The Effect of Renewable Energy Penetration on Supply Security Risk and Carbon Emissions: A Comparative Two-Scenario Model

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Abstract— **Decarbonizing electricity generation is now a central component of energy policy, yet the operational consequences of high renewable energy penetration remain contested. Renewable energy reduces carbon emissions and can weaken exposure to fossil fuel price volatility and import dependence. At the same time, high shares of variable renewable generation may increase short-term supply security risks when storage, dispatchable reserve capacity, demand-side flexibility, and transmission infrastructure are insufficient. This study develops a two-scenario comparative model to examine the trade-off between carbon performance and operational supply security. Annual electricity demand is normalized at 100 TWh. Scenario A assumes that 70% of generation is supplied by renewable sources and 30% by coal and natural gas, whereas Scenario B assumes 30% renewable generation and 70% coal and natural gas generation. Carbon emissions are estimated using life-cycle emission factors, while operational supply security is represented by a normalized index that combines variable generation exposure, controllable capacity adequacy, and system flexibility. The results indicate that Scenario A produces 22.45 MtCO2e per year, compared with 47.05 MtCO2e per year in Scenario B. However, the operational supply security risk index increases from 17.44 in Scenario B to 48.69 in Scenario A. The findings suggest that renewable energy expansion should not be assessed only through installed capacity or emission reduction metrics. A low-carbon electricity transition requires complementary investment in storage, flexible demand, grid reinforcement, reserve capacity, and market designs capable of integrating variable generation without compromising system reliability.**

Keywords— renewable energy; energy supply security; carbon emissions; electricity generation; energy transition; scenario analysis; operational risk

I. INTRODUCTION

Electricity systems are increasingly shaped by two policy imperatives that do not always move at the same pace. The first is the need to reduce greenhouse gas emissions from fossil fuel-based power generation. The second is the requirement to maintain a continuous, affordable, and reliable electricity supply. Renewable energy technologies are central to the first objective because they offer substantially lower life-cycle emissions than coal- and gas-fired generation [1], [2]. However, when the share of variable renewable energy becomes high, system operation becomes more dependent on weather conditions, temporal generation profiles, and the availability of flexibility resources.

The relationship between renewable energy and energy security is therefore not linear [3]. In the long term, renewable energy can improve strategic energy security by reducing exposure to imported fuels, international price volatility, and geopolitical disruptions. In the short term, however, high renewable penetration may create operational challenges associated with intermittency, balancing requirements, reserve margins, and grid stability. This distinction is important because energy security is a multidimensional concept. A system may become more secure in terms of import dependence while becoming more demanding in terms of real-time operation [3].

Against this background, the present study develops a simplified but transparent model to compare two electricity generation portfolios under the same annual demand assumption. The purpose is not to reproduce the full complexity of a national power system, but to clarify the direction and magnitude of the trade-off between carbon emissions and short-term operational supply security risk. The model is designed as a conceptual scenario analysis that can support further empirical applications using country-specific data.

The main research question is as follows: how does an increase in the renewable energy share affect carbon emissions and operational supply security risk under otherwise comparable electricity demand conditions? Three assumptions guide the analysis. First, a higher renewable energy share reduces the carbon intensity of electricity generation. Second, when system flexibility is limited, a higher share of variable renewable generation increases operational supply security risk. Third, a fossil-intensive generation portfolio may appear more stable in the short term, but it produces higher carbon emissions and reinforces long-term fuel dependency.

II. LITERATURE REVIEW

Recent studies emphasize that energy transition and renewable energy investment can reduce energy security risks by lowering reliance on fossil fuel markets and by supporting more sustainable energy systems [4]. Bashir, Pata, and Shahzad (2025), for example, argue that structural transformation in the energy sector can mitigate energy security risk, particularly when renewable energy investment is combined with broader transition policies [5]. Their findings are useful for understanding the strategic role of renewable energy in reducing fossil fuel-related vulnerability.

Khan et al. (2024) examine the causal relationship between renewable energy development and energy security and show that the direction and strength of this relationship can vary across periods and structural conditions [6]. Their results highlight the importance of policy context, infrastructure readiness, and economic or geopolitical disruptions. Renewable energy may enhance security, but this

effect depends on whether the system is able to absorb and manage the changing generation structure.

A portfolio-based interpretation is particularly relevant for the present study. Escribano Frances, Marin-Quemada, and San Martin Gonzalez (2013) argue that energy sources should be evaluated not only by their individual costs but also by their contribution to the risk profile of the overall energy portfolio [7]. From this perspective, renewables can reduce exposure to fossil fuel price volatility, yet they may introduce other forms of risk, especially when regulatory, technical, or flexibility conditions are weak.

Arian (2019) frames the transition to low-carbon energy as a combined technological, institutional, and infrastructural challenge [8]. This perspective is important because the decarbonization of electricity generation cannot be reduced to replacing one source with another. The integration of low-carbon technologies requires innovation, investment, system planning, and changes in both supply-side and demand-side behavior. Taken together, these studies support the central premise of this article: renewable energy expansion delivers clear carbon benefits, but its supply security implications depend on system-level integration capacity.

III. Methodology

The study uses a two-scenario comparative model. Total annual electricity demand is fixed at 100 TWh in both scenarios in order to isolate the effect of the generation mix. This normalization does not represent a particular country; rather, it provides a consistent basis for comparing emissions and operational supply security risk across alternative electricity portfolios.

Scenario A represents a high-renewable transition pathway. In this case, 70% of electricity generation is supplied by renewable energy, while coal and natural gas each provide 15%. Scenario B represents a fossil-intensive pathway. In this case, renewable energy supplies 30% of generation, while coal and natural gas each provide 35%. The fossil share is treated as controllable generation for the purposes of short-term operational adequacy, while the renewable share is assumed to contain a substantial variable component.

The table 1 presents the main assumptions used in the two-scenario electricity generation model. Annual electricity demand is fixed at 100 TWh/year in both scenarios. This allows the comparison to focus only on differences in the generation mix, rather than changes in electricity demand. The emission factors show the amount of carbon dioxide equivalent released per unit of electricity generated. Renewable energy has the lowest emission factor, 0.040 tCO_2e/MWh, while coal has the highest value, 0.820 tCO_2e/MWh. Natural gas is lower than coal but still much higher than renewables, with 0.490 tCO_2e/MWh. These values are used to calculate total carbon emissions under each scenario. The table also includes two parameters related to supply security. VRE = 0.75 represents the variability of the renewable energy portfolio, especially due to weather-dependent sources such as wind and solar power. A higher VRE value indicates greater exposure to intermittent generation. FLEX = 0.25 represents the flexibility of the electricity system. It reflects the contribution of storage, demand response, reserve capacity, and grid flexibility. Since this value is relatively low, the model assumes that the system has limited ability to balance variable renewable generation.

TABLE 1. MODEL PARAMETERS AND SCENARIO ASSUMPTIONS

Parameter	Symbol	Value	Explanation
Annual electricity demand	D	100 TWh/year	Normalized demand used for scenario comparison
Renewable emission factor	EF_RE	0.040 tCO2e/MWh	Representative life-cycle factor for a mixed renewable portfolio
Coal emission factor	EF_C	0.820 tCO2e/MWh	Life-cycle emission factor for coal-fired electricity
Natural gas emission factor	EF_G	0.490 tCO2e/MWh	Representative factor for natural gas combined-cycle generation
Variable renewable exposure	VRE	0.75	Coefficient representing the variability of the renewable portfolio
System flexibility	FLEX	0.25	Coefficient representing storage, demand response, and grid flexibility

Total carbon emissions are calculated as follows:

$$E_s = D \times [p_{RE,s} \times EF_{RE} + p_{C,s} \times EF_C + p_{G,s} \times EF_G] \quad (1)$$

where E_s denotes annual emissions in scenario s, D is annual electricity demand, $p_{i,s}$ is the generation share of source i in scenario s, and EF_i is the source-specific life-cycle emission factor.

Operational supply security risk is represented by the following normalized index:

$$OSRI_s = 100 \times [0.50 \times (p_{RE,s} \times VRE \times (1 - FLEX)) + 0.30 \times (1 - p_{DISP,s}) + 0.20 \times \max(0, p_{RE,s} - p_{DISP,s})] \quad (2)$$

In this index, $p_{DISP,s}$ denotes the share of dispatchable coal and natural gas generation. Higher values of the index indicate greater short-term operational pressure on the system due to variable renewable generation, limited dispatchable capacity, and insufficient flexibility. The index therefore captures operational supply security rather than long-term geopolitical fuel security.

IV. Scenario Design

The table 2 presents the electricity generation mix assumed under the two scenarios. Scenario A represents a high-renewable, low-carbon portfolio, in which 70% of electricity generation is supplied by renewable sources and the remaining 30% by coal and natural gas. Although this scenario provides lower carbon emissions, it requires higher operational balancing capacity due to the variability of renewable generation. Scenario B represents a more fossil-fuel-based and dispatchable generation portfolio, with 30% renewable energy and 70% coal and natural gas. This structure offers greater short-term controllability but results in higher carbon emissions.

TABLE 2. ELECTRICITY GENERATION MIX AND MAIN CHARACTERISTICS OF THE SCENARIOS

Scenario	Renewables	Coal	Natural gas	Main interpretation
A	70%	15%	15%	Low-carbon portfolio with higher operational balancing requirements
B	30%	35%	35%	More dispatchable portfolio with higher carbon emissions

The figure 1 compares the electricity generation mix under two scenarios.

In Scenario A, renewable energy has the dominant share, accounting for 70% of total electricity generation. Coal and natural gas each contribute 15%. This scenario therefore represents a low-carbon electricity portfolio, since most generation comes from renewable sources. However, because renewable sources such as wind and solar are variable, this scenario may require greater balancing capacity, storage, reserve generation, and grid flexibility.

In Scenario B, renewable energy accounts for only 30% of electricity generation, while coal and natural gas each provide 35%. This scenario represents a more fossil-fuel-based and dispatchable generation portfolio. The higher share of coal and natural gas can support short-term supply stability because these sources are more controllable, but it also leads to significantly higher carbon emissions.

Overall, the figure shows the core trade-off of the study: Scenario A reduces carbon emissions but increases operational balancing needs, whereas Scenario B provides greater dispatchability but produces higher emissions.

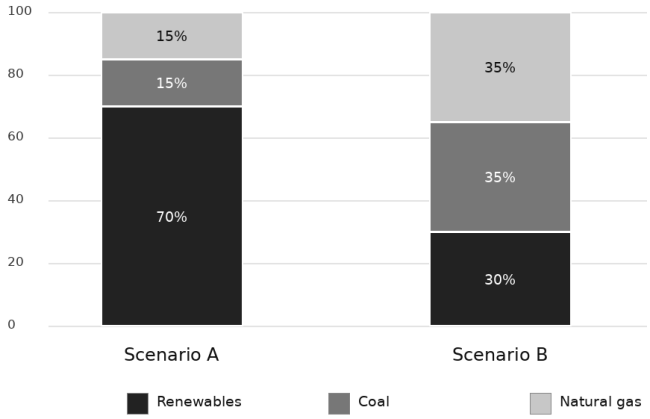

Fig. 1. Electricity generation mix by scenario.

V. RESULTS

This table compares the carbon emission results of Scenario A and Scenario B. Scenario A, which has a higher renewable energy share, produces 22.45 $MtCO_2e$/year, while Scenario B produces 47.05 $MtCO_2e$/year. This means that Scenario A generates approximately 52.3% lower annual emissions than Scenario B. The emission intensity also differs significantly between the two scenarios. Scenario A has an emission intensity of 224.5 $kgCO_2e$/MWh, whereas Scenario B reaches 470.5 $kgCO_2e$/MWh. This indicates that the fossil-intensive portfolio more than doubles the carbon intensity of electricity generation. The main reason for this difference is the fossil generation share. In Scenario A, fossil fuels account for only 30% of electricity generation, while in Scenario B this share increases to 70%. Therefore, the 40-percentage-point increase in fossil-based generation substantially raises both total emissions and emission intensity.

TABLE 3. CARBON EMISSION RESULTS OF THE ELECTRICITY GENERATION SCENARIOS

Indicator	Scenario A	Scenario B	Comparative interpretation
Total annual emissions	22.45 MtCO2e/year	47.05 MtCO2e/year	Scenario A produces 52.3% lower annual emissions.
Emission intensity	224.5 kgCO2e/MWh	470.5 kgCO2e/MWh	The fossil-intensive portfolio more than doubles carbon intensity.
Fossil generation share	30%	70%	A 40-point increase in fossil generation substantially raises total emissions.

The results show a clear carbon advantage for the high-renewable scenario. Under the same annual electricity demand, Scenario A generates 22.45 MtCO2e per year, whereas Scenario B generates 47.05 MtCO2e per year. The difference between the two portfolios is 24.60 MtCO2e annually. This result confirms that a higher renewable share substantially reduces the carbon intensity of electricity generation.

The table 4 compares the operational supply security risk components of Scenario A and Scenario B. Scenario A has high variable renewable exposure because it includes a larger share of weather-dependent generation, such as wind and solar power. Therefore, its electricity output is more sensitive to weather conditions and daily generation fluctuations.

Scenario B has a higher dispatchable generation share, reaching 70%, compared with only 30% in Scenario A. This means that Scenario B has a larger controllable generation base through coal and natural gas plants, which can more easily respond to demand changes.

The reserve and flexibility requirement is also higher in Scenario A. Since renewable generation is more variable, this scenario requires stronger storage systems, reserve capacity, grid flexibility, and demand-side response mechanisms.

The OSRI value confirms this difference. Scenario A has an operational supply security risk index of 48.69, while Scenario B has a lower value of 17.44. This indicates that operational supply security risk is higher in the high-renewable scenario unless sufficient flexibility and balancing resources are available

TABLE 4. OPERATIONAL SUPPLY SECURITY RISK COMPARISON OF THE SCENARIOS

Risk component	Scenario A	Scenario B	Interpretation
Variable renewable exposure	High	Low to moderate	Scenario A contains a larger share of weather-dependent generation.
Dispatchable generation share	30%	70%	Scenario B has a larger controllable generation base.
Reserve and flexibility requirement	High	Lower	Scenario A requires stronger storage, reserve, and demand-side flexibility.
OSRI value	48.69	17.44	Operational supply security risk is higher in Scenario A.

The supply security results move in the opposite direction. Scenario A, despite its lower carbon emissions, has a higher operational supply security risk because a larger share of generation is exposed to variability. The calculated OSRI value is 48.69 for Scenario A and 17.44 for Scenario B. Scenario B benefits from a larger dispatchable generation base, which can more directly support load following and short-term balancing. This result does not imply that fossil-intensive systems are more secure in every respect; rather, it shows that they may face lower operational balancing risk under the simplified assumptions used in this model.

The figure 2 compares carbon intensity and operational supply security risk under Scenario A and Scenario B. In Scenario A, carbon intensity is relatively low, at 224.5 $kgCO_2e/MWh$, because renewable energy accounts for 70% of electricity generation. However, the operational supply security risk is higher, with an OSRI value of 48.69, due to the larger share of variable renewable generation.

In Scenario B, the opposite pattern is observed. Carbon intensity increases to 470.5 $kgCO_2e/MWh$ because fossil fuels represent 70% of the generation mix. However, the operational supply security risk decreases to 17.44, as coal and natural gas provide a larger dispatchable generation base.

Overall, the figure illustrates the main trade-off of the study: Scenario A provides lower carbon emissions but higher operational supply security risk, while Scenario B provides lower operational risk but significantly higher carbon intensity.

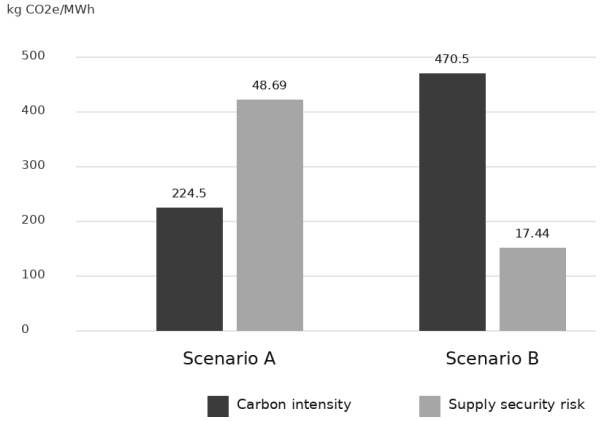

Fig. 2. Comparison of carbon intensity and operational supply security risk.

VI. DISCUSSION

The findings demonstrate that the energy transition cannot be evaluated through a single indicator. Scenario A is clearly preferable from a climate policy perspective because it sharply reduces emissions. Nevertheless, if the electricity system lacks sufficient flexibility, a high renewable share can increase operational vulnerability. This vulnerability may appear through balancing requirements, frequency control, voltage stability, reserve adequacy, and the need to meet peak demand during periods of low renewable output.

Scenario B appears more stable in short-term operational terms because coal and natural gas plants are treated as dispatchable resources. These plants can respond more predictably to load variations. Yet this apparent operational advantage is obtained at the cost of substantially higher carbon emissions. In addition, fossil-intensive systems remain exposed to long-term risks associated with fuel price volatility, import dependence, geopolitical disruptions, and environmental compliance costs.

The central implication is therefore not that renewable energy necessarily increases or decreases energy security in absolute terms. A more precise interpretation is that renewable energy reduces carbon risk and can reduce strategic fuel dependence, but it may increase operational supply security risk when system flexibility is inadequate. Conversely, fossil-based generation may reduce short-term operational balancing pressures, but it intensifies carbon emissions and long-term fuel-related vulnerabilities. Policy design must therefore distinguish between different dimensions of energy security rather than treating the concept as a single aggregate outcome.

- High-renewable electricity systems require parallel investment in battery storage, pumped hydro storage, hydrogen-based storage, and demand-side flexibility.
- Supply security planning should go beyond installed capacity and include flexible capacity, grid reinforcement, reserve adequacy, and real-time system operation.
- A rapid withdrawal from fossil generation should be coordinated with flexibility investments in order to avoid reliability problems during the transition period.
- Renewable energy expansion should be supported by regional interconnection, smart grid infrastructure, and market mechanisms that reward flexibility.
- Carbon reduction and energy security objectives should be assessed through multi-criteria planning models rather than through cost or emissions indicators alone.

VII. CONCLUSION

This article developed a two-scenario comparative model to examine how renewable energy penetration affects carbon emissions and operational supply security risk. The results show that a 70% renewable generation portfolio reduces annual emissions to 22.45 MtCO2e, while a 30% renewable

generation portfolio produces 47.05 MtCO2e under the same electricity demand. However, the operational supply security risk index is higher in the renewable-intensive scenario, indicating that emission reduction and operational reliability may move in different directions when flexibility resources are limited.

The study concludes that renewable energy expansion should be accompanied by deliberate system integration policies. Storage technologies, demand response, flexible generation, transmission expansion, and market reforms are essential for translating renewable energy growth into both low-carbon and reliable electricity supply. The results should be interpreted as a conceptual model rather than a country-specific forecast. Future studies may extend the model by incorporating hourly generation profiles, probabilistic reliability indicators, fuel price uncertainty, storage costs, and country-level electricity system data.

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