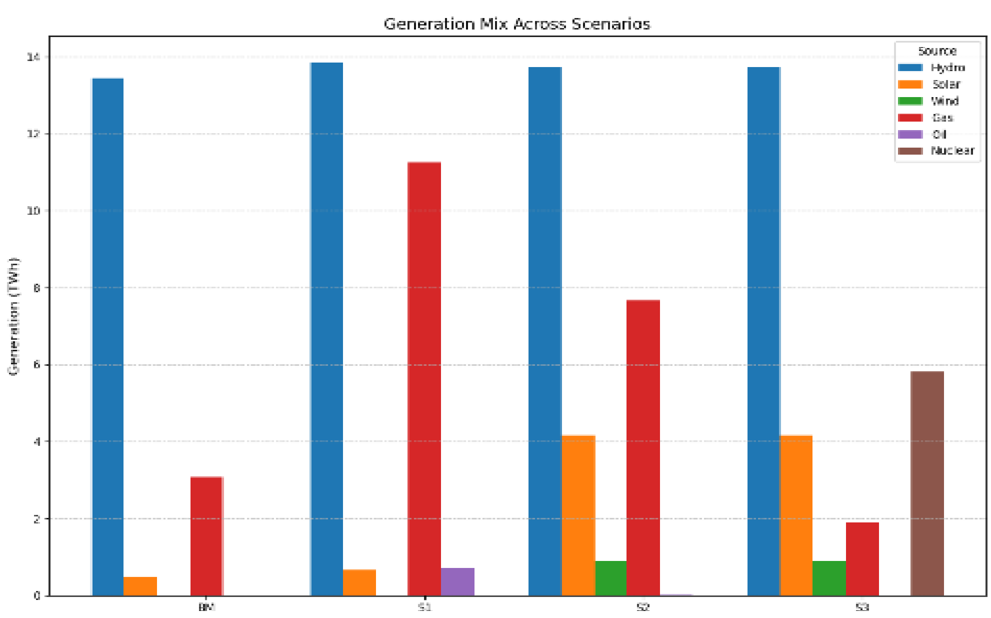
Scenario 3 – [Introduce and increase the share of nuclear in the energy generation mix to aid RE and Natural Gas].

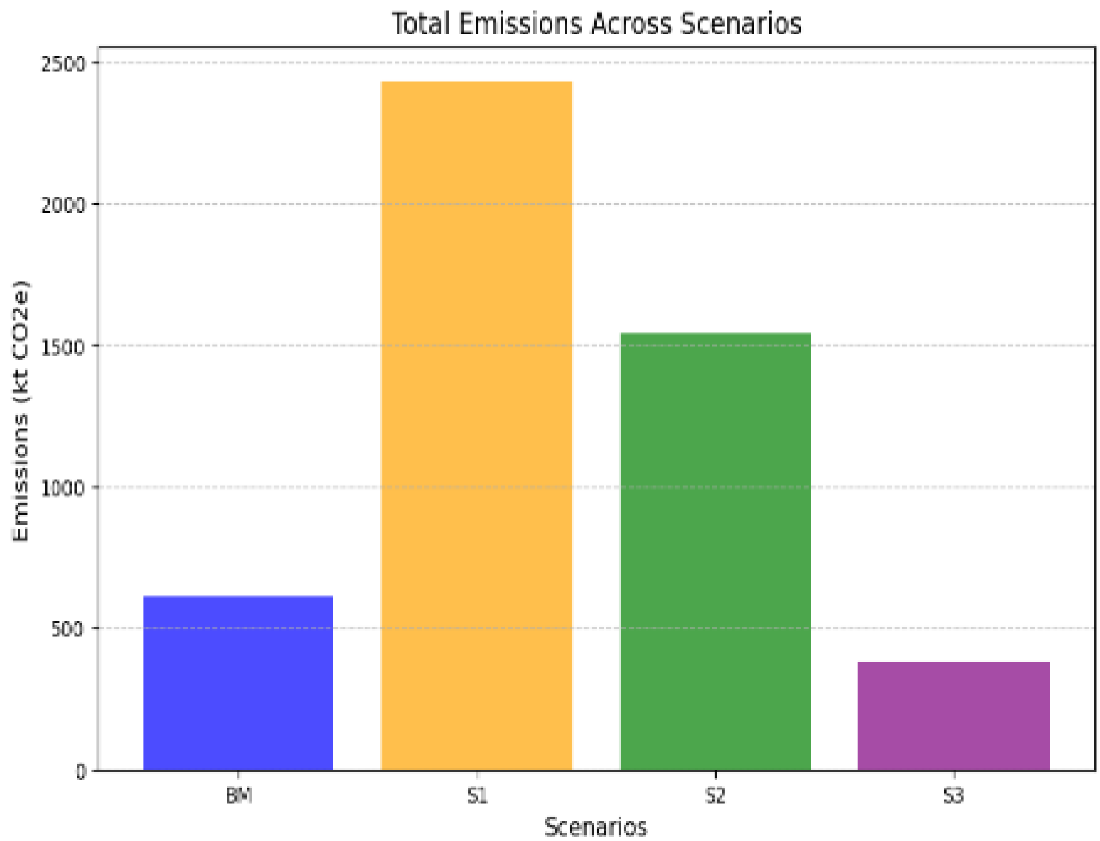
Nuclear Energy is a clean form of Energy that can serve as a baseload power to help achieve net-zero electricity production, diversify the energy generation mix and ensure energy security. As a result, Ghana aims to establish a 1 GW nuclear plant by 2030 to diversify the electricity system. This was modeled in this scenario in addition to natural gas and RE. I realized that adding a 1GW nuclear plant by 2030 reduces the total cost of the system (152.32), even than the baseline model (153.58). Emissions in this scenario are significantly reduced compared to the baseline, with only 377.35 kt of emissions, showcasing nuclear energy's potential for decarbonization. The addition of 1 GW of nuclear capacity provides 5.8 TWh of energy, reducing the reliance on gas and other thermal generators.

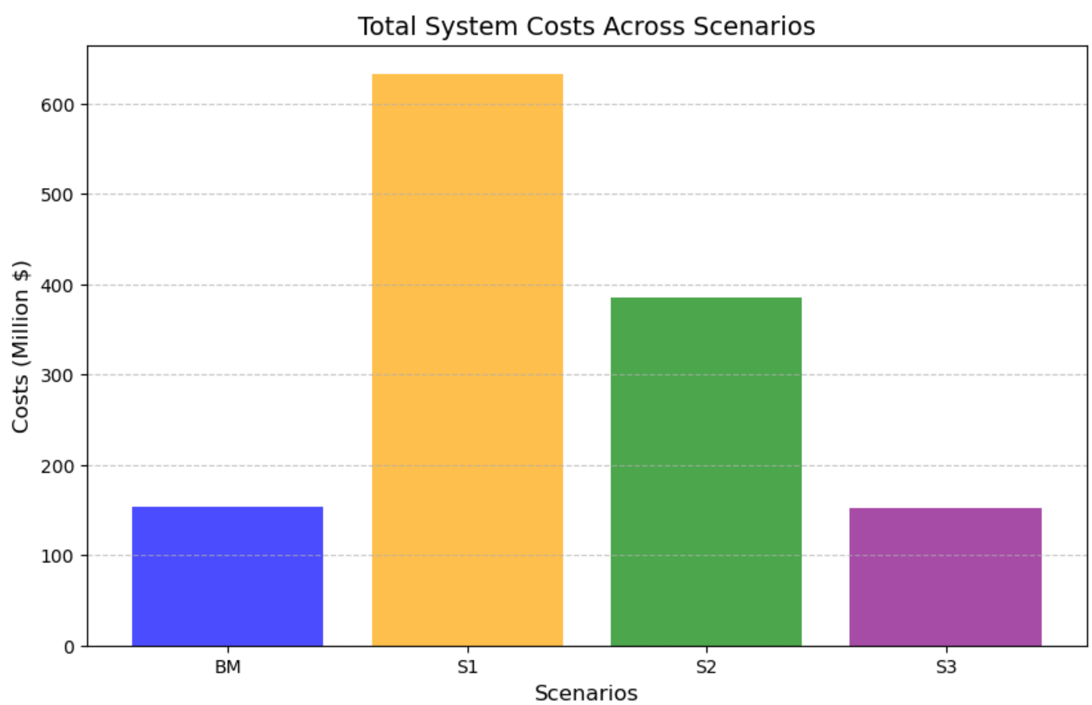




Comparison




Total Emissions Across Scenarios
Emissions (kt CO2e)
0
500
1000
1500
2000
2500
BM
S1
S2
S3
Scenarios


Total System Costs Across Scenarios
Costs (Million $)
0
100
200
300
400
500
600
BM
S1
S2
S3
Scenarios

Key Observations:

Cost Efficiency: The baseline and nuclear scenarios are the least expensive. Nuclear has the lowest emissions among all scenarios.

Emissions: The natural gas scenario increases emissions drastically, while nuclear achieves the lowest emissions.

Renewable Contributions: Scenarios focusing on renewables (solar, wind) moderately lower emissions, though system costs rise compared to the baseline.

Trade-offs: The natural gas scenario sacrifices environmental benefits for energy reliability, while renewable and nuclear scenarios strive for a balance between cost and decarbonization.

Cost-Effectiveness

Baseline Model (BM):

- Low system cost ($153.58 million), but emissions remain high (614.33 kt).
- The system heavily relies on hydro with minimal renewables, signaling underinvestment in new infrastructure.

Natural Gas Scenario (S1):

- Significant increase in system costs ($632.79 million, over 4x BM).
- Emissions rise drastically to 2432.50 kt due to fossil fuel reliance.
- Higher costs are driven by operational expenses for natural gas plants and increased fossil fuel dependency.

Renewables Scenario (S2):

- Moderate system cost ($385.35 million) with substantial emissions reductions (1538.43 kt).
- Costlier than BM but significantly cheaper than S1, showing renewables are competitive once integrated.
- Investments in solar and wind help decarbonize, reducing dependence on fossil fuels.

Nuclear Scenario (S3):

- Lowest system cost ($152.32 million) with the most significant emissions reduction (377.35 kt).
- High initial capital costs of nuclear energy are offset by its low operating costs, making it cost-effective for base-load generation.

Key Insight:

- S2 and S3 are better trade-offs for cost and emissions reduction compared to S1.
- Renewables (S2) require additional investments but reduce emissions substantially, while nuclear (S3) offers the best cost-emissions balance.

Emissions Reduction Potential

- S1 increases emissions, showing natural gas is not suitable for achieving decarbonization targets.

- S2 and S3 reduce emissions, but the nuclear scenario achieves this most efficiently:
- S3 cuts emissions by 38.6% compared to BM.
- S2 achieves a 60.7% reduction compared to S1 but falls short of nuclear in absolute terms.

Key Insight:

- While renewables provide substantial reductions, nuclear offers a pathway to deeper decarbonization at a potentially lower overall cost.

Reliability and Energy Security

Baseline Model:

- Relies heavily on hydro (13.44 TWh), posing risks during droughts or water shortages.

Natural Gas Scenario (S1):

- Improves energy security by introducing a stable fossil fuel supply but undermines climate targets.

Renewables Scenario (S2):

- Increased share of renewables (solar and wind, 5.028 GW capacity) introduces variability.
- Requires complementary technologies like energy storage or flexible backup systems for grid stability.

Nuclear Scenario (S3):

- Provides consistent base-load power, enhancing system reliability.
- Nuclear plants can operate continuously, reducing reliance on variable renewables or fossil fuels.

Key Insight:

- S2 will require grid upgrades or energy storage to handle renewable intermittency.
- S3 offers a more reliable energy supply but may require significant investments in safety and waste management infrastructure.

Infrastructure Needs

Baseline Model:

The current grid infrastructure is inadequate for decarbonization or handling renewables.

S1 (Natural Gas):

- Minimal infrastructure changes, but the increased reliance on gas plants adds pressure on pipelines and gas supply chains.

S2 (Renewables):

- Requires substantial infrastructure upgrades, including grid expansion, storage systems, and transmission lines for distributed energy resources.

S3 (Nuclear):

- Requires heavy upfront investment in nuclear plants, safety protocols, and waste disposal systems. However, it doesn’t necessitate extensive grid overhauls as nuclear provides steady output.

Key Insight:

- S2 involves more extensive grid upgrades for integrating intermittent renewables.
- S3 needs a smaller grid investment but higher upfront capital for nuclear power plants.

Policy and Social Considerations

Natural Gas (S1):

- Policies supporting natural gas expansion conflict with global decarbonization goals. The public perception of fossil fuels may hinder long-term acceptance. – (Consider CCUS)

Renewables (S2):

- Policies must incentivize solar and wind adoption while addressing land use and community impacts. Public support for renewables is generally high.

Nuclear (S3):

- Policies need to address public concerns around nuclear safety, waste disposal, and decommissioning. However, its potential as a low-emission technology aligns with climate goals.

Key Insight:

- Social acceptance and effective policies are crucial for renewable and nuclear adoption, with nuclear requiring more public trust-building efforts.

Recommendations

Balance Nuclear and Renewables:

A mixed approach combining nuclear (base load) with renewables (variable generation) may optimize reliability and emissions reductions.

Infrastructure Upgrades:

- Prioritize grid modernization and storage to handle renewable integration.
- Invest in nuclear safety and waste management facilities.

Policy Frameworks:

- Incentivize renewables through subsidies or tax benefits.
- Support nuclear through public education and transparent safety regulations.

Phased Implementation:

- Begin with renewables integration and grid updates while planning long-term investments in nuclear.

Caveats and Future Work

Caveats

1. **Model Assumptions**:

- The analysis relies on a simplified representation of the energy system. Factors such as operational constraints, maintenance schedules, and unplanned outages are not explicitly modeled.
- The cost assumptions for renewable and nuclear technologies may not account for regional variations, currency fluctuations, or future technological advancements.

2. **Carbon Emissions Accounting**:

- The emissions reductions are based on direct emissions from power generation. Upstream emissions (e.g., manufacturing solar panels, mining uranium, and natural gas production) are excluded, potentially underestimating the true carbon footprint.

3. **Renewable Intermittency**:

- The analysis does not incorporate the impact of variability in solar and wind generation on grid stability. Additional measures like energy storage and demand response mechanisms are needed for a more realistic evaluation.

4. **Public and Political Factors**:

- Social acceptance and political feasibility of nuclear energy or large-scale renewable deployment were not considered. Nuclear energy, for example, faces significant resistance in many regions despite its low emissions.

5. **Transmission and Distribution Costs**:

- Infrastructure costs for expanding transmission networks, integrating distributed generation, or addressing congestion in renewable-heavy grids are not fully accounted for.

6. **Limited Scenarios**:

- Other potential scenarios, such as hybrid renewable-nuclear systems or the inclusion of energy storage technologies (e.g., batteries or pumped hydro), were not analyzed.

7. **Exclusion of Demand-Side Measures**:

- The analysis focuses solely on supply-side interventions. Demand-side measures like energy efficiency improvements, demand response, and electrification of end-use sectors could significantly influence system costs and emissions.

Future Work

1. **Enhanced Modeling Framework**:

- Use more detailed energy system models (e.g., incorporating hourly time steps, storage technologies, and demand-side flexibility) to better simulate the dynamics of renewable integration and nuclear deployment.

2. **Scenario Diversification**:

- Investigate hybrid scenarios, such as combining nuclear with renewables to balance base-load power with intermittent generation.
- Assess the role of emerging technologies like hydrogen, carbon capture, and long-duration energy storage in decarbonizing the system.

3. **Economic and Financial Analysis**:

- Conduct a detailed lifecycle cost analysis, including the social cost of carbon, to understand long-term economic implications.
- Explore financing mechanisms and policy incentives needed for large-scale renewable and nuclear investments.

4. **Grid and Infrastructure Studies**:

- Analyze the grid's ability to integrate higher shares of renewables, including congestion, curtailment, and stability concerns.
- Quantify the costs of upgrading transmission and distribution networks to support distributed energy resources.

5. **Sector Coupling and Nexus Studies**:

- Investigate how increased renewable penetration affects the Climate-Land-Energy-Water Systems (CLEWS), particularly land use for solar and wind installations and water demand for nuclear cooling.

6. **Policy and Regulatory Frameworks**:

- Study the impact of different policy mechanisms, such as carbon pricing, renewable energy certificates, or nuclear subsidies, on technology adoption and emissions reductions.
- Explore public engagement strategies to build support for nuclear energy or large-scale renewable projects.

7. **Incorporating Climate Resilience**:

- Assess the resilience of the proposed energy systems to climate change impacts, such as changing precipitation patterns (affecting hydroelectric generation) or extreme weather events.

8. **Social and Behavioral Dimensions**:

- Include social acceptance, equity concerns, and workforce transitions in the evaluation of renewable and nuclear deployment strategies.

9. **Geographic-Specific Analysis**:

- Perform a region-specific study considering local resource availability, economic conditions, and energy demand profiles to refine the recommendations.

10. **Long-Term Projections**:

- Extend the analysis to 2050 or beyond to understand the implications of meeting net-zero targets and explore pathways for achieving these goals under different energy mixes.

Key Features

BL: Balanced generation mix, low reliance on solar, and moderate emissions.

S1: High gas usage for all sectors, highest emissions and system costs, reducing oil dependence.

S2: Increased renewable share (solar, wind), reduced oil and gas use, and moderate emissions reduction.

S3: Nuclear integration significantly lowers emissions and costs while maintaining a balanced energy mix.