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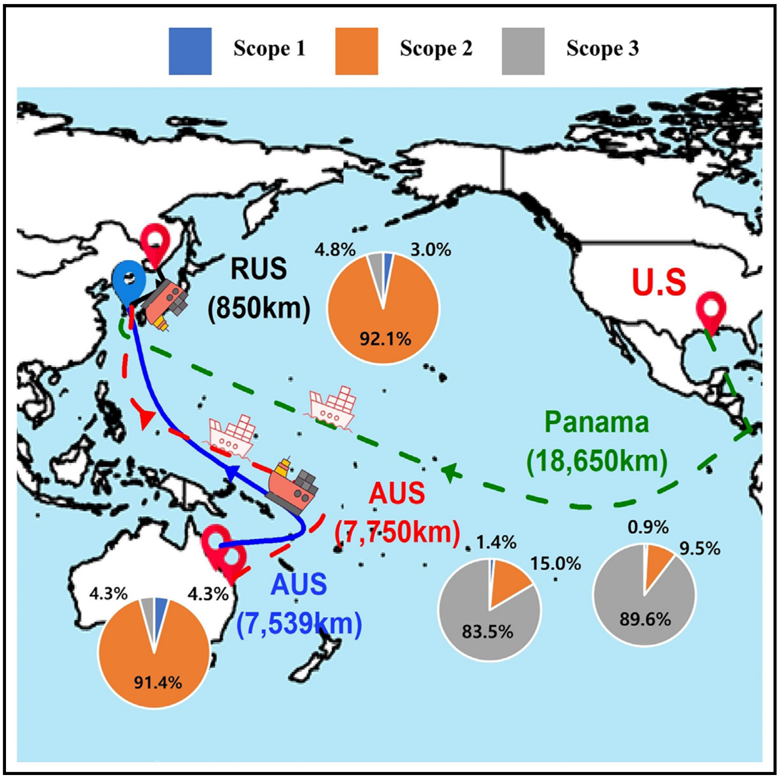
The unseen carbon: Scope 3 emissions transform understanding of electricity generation in import-dependent nations

Graphical abstract



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In brief

Energy sustainability; Energy systems; Energy Modeling

Highlights

- Comprehensive LCA of electricity generation in Korea, including Scope 3 emissions
- Transportation-related emissions significantly impact overall GHG footprint
- Natural gas shows higher environmental impact than coal when including import emissions
- Findings inform strategies for carbon neutrality in energy-dependent nations

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The unseen carbon: Scope 3 emissions transform understanding of electricity generation in import-dependent nations

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SUMMARY

Energy system decarbonization requires accurate emissions accounting. While many import-dependent nations rely on foreign fuels, infrastructure, and technologies for electricity generation, their emissions calculations often overlook critical supply chain and life cycle impacts. This study applies life cycle assessment to evaluate the comprehensive carbon footprint of electricity production in import-dependent economies, encompassing direct operations (Scope 1), energy use (Scope 2), and supply chain emissions (Scope 3). Analysis reveals that conventional accounting methods significantly underestimate environmental impacts by excluding upstream and downstream emissions. This expanded assessment framework provides policymakers and investors with more accurate data for evaluating decarbonization strategies. The findings demonstrate the importance of incorporating complete supply chain emissions into national inventories to effectively guide energy transition policies and investment decisions toward genuine carbon reduction goals.

INTRODUCTION

Global climate change is already manifesting through extreme weather events worldwide. Achieving ‘‘carbon neutrality by 2050,’’—a state where we balance carbon emissions with carbon absorption from the atmosphere—has become one of our most urgent global priorities.[1–3]

To accelerate progress toward carbon neutrality, various international initiatives have emerged. In August 2022, the United States (US) enacted the Inflation Reduction Act (IRA), a landmark federal law that makes significant investments in climate action. This legislation is projected to reduce US greenhouse gas (GHG) emissions by approximately 40% by 2030 while supporting the clean energy industry.[4] Similarly, the European Union has introduced Euro 7 standards, which build upon Euro 6 regulations. These new standards address not only exhaust emissions from internal combustion engines but also establish limits for non-exhaust pollutants, such as fine particles generated by tire and brake pad wear.[5]

In response to these global efforts, South Korea has established the ‘‘2050 Carbon Neutrality Promotion Strategy’’. This initiative marks the beginning of Korea’s transition to a low-carbon era, encompassing a wide range of policies. These include measures closely related to daily life, such as mandating the purchase of eco-friendly vehicles by public institutions and providing subsidies for electric vehicles. The strategy also extends to industrial support, mandating zero-energy construction for new buildings and aiming to convert more than 80% of hydrogen energy production to green H_2.[6]

The rapidly changing social awareness of environmental issues has made accurate calculation of GHG emissions essential for demonstrating compliance with regulations by both countries and companies. The European Union, through its Corporate Sustainability Reporting Directive (CSRD), has mandated comprehensive environmental reporting, including climate change and pollution metrics, for all EU and foreign companies operating within the EU by the 2028 fiscal year.[7] This directive requires high accuracy in calculating Scope 1, 2, and 3 emissions.

Korea has also taken steps to align with these global trends. The Korea Sustainability Standards Board (KSSB), under the Korea Accounting Standards Institute, has announced ‘‘Climate-related disclosures’’as part of its sustainability disclosure standard.[8] Additionally, the country is supporting small and medium-sized enterprises in building their energy and carbon inventories, as per Article 55 (4) of the Framework Act on Low Carbon, Green Growth.[9]

However, the implementation of these standards in Korea is still in progress. While the Financial Services Commission has outlined plans to mandate sustainability reporting for all KOSPI-listed companies by 2030, starting with larger companies (assets of about KRW 2 trillion) by 2025, specific details remain to be determined. In the interim, domestic companies are encouraged to voluntarily prepare and disclose sustainability management reports using international frameworks such as the Task

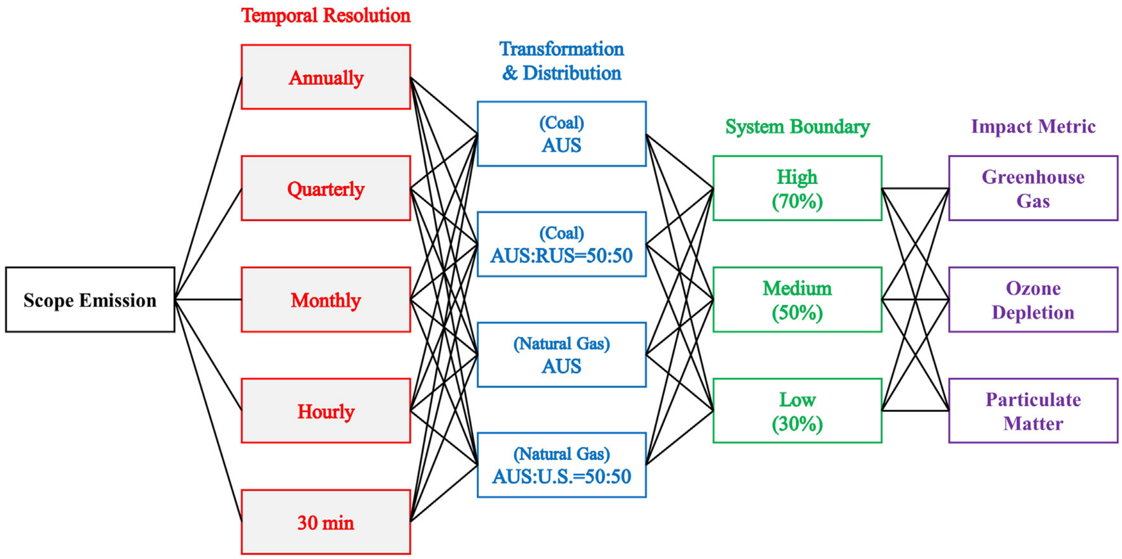

Figure 1. Comprehensive methodology for assessing environmental impacts of electricity generation in Korea

Force on Climate-related Financial Disclosures (TCFD), the Global Reporting Initiative (GRI), and the Sustainability Accounting Standards Board (SASB).[10]

The accuracy of national GHG emissions calculations in Korea also presents challenges. Following the enactment of the Framework Act on Low Carbon, Green Growth in September 2021, 17 metropolitan local governments are developing initial legal plans for carbon neutrality and green growth. However, some regions, such as Gyeonggi-do, have never independently calculated their GHG emissions. This has led to a reliance on emissions data calculated and reported by the GHG Inventory and Research Center, resulting in a two-year lag between the announcement of GHG emissions statistics and the actual timing of emissions.[11] This delay hinders the prompt implementation and evaluation of policies. Furthermore, high uncertainty in the Land Use, Land-Use Change and Forestry (LULUCF) absorption source data have been highlighted as an issue.[12]

Similar challenges in GHG emissions reporting have been observed internationally. In the United States, K.R. Gurney et al. (2021)[13] found that self-reported GHG emissions in US cities were, on average, 18.3% lower than their actual emissions, as determined by independent estimates using the Vulcan v3.0 carbon emissions data product.[14] In a study of 42 cities, including major European capitals, Parvez Mia et al. (2019)[15] pointed out that existing city-level GHG information is often outdated, incomplete, and inconsistent, making comparisons difficult. While research in Korea has explored the importance of Scope 3 emissions in construction projects using Environmental Impact Assessment (EIA) and Life Cycle Assessment (LCA) methodologies (Kim. K. T. & Kim. I., 2021),[16] few studies have examined emissions from electricity generation in Korea, considering both temporal and spatial characteristics. Furthermore, Seaver Wang et al. (2023)[17] evaluated 75 climate-energy scenarios to assess global power infrastructure resource demands, concluding that annual production of critical materials—neodymium, dysprosium, tellurium, glass fiber, and polysilicon—for solar power must increase significantly, despite resource demands remaining within geological reserves.

To address these gaps, this study aims to calculate GHG emissions of the grid emission factor (GEF) in Korea, a country highly dependent on energy imports. The research seeks to provide data that can assist in investigating the current status and trends of GHG emissions in Korea and establish measures to reduce them. Unlike previous studies that focused on annual emissions, this study comprehensively calculates Scope 1, 2, and 3 emissions using detailed data by time (quarterly, monthly, hourly, 30 min), energy source (coal and natural gas), and energy-exporting country (Australia, US, and Russia).

This approach enables a better understanding of interactions between sectors and overall emission characteristics. Additionally, considering Korea's high dependence on energy imports, this study presents a more comprehensive perspective that considers networks not only within Korea but also between countries. The methodology developed in this study can serve as a model for other countries heavily dependent on energy imports, offering a more holistic view of their carbon footprint.

Furthermore, this study proposes a methodology for estimating Scope 3 emissions at the corporate and institutional levels, responding to changes in domestic and international climate-related disclosure standards. The methodology presented here can contribute to enhancing the GHG emissions management and disclosure capabilities of companies and institutions. Lastly, this study's approach to analyzing the GEF in the context of international energy dependence could inform global strategies for transitioning to cleaner energy sources.

RESULTS

The present study established relationships to derive influential factor values corresponding to various temporal resolutions, transportation and distribution parameters, and efficiency

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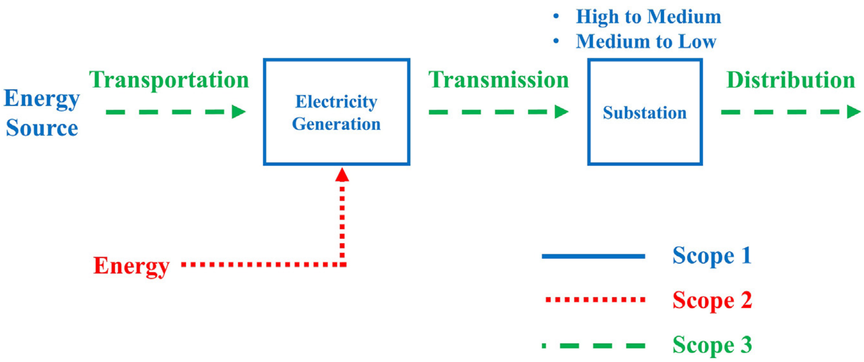

Figure 2. System boundary and scope of the study on the environmental impact of electricity generation and distribution in South Korea

The process includes the transportation of raw materials (coal and natural gas) from their sources to electricity generation facilities, where electricity is generated at three efficiency levels: high to medium, medium to low, and low. The generated electricity is then transmitted and distributed to end-users.

metrics, as illustrated in Figure 1. These relationships were subsequently utilized to compute the respective values.

Emission factors across different scenarios

Within the system boundary defined in this study, the sections corresponding to Scope 1, 2, and 3 emissions were classified and presented in Figure 2. Specifically, processes involving energy sources, electricity generation, and substation operations are categorized as Scope 1; external electricity utilization is designated as Scope 2; and energy source transportation along with transmission and distribution processes are classified as Scope 3.

For the energy source transportation process defined within the system boundary, the selected countries and their respective transportation routes are illustrated in Figure 3. The study considers coal imports from Australia and Russia, and natural gas imports from Australia and the United States. For imports from the United States, two potential transportation routes were evaluated: one through the Panama Canal and another via Cape Town. Based on distance optimization analysis, the Panama Canal route was selected for this study. Table 1 presents the greenhouse gas (GHG) emissions across four scenarios, categorized by Scope 1, 2, and 3 emissions.

The coal-based scenarios exhibit a concentration of emissions in Scope 2, with the Australia (AUS) scenario showing marginally lower total emissions (1.107 kg CO_2 eq/kWh) compared to the Australia-Russia (AUS:RUS) scenario (1.117 kg CO_2 eq/kWh). In contrast, the natural gas-based scenarios demonstrate substantially higher Scope 3 emissions. Notably, the Australia-US (AUS:US) scenario yields the highest total emissions (6.357 kg CO_2 eq/kWh) among all scenarios analyzed. At this time, the emission of Transmission and Distribution in Scope 3 is

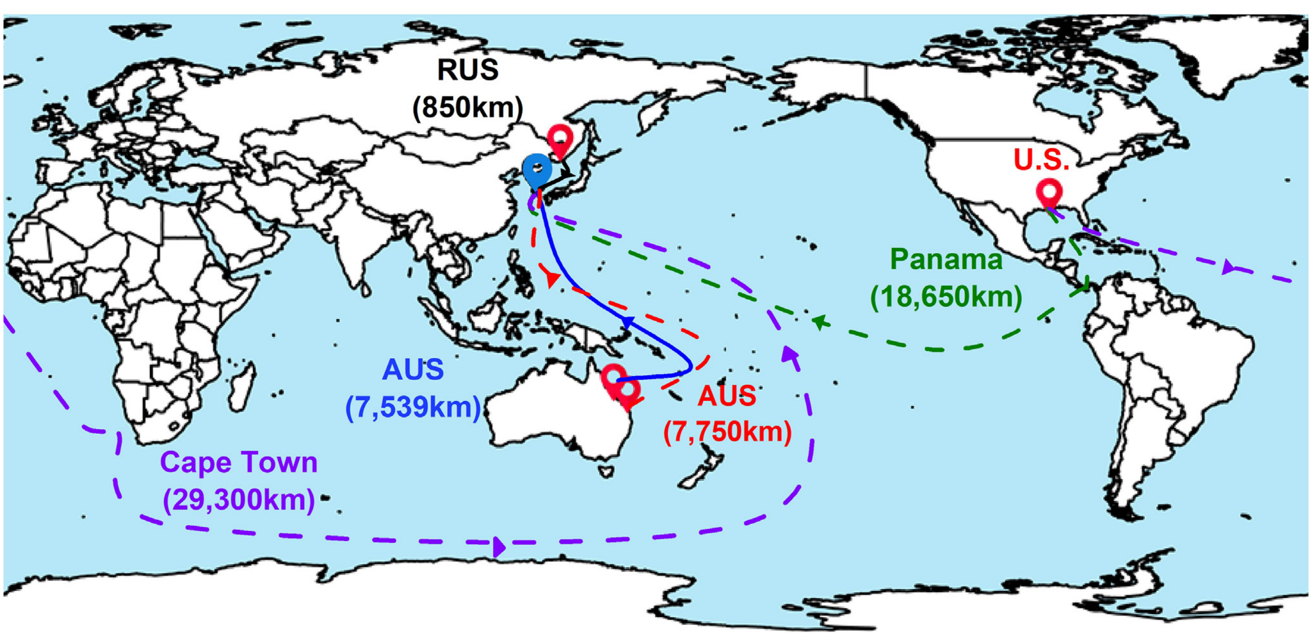

Figure 3. Energy import routes and distances for South Korea

Natural gas transport distances are indicated by dash lines and coal transport distances by solid lines. There are two coal transport routes in the United States, which can pass through the Panama Canal and through Cape Town.

Table 1. GHG emissions (100% efficiency) without uncertainty according to the Scope emission calculated in the scenarios of this study

Emissions (kg CO_2 eq/kWh) by Scope and Scenario	Scope 1	Scope 2	Scope 3	Total
Coal				
AUS	0.033	1.020	0.054	1.107
AUS:RUS	0.0487	1.020	0.048	1.117
Natural gas				
AUS	0.058	0.604	3.360	4.022
AUS:U.S.	0.058	0.604	5.695	6.357

Scope 3 include 4.02E-02 kg CO_2 eq/kWh about transmission and distribution GHG emissions with Korea's loss rate.

calculated as 4.02E-02 kg CO_2 eq/kWh, which is the emission calculated by applying 3.53% of Korea's transmission and distribution loss rate to the GREET program.

A significant disparity is observed in Scope 3 emissions (transportation and distribution) between coal and natural gas importation from Australia. This discrepancy is attributed to the transportation requirements in SimaPro, which uses distance in tonne-kilometers. Due to its physical properties, natural gas necessitates approximately 2.2 times more transportation per unit compared to coal.

Impact of transportation on emission factors

Figure 4 presents a comprehensive analysis of EFs from coal and natural gas electricity generation under various scenarios and efficiency levels.

Figure 4A provides an overview of GHG EFs across different scenarios and efficiency levels. It clearly demonstrates that for both coal and natural gas, EFs increase as efficiency decreases from high (70%, black line) to low (30%, blue line). A notable observation is that natural gas scenarios (AUS and AUS:US) exhibit significantly higher EFs compared to coal scenarios (AUS and AUS:RUS), particularly at lower efficiency levels. The inset graph, which magnifies the coal scenarios, reveals a slight increase in emissions when sourcing from both Australia and Russia (AUS:RUS) compared to Australia alone (AUS).

Figures 4B–4D offer a detailed breakdown of Scope 1, 2, and 3 emissions for high, medium, and low efficiency scenarios, respectively. These panels reveal several important trends. In coal scenarios, Scope 2 emissions dominate, while for natural gas scenarios, Scope 3 emissions are the largest contributor. As efficiency decreases from high to low, the total emissions (in kg CO_2eq/kWh) increase for all scenarios, with this increase being more pronounced for natural gas scenarios.

A key finding illustrated by these panels is that when considering all scopes, natural gas scenarios show substantially higher total emissions compared to coal scenarios across all efficiency levels. This difference is primarily driven by the large Scope 3 emissions in natural gas scenarios. Furthermore, the AUS:US natural gas scenario consistently shows higher emissions compared to the AUS scenario, indicating that sourcing natural gas from both Australia and the US results in greater environmental impact.

Scope 1 emissions, representing direct emissions from the combustion process, are relatively small for all scenarios but increase as efficiency decreases. Scope 2 emissions, representing indirect emissions associated with the production of the fuel, are more significant for coal scenarios. Scope 3 emissions, which dominate in natural gas scenarios, likely reflect the substantial emissions associated with the transportation and distribution of natural gas.

This comprehensive analysis reveals that when considering the full life cycle of electricity generation, including Scope 3 emissions, natural gas can have a significantly higher environmental impact than coal, especially in scenarios involving long-distance transportation. This finding challenges the conventional wisdom that natural gas is always a cleaner alternative to coal and underscores the importance of comprehensive life cycle assessments in energy policy decisions. The results highlight the critical need to consider transportation-related emissions, particularly for countries heavily dependent on energy imports, in evaluating the true environmental impact of different energy sources.

The trends observed in greenhouse gas emissions are mirrored in the EFs for ozone depletion and fine particulate matter, as illustrated in Table 2. For both CFC-11 (a measure of ozone depletion potential) and PM 2.5 (fine particulate matter), the data reveal a pattern analogous to carbon dioxide emissions: as efficiency decreases, emissions increase across all scenarios.

A notable observation arises when comparing PM 2.5 emissions in coal and natural gas scenarios. The coal scenarios consistently show lower EFs than the natural gas scenarios. This finding indicates that, despite the emissions from the mining or extraction processes of each energy source, the transportation and importation of natural gas produce more fine particles than the transportation of coal. This result underscores the significant contribution of transportation-related emissions to the overall environmental impact of natural gas.

However, it is crucial to note that when transportation-related emissions are excluded from the analysis (represented by the sum of orange and green bars in Figure 4), natural gas demonstrates lower EFs across all three environmental impact categories considered in this study: greenhouse gas emissions, ozone depletion potential, and fine particulate matter. This stark contrast highlights the substantial role that transportation plays in the overall environmental impact of natural gas, particularly in the context of South Korea's energy imports.

This analysis reveals the complex interplay between different stages of the energy supply chain and their respective contributions to various environmental impacts. It emphasizes the critical importance of considering the full life cycle of energy sources, including extraction, processing, and transportation, when assessing their environmental implications. For energy-importing nations like South Korea, these findings underscore the need to carefully evaluate the trade-offs between different energy sources, taking into account not only their direct emissions during combustion but also the often-overlooked impacts associated with their transportation and distribution.

Comparison with official emission factors

Figure 5 presents a comparative analysis of the EFs calculated in this study, excluding transportation, with Korea's officially disclosed EFs.

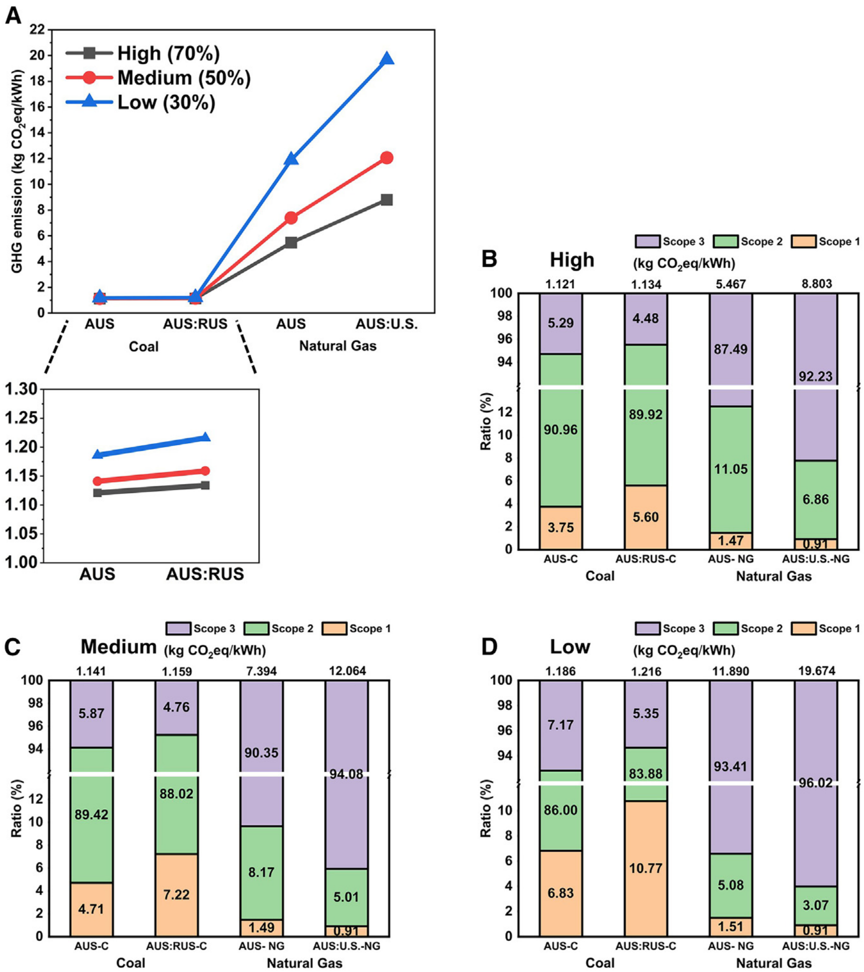

Figure 4. Environmental emission factors (EFs) for coal and natural gas under different efficiency levels and sourcing scenarios

(A) Comparison of GHG emission factors (EFs) across different fuel sources and efficiency scenarios. The main graph shows GHG emissions (kg CO_2eq/kWh) for both coal and natural gas under three efficiency levels: High (70%, black squares), Medium (50%, red circles), and Low (30%, blue triangles). Due to the significant differences in emission scales, coal emissions (1.1–1.3 kg CO_2eq/kWh) are magnified in the inset graph below. Natural gas scenarios show substantially higher emissions (ranging from ∼4 to ∼19 kg CO_2eq/kWh) compared to coal, with emissions increasing dramatically when sourcing changes from AUS to AUS:U.S. The efficiency level has a pronounced impact on emissions, particularly for natural gas, where Low efficiency results in the steepest increase. The inset graph reveals the subtle but important variations in coal emissions between AUS and AUS:RUS sourcing scenarios, which would otherwise be indiscernible in the main plot's scale. Inset shows a magnified view of coal scenarios, highlighting subtle differences between AUS and AUS:RUS.

(B–D) Breakdown of Scope 1, 2, and 3 emissions (as percentages and total kgCO_2e/kWh) for (B) high (70%), (C) medium (50%), and (D) low (30%) efficiency scenarios, respectively.

The comparison reveals that our calculated EFs consistently exceed Korea's official EFs for both coal and natural gas. This discrepancy has several significant implications for environmental assessment and policy-making.

Our study's higher EFs likely stem from the unified combustion methods considered in our scenarios. While our calculations for coal electricity generation are based on the operation of a simple plant, Korea's actual coal-fired thermal power plants employ more advanced technologies, including supercritical pressure and ultra-supercritical pressure units. These advanced technologies generally yield higher efficiency and lower emissions.[18]

Korea's lower official EFs for coal combustion reflect the country's investment in advanced pollution prevention facilities and high-efficiency power plants.[19] Similarly, for natural gas, Korea's power plant infrastructure comprises a mix of combined cycle thermal plants with various capacities, utilizing eco-friendly processes.[20] Our calculations, using SimaPro's default value for a 100MW combined cycle thermal plant, may overestimate emissions compared to these more advanced systems.

However, it is crucial to note that the reliability of Korea's official EF values is questionable due to the lack of transparency in their calculation process. Without detailed information on how these official EFs are derived, it is challenging to validate their accuracy or understand the underlying assumptions. This lack of transparency not only hinders proper comparison but also raises concerns about the credibility of the official figures.

The discrepancy between our calculated EFs and Korea's official EFs underscores the importance of country-specific data in policy-making. Using generalized models might lead to overestimation of emissions, potentially resulting in misguided policies. Conversely, potentially underestimated official EFs could lead to complacency in emission reduction efforts.

The observed differences highlight the need for more detailed, country-specific life cycle assessments of energy systems. Future research should focus on incorporating the specific technologies and processes used in Korea's power sector to provide more accurate EFs.

These implications collectively underscore the complexity of assessing the environmental impact of different energy sources. They emphasize the critical importance of considering local context, technological advancements, and specific power generation mix in environmental impact assessments. Moreover, they stress the urgent need for greater transparency in the calculation and reporting of official EFs to ensure accurate environmental assessments and effective policy-making.

Temporal resolution analysis

Detailed analysis of temporal variations in GHG emissions from coal and natural gas electricity generation are presented in the

Table 2. Ozone depletion and particulate matter factor with transportation according to efficiency

Ozone depletion (kg CFC-11eq/kWh)	Coal		Natural gas	
	Only AUS	AUS:RUS	Only AUS	AUS:U.S.
High (70%)	2.55E-07	2.51E-07	2.41E-06	3.98E-06
Medium (50%)	2.74E-07	2.69E-07	3.30E-06	5.50E-06
Low (30%)	3.20E-07	3.11E-07	5.39E-06	9.05E-06
Particulate matter (kg PM 2.5eq/kWh)	Coal		Natural gas	
	Only AUS	AUS:RUS	Only AUS	AUS:U.S.
High (70%)	6.22E-04	5.84E-04	2.61E-02	4.44E-02
Medium (50%)	6.82E-04	6.28E-04	3.66E-02	6.22E-02
Low (30%)	8.21E-04	7.31E-04	6.09E-02	1.04E-01

Supporting Information. The temporal resolution in this study spans multiple scales: annual, quarterly, monthly, daily, hourly, and 30-min intervals. To demonstrate how different temporal resolutions affect trend identification, we compared monthly (Figure S1) and 30-min data (Figure S2) through graphical analysis. Our findings indicate that higher temporal resolution data, achieved through shorter time intervals, significantly improves both the accuracy and validity of GHG emission predictions by capturing greater variability in emission patterns.

Scenario-based emissions calculation

Finally, this study utilizes the environmental impact coefficients from the considered scenarios to calculate the amount of environmental pollutant emissions based on the total electricity generation in each year and compares these to the actual emissions for the corresponding years in Figure 6.

Analysis of scenario-based emissions

As shown in Figure 4, scenarios using only natural gas result in approximately 5 $\sim$ 20 times the emissions of those using only coal, indicating that the GHG emissions throughout the entire process of natural gas utilization are significantly higher. This stark difference underscores the necessity of reducing emissions during the natural gas transportation process.

Implications of energy mix on emissions

The analysis reveals a notable pattern regarding Scope 3 emissions, particularly in scenarios simulating energy import-dependent countries. As evidenced by the data, greenhouse gas emissions associated with combustion, electricity generation, and substation processes (Scope 1 and 2 emissions) are substantially lower for natural gas compared to coal. However, the inclusion of Scope 3 emissions alters this relationship significantly.

In the scenarios examined, countries with domestic energy resources, such as the United States, Russia, and Australia, demonstrate considerably lower Scope 3 emissions related to upstream transportation. Conversely, the model indicates that energy import-dependent nations, exemplified by countries like Korea and Japan, would experience markedly higher Scope 3 emissions.

Quantitative comparison of emissions

When it's 100% efficient, while natural gas scenarios exhibit lower Scope 1 and 2 emissions (0.662 kg CO_2 eq/kWh for both AUS and AUS:US scenarios) compared to coal scenarios (1.053 kg CO_2 eq/kWh for AUS and 1.068 kg CO_2 eq/kWh for AUS:RUS), the inclusion of Scope 3 emissions reverses this trend. Specifically, total emissions for natural gas scenarios (4.022 kg CO_2 eq/kWh for AUS and 6.357 kg CO_2 eq/kWh for AUS:US) surpass those of coal scenarios (1.107 kg CO_2 eq/kWh for AUS and 1.116 kg CO_2 eq/kWh for AUS:RUS) when Scope 3 is considered.

These results underscore the significant contribution of transportation-related emissions to the overall GHG profile in energy import scenarios, particularly for natural gas. The data suggest that while natural gas demonstrates lower environmental impact in terms of direct electricity generation, the emissions associated with its international transportation can substantially increase its overall GHG footprint in import-dependent contexts.

This comprehensive analysis, incorporating high-resolution temporal data and scenario-based calculations, provides a

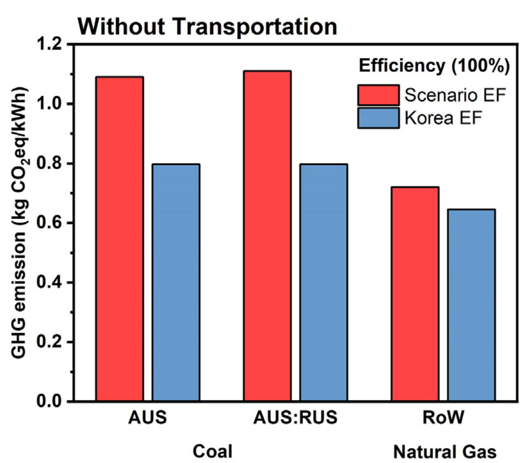

Figure 5. Comparison of GHG emission factors (EFs) for different energy sources: scenarios excluding transportation in this study (red bars) versus officially disclosed EFs in Korea (blue bars)

The graph presents EFs for coal from Australia (AUS), coal from Australia and Russia (AUS: RUS), and natural gas from Rest of World (RoW). All values are expressed in $kgCO_2$-equivalent per kWh.

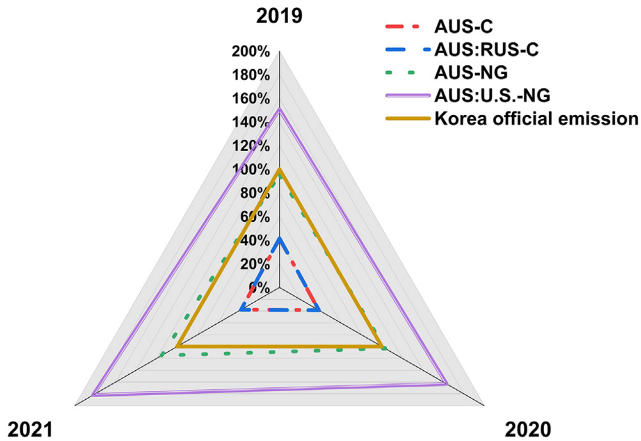

Figure 6. Ratio of the scenario emissions to total annual GHG emissions in Korea

"C" represents coal and "NG" represents natural gas. The ratio is calculated using the total GHG emissions in 2019, 2020, and 2021[21–24] based on the four scenarios: AUS Coal only, AUS:RUS (Coal), AUS Natural Gas only, and AUS:U.S. (Panama) Natural Gas.

nuanced understanding of the complexities involved in assessing and managing GHG emissions in the context of South Korea's energy sector. The findings highlight the critical importance of considering transportation-related emissions, particularly for import-dependent countries, and the value of high-resolution data in developing effective emission reduction strategies.

Emissions with uncertainty

Uncertainty refers to the possibility or extent of occurrence of unexpected items in addition to considerations of scenarios that set system boundaries. The results performed in this study are values for GHG emissions, ozone depletion, and particulate matter that occurs when only the assumptions in most scenarios are considered. So, for considering uncertainty, Monte Carlo simulation method is used to analyze the uncertainty and sensitivity of the main parameters. Through this, a 95% confidence interval is presented and the difference in the emission range due to in transport distance and fuel calorific value is identified. Table 3 provides information on the mean, median, and reliability of the uncertainty analysis for each scenario, and Figure 7 is a graph of the range of emissions calculated by the uncertainty analysis.

In Figure 7, natural gas scenario exhibiting higher emissions centered at 6.315 kg CO_2eq/kWh with a tight distribution (6.310–6.320). The probability distributions reveal that natural gas scenarios (c,d) result in significantly higher GHG emissions compared to coal scenarios (a,b), with the mixed US-Australian natural gas sources showing the highest emissions. All scenarios demonstrate normal distributions with varying degrees of spread, reflecting the uncertainty in emission calculations.

Conclusion

In the case of GHG emissions by scope emission in four scenarios through this study, when using AUS coal only, Scope 1 is 0.033 kg CO_2eq/kWh, Scope 2 is 1.020 kg CO_2eq/kWh, and Scope 3 is 0.54kg CO_2eq/kWh. When using AUS:RUS = 50:50 coal, Scope 2 is the same, but Scope 1 is 0.0487 kg CO_2eq/kWh and Scope 3 is 0.048 kg CO_2eq/kWh. In addition, when using AUS NG only, Scope 1 is 0.058 kg CO_2eq/kWh, Scope 2 is 0.604 kg CO_2eq/kWh, and Scope 3 is 3.360 kg CO_2eq/kWh, and when using AUS:U.S. = 50:50 NG, Scope 1 and 2 are the same, but Scope 3 is 5.695 kg CO_2eq/kWh which showed a big difference. When calculating emissions excluding transportation (Scope 3), so it is 1.053 kg CO_2eq/kWh when using only AUS coal, 1.0687 kg CO_2eq/kWh for AUS:RUS = 50:50 coal, and 0.662 kg CO_2eq/kWh for natural gas. In other words, compared to coal, natural gas is greatly affected by emissions during transportation.

When transportation is not considered, the emission of coal is higher than that of official domestic emissions, while natural gas showed relatively similar emissions, which also means that it is essential to consider emissions when transporting natural gas during the power generation process using natural gas. This trend is the same in ozone depletion and fine particulate matter.

Table 3. Values related to GHG emissions (100% efficiency) in each scenario considering uncertainty

kg CO_2 eq/kWh		Mean	Median	SD	CV	2.5%	97.5%
Coal	AUS	1.05	1.05	0.00138	0.131%	1.05	1.05
	AUS:RUS	1.06	1.06	0.00133	0.125%	1.06	1.07
Natural Gas	AUS	3.98	3.98	0.00119	0.03%	3.98	3.98
	AUS:U.S.	6.31	6.31	0.00115	0.0183%	6.31	6.32

The emission range considering uncertainty is the value excluding the transmission and distribution GHG emission with transmission and distribution loss rate obtained from GREET. This is because it is not possible to add the process of directly adding the emissions calculated through GREET.

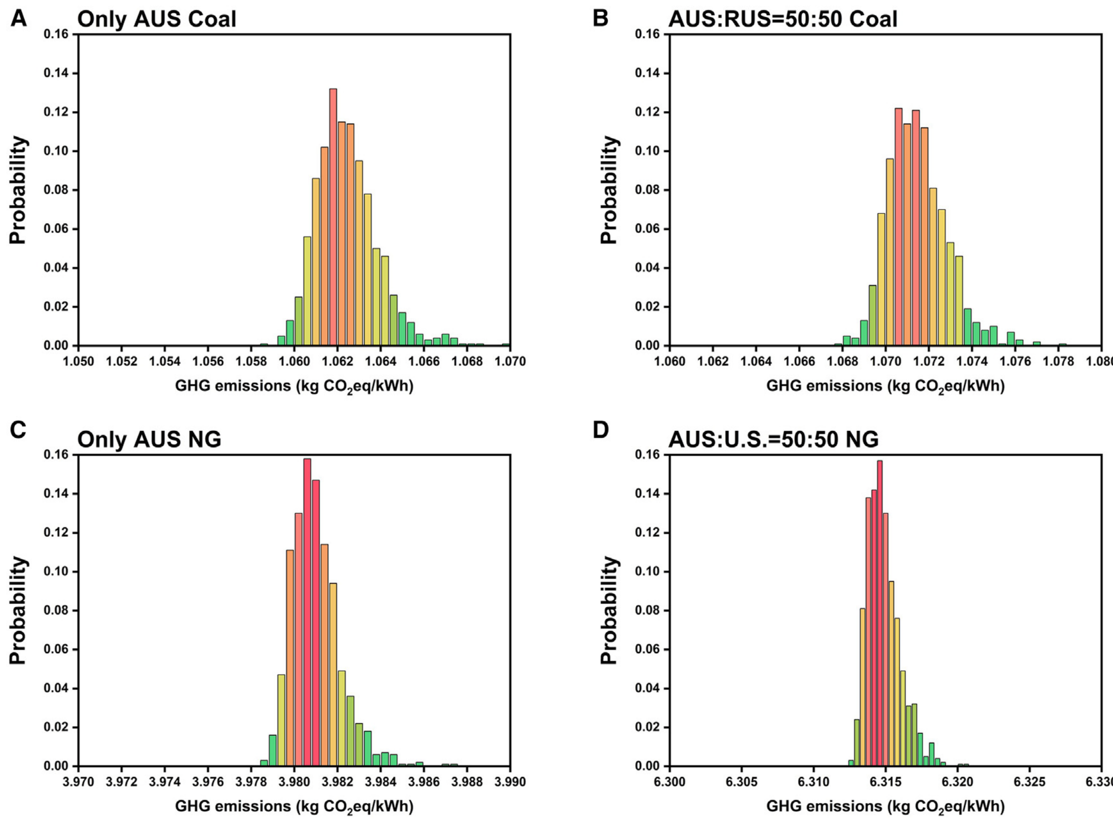

Figure 7. Probability distributions of GHG emissions calculated using Monte Carlo simulation for different fuel sourcing scenarios

(A) Only AUS Coal scenario.

(B) AUS:RUS = 50:50 Coal scenario showing emissions centered around 1.072 kg CO_2eq/kWh with a narrow distribution range (1.068–1.078), indicating relatively stable emissions.

(C) Only AUS Natural Gas scenario demonstrating emissions concentrated at approximately 3.982 kg CO_2eq/kWh with moderate variability (3.978–3.986).

(D) AUS:U.S. = 50:50 natural gas scenario.(6.312–6.322).

In short, these results underscore the significant contribution of transportation-related emissions to the overall GHG profile in energy import scenarios, particularly for natural gas. The data suggest that while natural gas demonstrates lower environmental impact in terms of direct electricity generation, the emissions associated with its international transportation can substantially increase its overall GHG footprint in import-dependent contexts.

Based on these emissions, Korea's electricity consumption collected in time series is used to identify trends in emissions and trends in future emissions. The maximum, minimum, and average emission values are calculated using monthly and 30-min power usage data and then graphed. Unlike monthly data, which is difficult to grasp volatility due to data limitations, 30-min data have the advantage of being relatively easy to grasp volatility. So, this comprehensive analysis, incorporating high-resolution temporal data and scenario-based calculations, provides a nuanced understanding of the complexities involved in assessing and managing GHG emissions in the context of South Korea's energy sector. The findings highlight the critical importance of considering transportation-related emissions, particularly for import-dependent countries, and the value of high-resolution data in developing effective emission reduction strategies.

DISCUSSION

This study has quantified the greenhouse gas (GHG) emission factors associated with electricity-related activities for Korea's primary energy sources, providing data to elucidate GHG emission trends. The findings highlight that, due to Korea's high dependence on energy imports, GHG emissions attributable to transportation significantly exceed those from electricity generation, resource extraction, and storage.

Japan and Taiwan face similar energy dependency challenges, with energy self-sufficiency rates of approximately 12.6% (as of 2022)[25,26] and 3.8%, respectively. Japan and Korea have geographically similar conditions, so Scope 3 emissions are mostly determined by Upstream Transportation. The European Union's introduction of the CSRD exemplifies a global trend toward enhanced transparency in environmental, social, and governance (ESG) reporting. This directive mandates the inclusion of Scope 1, 2, and 3 emissions data in accordance with the Greenhouse Gas Protocol. As a result, nations heavily dependent on energy imports, such as Japan, Korea, and Taiwan, must urgently develop accurate quantification methods and implement reduction strategies for upstream transportation emissions within Scope 3. In response to these challenges, Japan has introduced its 2021 "Green Growth Strategy," which includes plans to commercialize e-fuels by 2050.[27] Similarly, Taiwan's "2050 Carbon Neutrality Roadmap" focuses on expanding de-nuclearization and renewable energy initiatives to reduce transportation-related GHG emissions.

While the transition to eco-friendly fuels in energy import-dependent countries is prioritized, and efforts to reduce GHG emissions using existing infrastructure continue, the ultimate objective remains achieving "Net Zero" emissions. This goal necessitates the expansion of renewable energy sources, which are currently recognized for their minimal GHG emissions. For Korea, where geographical conditions may limit renewable energy installation, further research into technologies that maintain electricity generation efficiency across varied topographies and climates is crucial.

However, it is important to acknowledge the limitations of this study. The Scope emissions methodology, while providing valuable insights, is still a developing approach for calculating greenhouse gas emissions. The complexity of supply chains and the variability in data quality and availability across different sectors can lead to uncertainties in Scope 3 emissions calculations. Furthermore, our study focused primarily on transportation-related Scope 3 emissions, which may not fully capture all indirect emissions associated with electricity generation and distribution.

Future research should address these limitations by expanding the analysis to include a more comprehensive range of Scope 3 emissions categories and developing more robust methodologies for quantifying and verifying Scope 3 emissions, particularly in the context of international energy trade. Investigating the potential for emerging technologies, such as blockchain, to improve the traceability and accuracy of emissions data throughout the supply chain could also prove beneficial. Conducting comparative studies across multiple countries with similar energy import dependencies could identify best practices and potential areas for international cooperation in emissions reduction. Additionally, exploring the long-term implications of transitioning to renewable energy sources on Scope 3 emissions, particularly in countries with limited domestic renewable resources, would provide valuable insights.

To strengthen efforts in reducing GHG emissions, we recommend implementing more stringent reporting requirements for Scope 3 emissions, particularly for companies involved in international energy trade. Developing and adopting standardized methodologies for calculating and reporting Scope 3 emissions across different industries and countries would ensure comparability and transparency. Investing in research and development of low-emission transportation technologies specifically tailored for long-distance energy transport is crucial. Establishing international collaborations to create a more efficient and less emission-intensive global energy supply chain should be prioritized. Integrating high-resolution temporal data analysis into national and corporate emissions monitoring systems would enable more targeted and effective emission reduction strategies. Finally, encouraging the development of local renewable energy sources, even in geographically challenging areas, through targeted policy incentives and technological innovation is essential.

In conclusion, while this study provides valuable insights into the complexities of GHG emissions in energy-dependent countries like Korea, it also underscores the need for continued research and international cooperation in addressing the challenges of climate change. By adopting a more comprehensive approach to emissions calculation and implementing targeted strategies for reduction, countries can move closer to achieving their net-zero emissions goals and contributing to global climate mitigation efforts.

Limitations of the study

The emission calculations in this study are based on specific scenarios and assumptions about transportation routes and energy source combinations, which may differ from real-world emissions depending on actual transportation paths and fuel sourcing decisions. While our uncertainty analysis considers variations in transport distance and fuel calorific value, it may not capture all potential sources of variability in the complete life cycle of electricity generation. The study focuses primarily on transportation-related Scope 3 emissions, which may result in incomplete capture of all indirect emissions associated with electricity generation and distribution. Our analysis using high-resolution temporal data provides valuable insights but is limited to the 2019–2021 period, potentially not fully reflecting longer-term trends or future scenarios. The comparison with official emission factors is constrained by limited transparency in how these official values are calculated in Korea. Furthermore, the study's findings are most directly applicable to countries with similar energy import dependencies and infrastructure to South Korea, and may require adaptation for countries with different energy profiles.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Boreum Lee (boreum.lee@jnu.ac.kr).

Materials availability

This study did not generate new unique reagents or materials.

Data and code availability

- Data: Historic electricity generation and consumption data used in this study were obtained from Korea Electric Power Corporation (KEPCO) monthly reports (2019–2021). These reports are publicly available through KEPCO's website.
- Code: The SimaPro and GREET analyses performed in this study used standard software packages and did not require custom code development. The calculation methodologies are fully described in the method details section.
- All other requests: Any additional information required to reanalyze the data reported will be shared by the lead contact upon request.

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AUTHOR CONTRIBUTIONS

Conceptualization and methodology, writing—original draft, S.Kim; investigation, validation, software, S.Koh; writing—review and editing, project administration, supervision, funding acquisition, B.L.

DECLARATION OF INTERESTS

The authors declare no competing interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used Claude in order to correct grammar and spelling. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- METHOD DETAILS
  - Goal and scope definition
  - Input data
  - Design parameters
  - Impact metric
  - System boundary
  - Transportation & distribution
  - Temporal resolution
  - Loop Data
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Toward standardized grid emission factors: methodological insights and best practices	Schäfer et al.[14]	https://doi.org/10.1039/D3EE04394K
Overseas Countries regarding LNG imports with Long-term Contracts and Port Status	KOGAS[28]	https://www.kogas.or.kr/site/eng/1060101030000
A study on the Coal Resource Transport Routes Between Russia and South Korea	Subeom et al.[29]	https://doi.org/10.22892/ksc2021.25.2.02
Life Cycle Analysis of Greenhouse Gas Emissions of By-Product Hydrogen Produced from Coke Oven Gas in Steel Mill	Yeim et al.[30]	https://doi.org/10.7316/KHNES.2022.33.6.636
Software and algorithms		
SimaPro	PRé Sustainability	https://simapro.com/
GREET	U.S. Department of ENERGY	https://greet.anl.gov/index.php?content=greetdotnet

METHOD DETAILS

Goal and scope definition

This study aims to establish guidelines for evaluating GHG emissions in the power sector of countries highly dependent on energy imports. As a representative case study, we examine Korea, where energy import dependence reaches approximately 94%.[31] For the Life Cycle Assessment (LCA), we adopt the Cradle-to-Gate approach, which calculates emissions from electricity generation through point of sale. While a Cradle-to-Grave analysis would be theoretically ideal, its expansive system boundaries necessitate a global modeling approach that introduces significant complexity. Therefore, we deliberately chose the Cradle-to-Gate methodology to maintain analytical precision while ensuring practical applicability.[32]

Input data

This study utilizes data from multiple sources to ensure a comprehensive analysis. The primary datasets include 1) Korea Electric Electricity Exchange: Electricity Demand by Hour from the Korea Statistical Office and public data portal and 2) Electricity Use by Industry Classification and by Purpose from the electricity data open portal system.

These datasets are synthesized to create stationary data, which is subsequently analyzed using SimaPro software, developed by Pré Sustainability in the Netherlands. SimaPro is a widely used life cycle assessment tool that allows for the evaluation of environmental impacts across various industries and products.

For transportation-related data, this study employs the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) 2023 model, developed by Argonne National Lab in the United States. The GREET model is a comprehensive tool for analyzing total energy consumption, fossil fuel energy use, and other relevant parameters for energy and vehicle systems.

Design parameters

This section elucidates the setting values and rationale for determining various factors essential for calculating the EF for GHG emissions, as illustrated in Figure 1.

Impact metric

This study focuses on assessing environmental impacts, particularly GHG emissions (kgCO_2-eq), ozone depletion (ODP, kgCFC11-eq), and fine particulate matter (PM, kgPM2.5-eq). For calculating GHG emissions, we employ the Global Warming Potential over a 100-year time horizon (GWP100). This selection aligns with the European Commission's Joint Research Center recommendations, which identifies global warming, ozone depletion, and particulate matter/respiratory inorganics (I/II) as Quality Level 1 indicators most suitable for Life Cycle Assessment9. Following these guidelines, we adopt these Quality Level 1 metrics (GHG, Ozone Depletion, and Fine Particulate Matter) as our impact indicators.[32] The choice of GWP100 is particularly appropriate as it provides an optimal balance between short-term and long-term impacts while being the most widely accepted metric in climate policy and research.[33] While alternative time horizons such as GWP20 or GWP500 can provide insights into short-term or very long-term effects, GWP100 aligns with international reporting standards and allows for comparability with other studies in the field.

The study adopts an LCA approach, which can be conducted at three different levels of detail: High, Medium, or Low. The selected level of detail determines the comprehensiveness of the LCA. For the transportation and distribution of raw materials (coal and natural gas), we consider four scenarios involving different sourcing locations 1) Australia (Coal 100%), all coal is sourced from Australia, 2) Australia (Natural gas 100%), all natural gas is sourced from Australia, 3) Australia and Russia (Coal 50:50), Coal is sourced equally from Australia and Russia, and 4) Australia and the U.S. (Natural gas 50:50), Natural gas is sourced equally from Australia and the U.S.

The study considers various temporal scales for analysis, including annual, seasonal, monthly, hourly, and 30-min intervals. The selection of temporal resolution depends on data availability and the specific objectives of each analysis phase.

System boundary

Figure 2 presents the system boundary and scope of the study, which aims to assess the environmental impact of electricity generation and distribution in South Korea.

The process commences with the transportation of raw materials, specifically coal and natural gas, from their respective sources to electricity generation facilities. Upon arrival at the power plants, the raw materials undergo electricity generation, which is categorized into three efficiency levels: high, medium, and low, representing the conversion of energy content into usable electricity. Following the generation process, the electricity is transmitted through the transmission network and subsequently distributed to end-users via the distribution network.

The study accounts for the emissions associated with these stages of the electricity supply chain. The system boundary of the study encompasses three distinct scopes of emissions: 1) Scope 1 emissions, which refer to direct emissions resulting from the electricity generation process at the power plants. 2) Scope 2 emissions, which include indirect emissions associated with the production of the raw materials (coal and natural gas) utilized in the electricity generation process. 3) Scope 3 emissions, which account for indirect emissions related to the transportation of raw materials from their sources to the electricity generation facilities.[34]

This comprehensive approach allows for a holistic assessment of the environmental impact, considering the entire life cycle from raw material extraction to end-use of generated electricity.

Regarding energy materials, South Korea heavily relies on imports rather than domestic production, with approximately 94% of its energy dependence attribute to imports in 2023.[31]

To accurately calculate the total GHG emissions during the energy production process, it is crucial to simultaneously consider the emissions from transportation and distribution associated with imported energy sources. This study, following the GHG Protocol, classifies Scope 1, 2, and 3 emissions as follows: 1) Scope 1 encompasses direct GHG emissions from the electricity generation process, including emissions resulting from fuel combustion at power plants. 2) Scope 2 includes indirect GHG emissions associated with energy production processes, particularly those from the production of purchased energy. 3) Scope 3 comprises GHG emissions from transportation processes, specifically emissions occurring during the transport of energy resources. It also includes indirect emissions due to losses in the transmission and distribution processes, as well as those related to substation operations.

It is important to note that this study focuses primarily on upstream and downstream transportation within the Scope 3 emissions category. This approach was necessitated by limitations in data availability from real companies and the need to avoid making numerous assumptions for calculating other Scope 3 emission categories. The complexity and potential inaccuracies involved in estimating other Scope 3 categories, such as employee commuting or end-of-life treatment of sold products, led to their exclusion from this analysis. While the relative contribution of these omitted categories to the overall emissions profile in the context of energy production and distribution is not precisely known, the focus on transportation-related emissions is expected to capture a significant portion of the Scope 3 emissions relevant to this sector. This limitation should be considered when interpreting the results and comparing them to other comprehensive Scope 3 emission assessments.

The efficiency (yield) according to the loss rate is categorized into three levels: High (70%), Medium (50%), and Low (30%). These percentages are assumed values, and it is important to note that the efficiency levels in this context refer to the efficiency of the fuel required to produce 1 kWh of electricity, rather than the electricity loss rate.

In this study, the total electricity production in Korea is set to 566.86 TWh, which is approximately similar to the 614.19 TWh generated in South Korea in 2023 and 52 times lower compared to the 29,480.35 TWh generated worldwide in the same year.[35] This value represents the total amount of electricity transmitted and distributed. The production of coal and natural gas is calculated accordingly.

Based on the energy calorific conversion standard outlined in the Enforcement Regulations of the Energy Act, imported anthracite for fuel has a calorific value of 5,500 kcal per kg, equivalent to approximately 6.4 kWh. For natural gas, liquefied natural gas (LNG) has a calorific value of 10,190 kcal per Nm^3 of LNG based on city gas, which is approximately 11.85 kWh. Considering the density of natural gas at 456 kg/N m^3, the imported anthracite required for fuel when only coal is used amounts to approximately 88,572,653 tons. In contrast, LNG amounts to about 21,813,538,317 tons. These calculated values are the basis for determining the values in the following scenario.[36–38] Subsequently, the study investigates the proportion of environmental pollutants in the energy sector relative to the total production of environmental pollutants in Korea when the scenarios of this study are applied.

Transportation & distribution

This section establishes standards for South Korea's energy source import routes and the subsequent transmission and distribution processes following electricity generation. For coal imports, both Australia and Russia utilize bulk carriers, while for natural gas, Australia and the U.S. employ LNG carriers. The selection of these specific vessel types is primarily influenced by the distinct physical characteristics and transportation requirements associated with each energy source.

Coal is well-suited for storage and transportation in large quantities. Bulk carriers are vessels specifically designed to accommodate the transportation of unpackaged, loose bulk cargo such as coal, grains, and ore. In contrast, natural gas exists in a gaseous state under ambient temperature and pressure conditions. To optimize transportation efficiency over extended distances, natural gas undergoes a liquefaction process, which involves cooling the gas to approximately −162°C (−260°F) at atmospheric pressure.[39] LNG carriers are specialized vessels designed to transport this cryogenic liquid safely and efficiently. The distances from the energy source exporting countries (Australia, Russia, and the United States)[28–30] to South Korea are presented in Figure 3.

Specifically, Figure 3 presents two potential routes from the US to South Korea. Upon analysis, the route traversing the Panama Canal demonstrates superior efficiency in terms of both distance and time compared to the alternative route passing through Cape Town. Consequently, for the purposes of this study, the Panama Canal route has been selected as the preferred option for energy transportation from the U.S.

Regarding import terminals in South Korea, it is important to note that while multiple LNG and coal import facilities exist throughout the country, specific ports have been designated for this analysis based on their strategic importance and operational capabilities. For coal imports, the ports by Busan and Pohang have been selected, while for natural gas imports, Incheon Port has been designated as the primary point of entry. This selection is due to Busan and Pohang having significant industrial centers with high coal demand, while Incheon is a major LNG terminal. The choice of different locations for coal and natural gas imports is based on strategic factors. Busan and Pohang, chosen for coal imports, are major industrial centers with high coal demand due to nearby steel mills and heavy industries. Incheon Port, designated for natural gas imports, boasts specialized LNG handling facilities including cryogenic storage and regasification plants.[40] This allocation optimizes the supply chain, leverages existing infrastructure, and aligns with regional energy needs.

For the weight of coal and natural gas per transport, this study utilizes GREET's Default values. It is assumed that each coal shipment transports 27,216 tons, while each natural gas shipment carries 58,967 tons. These factors are incorporated into the transportation component of the SimaPro for analysis.

Transmission and distribution lines play a crucial role in the process of distributing electricity post-generation. However, this study excludes most of the electricity transfer and distribution lines, as well as emergency generators owned by the private sector and various workplaces, as they operate only in specific situations and are not continuous in nature. Furthermore, the current domestic transmission line infrastructure does not require additional installation; thus, additional infrastructure construction is not considered in this analysis.

To calculate the EF for transmission line, the study incorporates the transmission line length value into the calculation prior to the electricity generation and substation process, using the default values provided by the SimaPro. Since the GHG emission coefficient according to the electricity loss rate through the transmission line is difficult to calculate by SimaPro, the final emission coefficient is calculated by summing GREET's transmission line emission coefficient with each coefficient calculated by SimaPro. This approach is necessitated by the current classification of domestic transmission line information, which is organized by voltage without clear information on the purpose of each voltage level.

Transmission and Distribution Loss Analysis in South Korea's Electricity Network

Electricity line (MWh)		566,864,976			
Electricity Transmission Loss	Electricity distributor	557,950,473	Electricity Distribution Loss	Sales Volume	546,845,160
	Loss	8,914,502		Loss	11,105,313
	Loss (%)	1.57%		Loss (%)	1.99%
Total Loss		20,019,815		3.53%	

Since there are no coefficients for substations within SimaPro, the calculation of substation coefficients is replaced through the process of converting electricity from high voltage to low voltage. During this process, high voltage is classified as factory operation (Plant), medium voltage as company operation, and low voltage as residential use. This classification refers to each proportion of Korea's electricity consumption in 2022 (15% for residential use, 23% for general, 54% for industrial use).[41] High voltage electricity is assumed to constitute 55% of the total electricity mix. To reflect this distribution, SimaPro has been configured to allocate 27% to medium voltage and 18% to low voltage electricity.

Temporal resolution

Regarding temporal resolution, previous studies[42,43] typically presented electricity consumption on annual, seasonal, monthly, and hourly bases when calculating electricity usage. However, subdividing the time unit when calculating GHG emissions related to electricity consumption can contribute to a more accurate evaluation of GHG emissions.[44] Consequently, this study employs a more granular approach by utilizing 1-h interval values. To achieve this, 30-min interval values between each pair of hourly data points are interpolated, based on the methodology. By adopting this more refined temporal resolution, our study aims to contribute to a more accurate evaluation of GHG emissions, offering a more detailed analysis than previous approaches.

Loop Data

Loop Data generated during the entire cycle is incorporated into the final EF calculation. It represents the resource or energy cycles within a specific process, particularly those related to reuse, recycling, and energy recovery in the product system. This concept is crucial for understanding the circular aspects of resource utilization. Within the system boundary established for this study, the EF calculation takes into account various forms of Loop data. A prime example is recycling in Carbon Capture, Utilization, and Storage (CCUS) technology. By incorporating these circular processes, our analysis aims to provide a more comprehensive and accurate assessment of the overall environmental impact.

QUANTIFICATION AND STATISTICAL ANALYSIS

All statistical analyses were performed in SimaPro & GREET.