Supplementary Information for Aligning EU Energy Security and Climate Mitigation through Targeted Transition Strategies

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This file includes:

- Supplementary Discussions
- Supplementary Methods
- Supplementary Figures 1 to 65
- Supplementary Tables 1 to 13

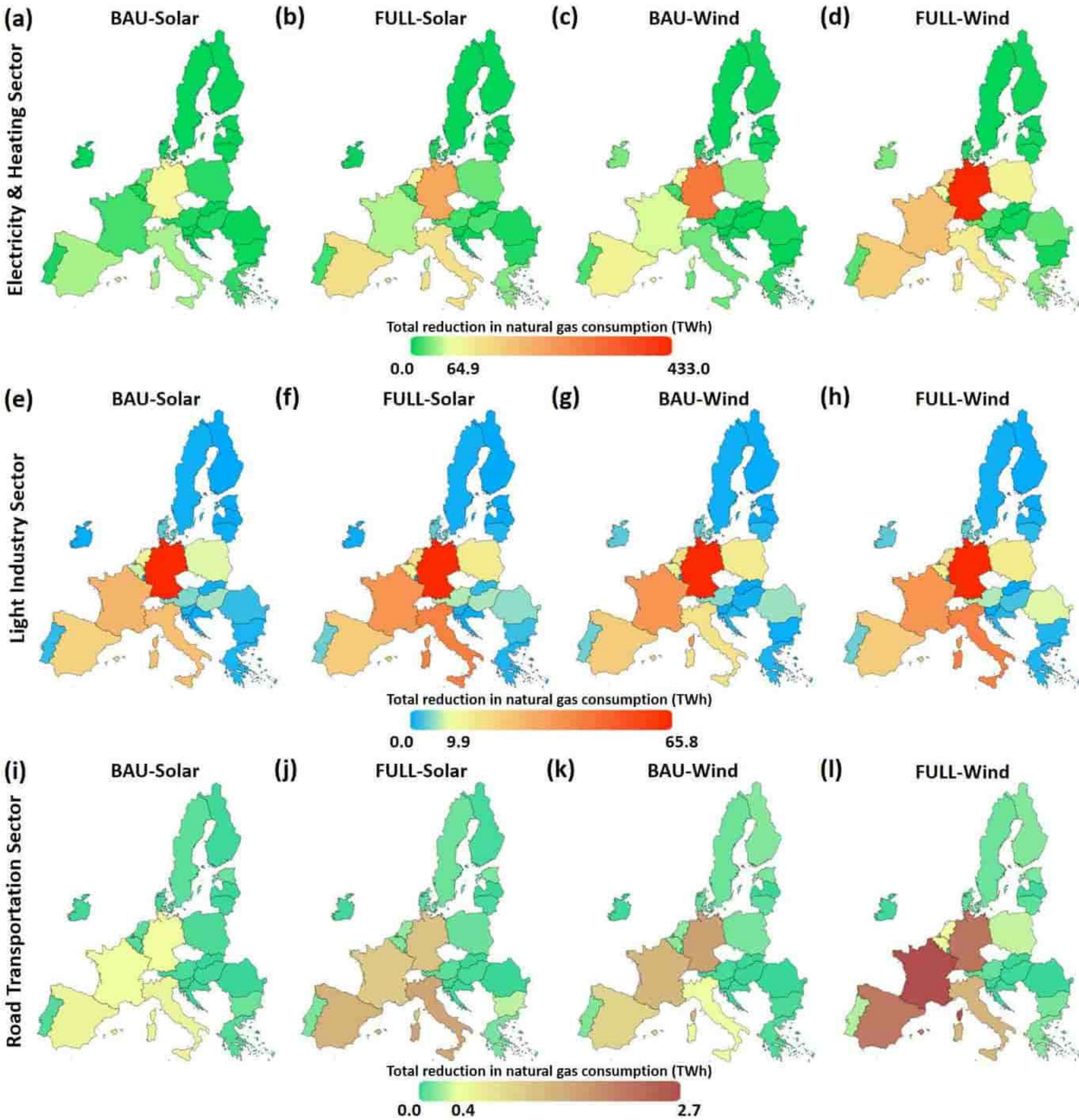
Supplementary Information

In this supplementary text, we present the detailed analysis and methodology employed to evaluate the scenarios for enhancing the EU's energy security and decarbonization potential amidst recent geopolitical disruptions. **Supplementary Discussion 1** presents supplementary results on sector-specific natural gas reductions, emissions trends, potential trade dynamics, regional cost evaluations across EU countries, and a comparative summary of insights from prior literature alongside the contributions of this work. **Supplementary Discussion 2** focuses on the grid integration challenges associated with fluctuating renewable energy sources, evaluated through the frequency distribution of net load ramp rates across different scenarios and time horizons. In **Supplementary Discussion 3**, we explore the technological penetration required in the EU's energy landscape to implement the electrification, green hydrogen, and carbon offsetting strategies based on renewable power growth scenarios. **Supplementary Methods** presents the comprehensive material and methods, including the scenario design, and optimization modeling framework utilized to assess the energy security benefits, decarbonization potential, and economic implications across different scenarios.

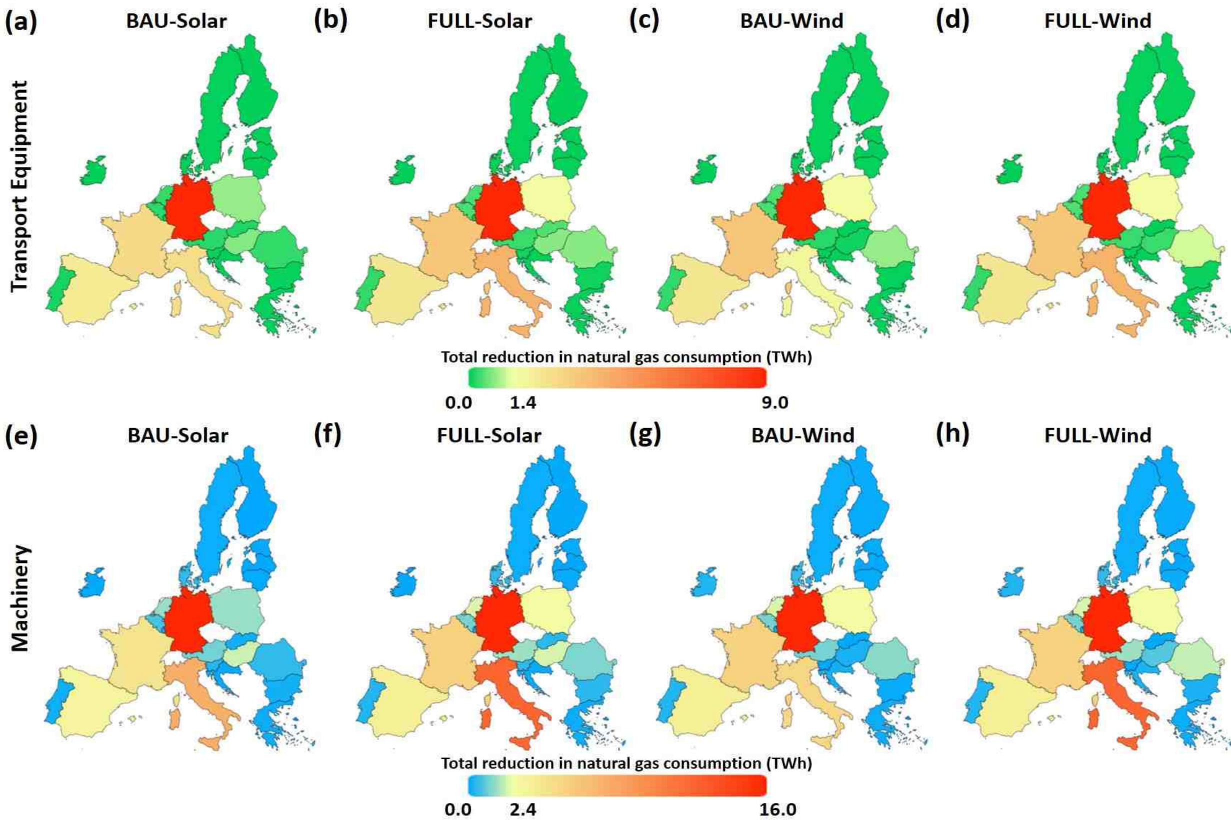
Supplementary Discussion 1: Sectoral Natural Gas Reductions, Emissions Trends, Trade Dynamics, and Regional Cost Evaluations Across the EU

In this section, we present the detailed sector-specific breakdown of the energy security and decarbonization benefits that can be attained across the EU countries under the investigated scenarios. The spatial analysis depicted in **Supplementary Figs. 1-11** reveals pertinent insights into the reduction of natural gas dependence in various sectors by 2050 under the BAU and FULL implementation scenarios for solar and wind power growth. The results highlight significant variations in the reduction of natural gas reliance across EU member states and sectors, with the most pronounced impact in countries such as Germany, Italy, France, and Spain. For instance, under the FULL-wind scenario, Germany achieves a potential reduction of up to 433.0 TWh in natural gas consumption in the electricity and heating sector alone, compared to a decrease of 296.4 TWh under the BAU-wind scenario. Similar trends are observed in countries such as Italy, where the FULL-wind scenario offers a more aggressive trajectory for energy security benefits, with up to 243.0% increased impact over the BAU scenario. In the light industrial sector, countries such as Germany and France exhibit a substantial decline in natural gas consumption, particularly under the FULL-wind scenario, which shows a reduction of up to 65.8 TWh and 36.7 TWh, respectively, by 2050. In contrast, the BAU-solar scenario offers more modest reductions of 28.7 TWh in France. Notably, in the road transportation sector, electrification potential leads to significant reductions, particularly in countries like Italy and France, where natural gas use in vehicles is displaced by clean electricity. The FULL-wind power reduces 1.4 TWh in Italy and 2.7 TWh in France, compared to 0.6 TWh and 0.4 TWh under the BAU-solar scenario, respectively. The impact of green hydrogen is particularly prominent in heavy industrial sectors such as iron and steel, non-ferrous metals, paper, pulp, and printing, refining, etc. The FULL implementation scenarios with the green hydrogen strategy show a decline of up to 19.5 TWh in natural gas use in the iron and steel sector in Germany, with other sectors such as ammonia production and refining contributing 11.7 TWh and 23.0 TWh of reduced dependence, respectively. In comparison, the BAU scenarios show a more limited impact, underscoring the importance of scaling up renewable capacity and green hydrogen deployment for maximum energy security and decarbonization impact. Countries with larger industrial footprints, such as Germany, Italy, France, and Spain, stand to benefit the most from increased adoption of electrification and green hydrogen technologies, particularly in sectors that are harder to decarbonize. Therefore, these findings highlight the need for targeted country-specific strategies to leverage the potential of renewables in mitigating natural gas reliance, especially amidst the escalating geopolitical uncertainties.

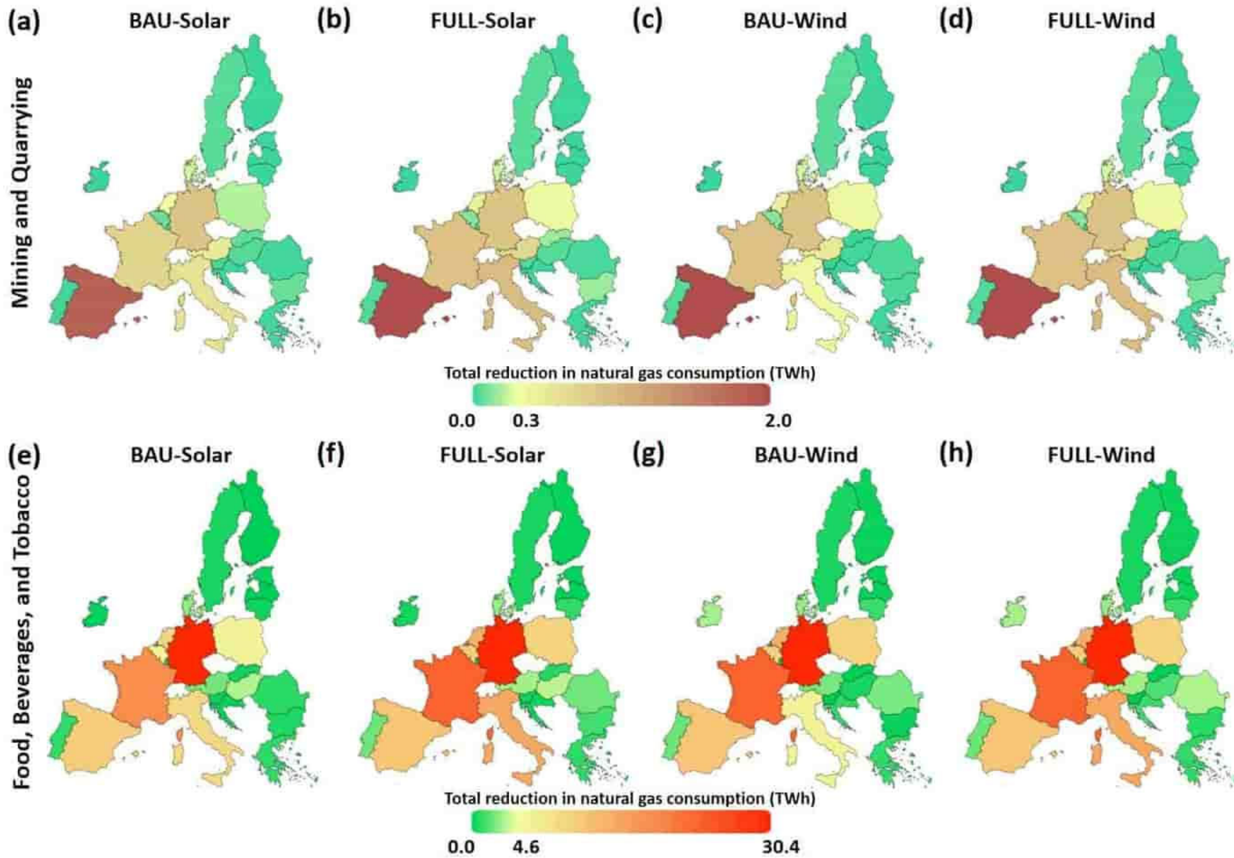
In order to evaluate the potential climate benefits, **Supplementary Figs. 12-21** depict the cumulative avoided emissions across various sectors in the EU countries that can be attained under the BAU and FULL implementation scenarios for solar and wind power growth. The results suggest that the electrification and green hydrogen strategies yield substantial emissions reductions in various light industries, heavy industries, and the road transportation sector, with notable spatial differences. In countries such as Germany and France, the FULL-wind scenario can achieve emissions reductions of up to 42.9 $MtCO_2$ and 15.5 $MtCO_2$ in the transportation equipment sector, while similar trends are observed in the machinery sector. Similarly, the high concentration of the non-ferrous metal sector in Germany and Spain drives its significant potential for avoided emissions. Under the FULL-wind scenario, the green hydrogen strategy in this sector alone accounts for up to 19.9 $MtCO_2$ and 5.0 $MtCO_2$ of avoided emissions in Germany and Spain by 2050, respectively. France, Italy, and Spain also show notable contributions to the avoided emissions in the food, beverages, and tobacco sectors. For instance, in Italy, cumulative emissions reductions under the FULL-solar power reach 58.4 $MtCO_2$ by 2050. Meanwhile, countries such as Poland and the Netherlands show significant emissions avoidance in sectors like refining and ammonia production, where green hydrogen can replace natural gas-based hydrogen. Similarly, Sweden and Finland can attain substantial climate benefits in sectors such as the paper, pulp, and printing industries, highlighting the regional diversity in decarbonization opportunities across the EU. Across the investigated scenarios, green hydrogen also plays a crucial role in industries such as cement/clinker and container glass, with Germany as the potential hotspot in these sectors. The FULL-wind scenario results in avoided emissions of up to 30.2 $MtCO_2$ and 5.7 $MtCO_2$ in Germany's cement and container glass sectors, respectively. These findings demonstrate that while larger economies like Germany, France, Spain, and Italy provide the majority of avoided emissions, there are significant opportunities across all EU member states. The spatial distribution in emissions reduction potential further highlights the importance of tailored country-specific strategies to achieve sector-specific decarbonization and energy security benefits.



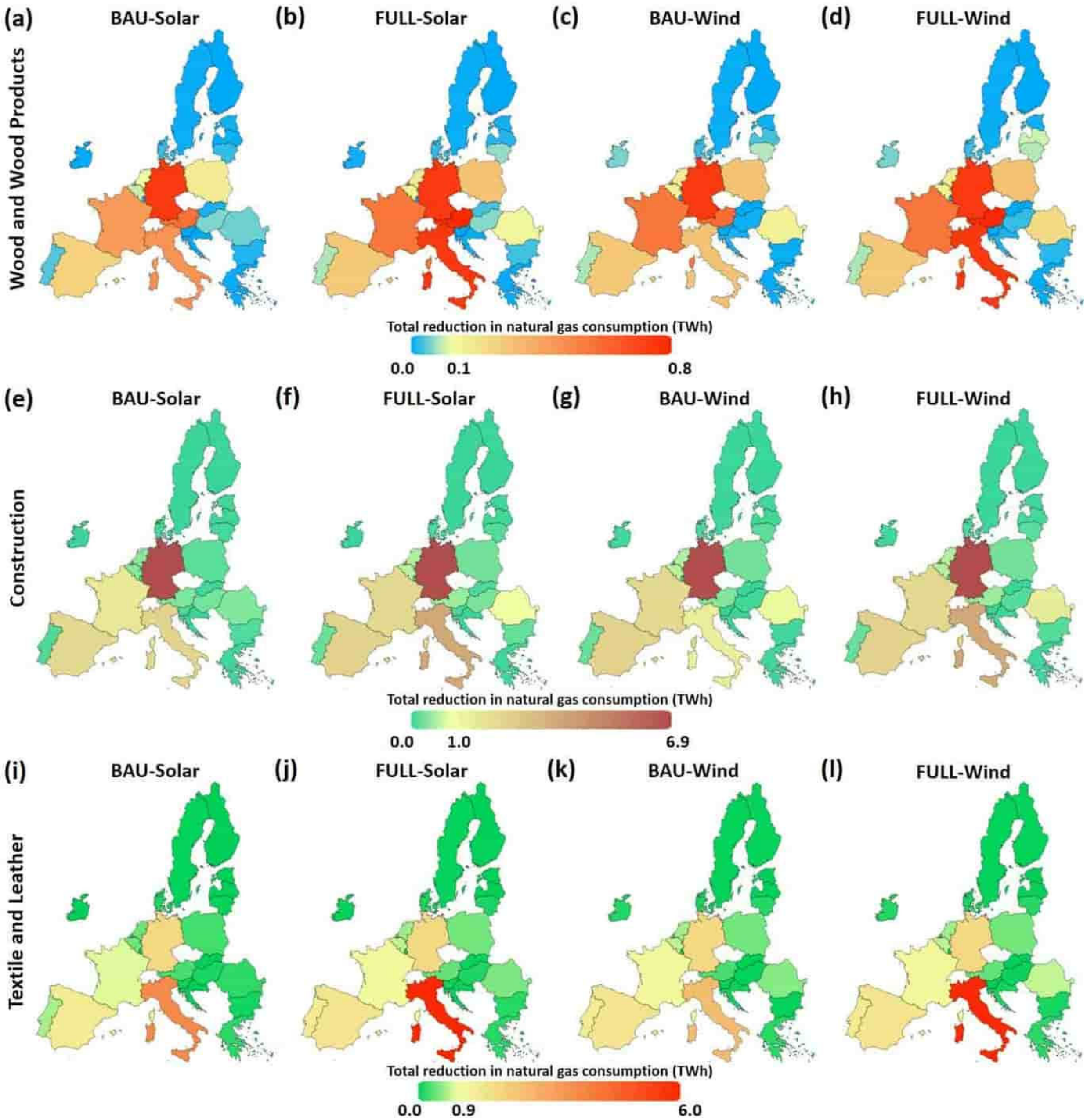
Supplementary Figure 1. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the electricity and heating sector, light industrial sector, and road transportation sector. a., Electricity and heating sector under the BAU-solar scenario. **b.,** Electricity and heating sector under the FULL-solar scenario. **c.,** Electricity and heating sector under the BAU-wind scenario. **d.,** Electricity and heating sector under the FULL-wind scenario. **e.,** Light industrial sector under the BAU-solar scenario. **f.,** Light industrial sector under the FULL-solar scenario. **g.,** Light industrial sector under the BAU-wind scenario. **h.,** Light industrial sector under the FULL-wind scenario. **i.,** Road transportation sector under the BAU-solar scenario. **j.,** Road transportation sector under the FULL-solar scenario. **k.,** Road transportation sector under the BAU-wind scenario. **l.,** Road transportation sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



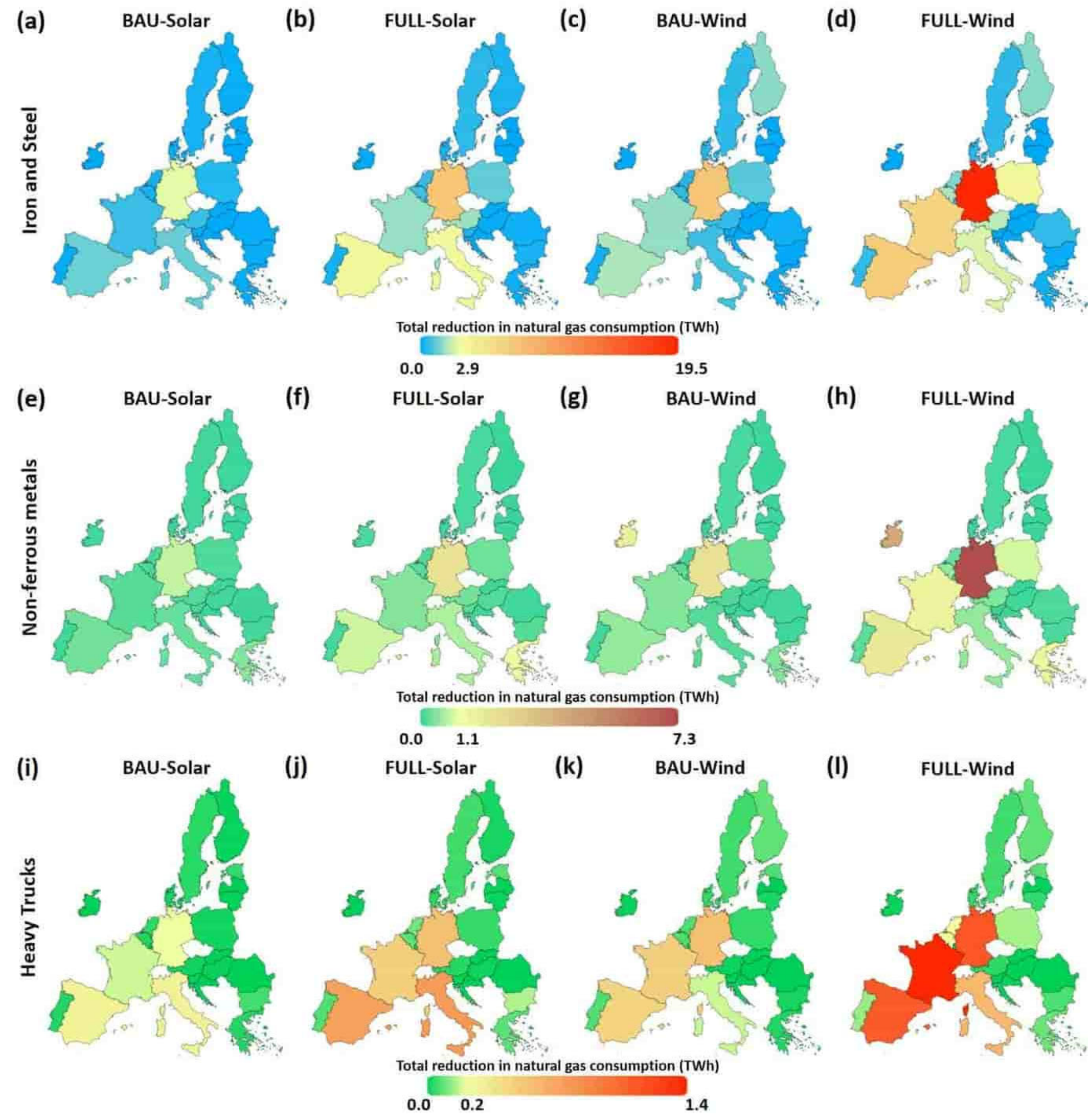
Supplementary Figure 2. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the transportation equipment sector and machinery sector. a., Transportation equipment sector under the BAU-solar scenario. **b.,** Transportation equipment sector under the FULL-solar scenario. **c.,** Transportation equipment sector under the BAU-wind scenario. **d.,** Transportation equipment sector under the FULL-wind scenario. **e.,** Machinery sector under the BAU-solar scenario. **f.,** Machinery sector under the FULL-solar scenario. **g.,** Machinery sector under the BAU-wind scenario. **h.,** Machinery sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



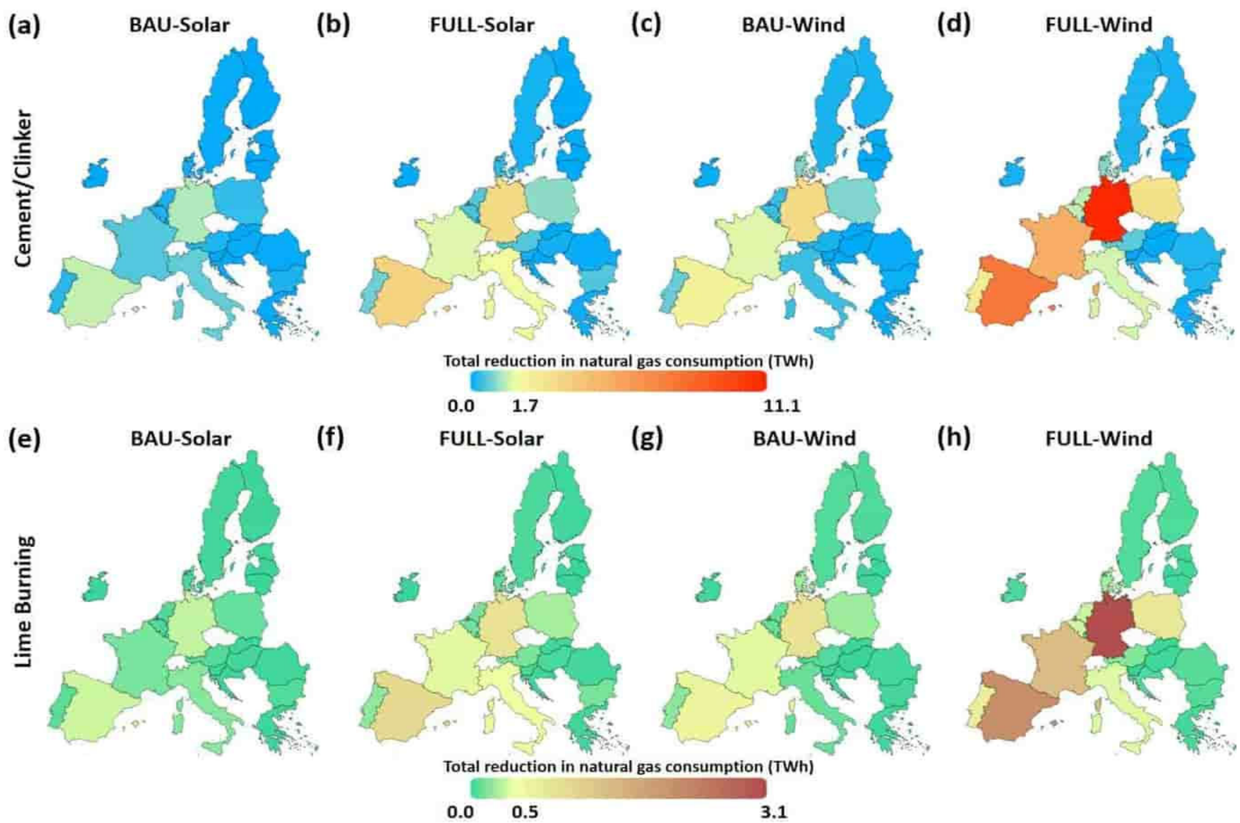
Supplementary Figure 3. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the mining and quarrying sector and the food, beverages, and tobacco sector. a., Mining and quarrying sector under the BAU-solar scenario. **b.,** Mining and quarrying sector under the FULL-solar scenario. **c.,** Mining and quarrying sector under the BAU-wind scenario. **d.,** Mining and quarrying sector under the FULL-wind scenario. **e.,** Food, beverages, and tobacco sector under the BAU-solar scenario. **f.,** Food, beverages, and tobacco sector under the FULL-solar scenario. **g.,** Food, beverages, and tobacco sector under the BAU-wind scenario. **h.,** Food, beverages, and tobacco sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



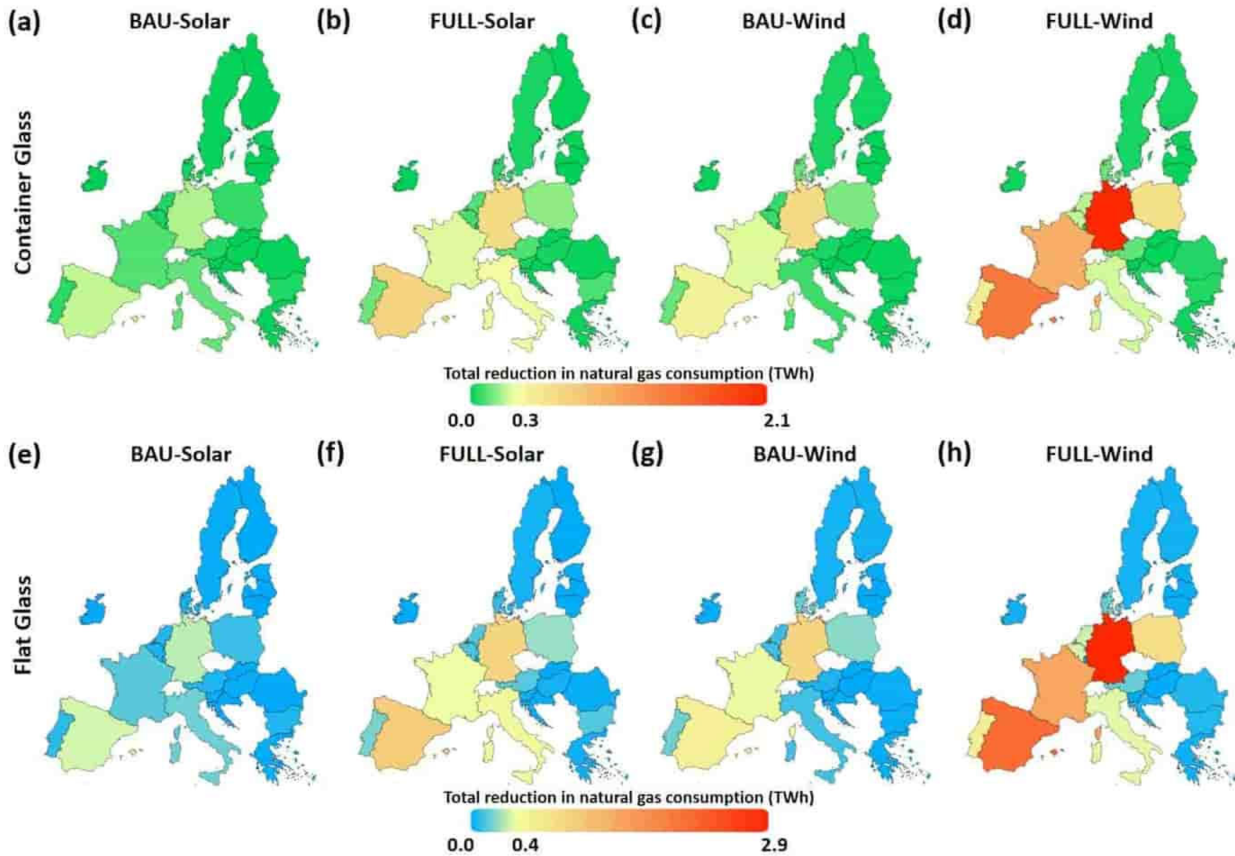
Supplementary Figure 4. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the wood and wood products sector, construction sector, and textile and leather sector. a., Wood and wood products sector under the BAU-solar scenario. **b.,** Wood and wood products sector under the FULL-solar scenario. **c.,** Wood and wood products sector under the BAU-wind scenario. **d.,** Wood and wood products sector under the FULL-wind scenario. **e.,** Construction sector under the BAU-solar scenario. **f.,** Construction sector under the FULL-solar scenario. **g.,** Construction sector under the BAU-wind scenario. **h.,** Construction sector under the FULL-wind scenario. **i.,** Textile and leather sector under the BAU-solar scenario. **j.,** Textile and leather sector under the FULL-solar scenario. **k.,** Textile and leather sector under the BAU-wind scenario. **l.,** Textile and leather sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



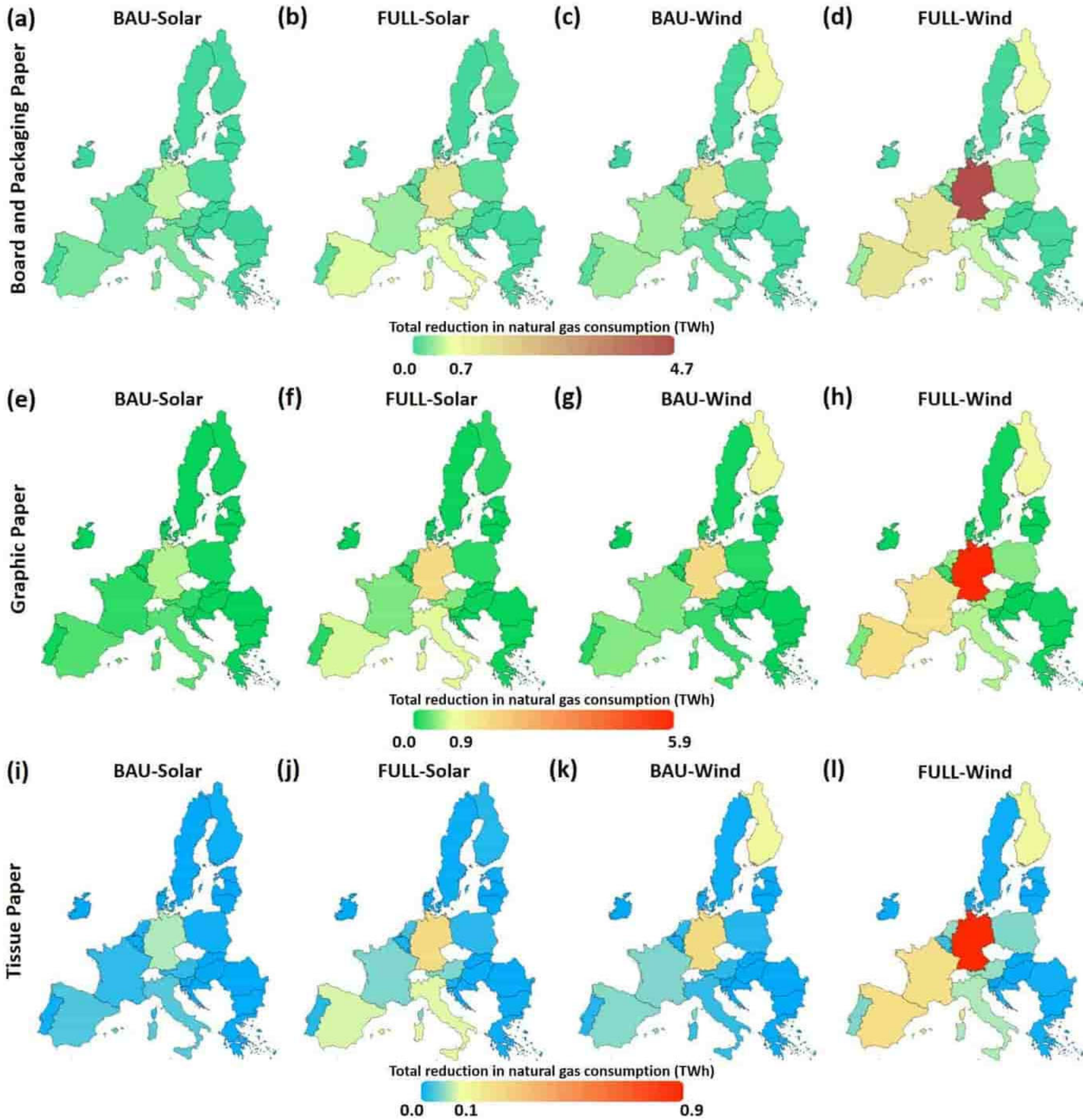
Supplementary Figure 5. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the iron and steel sector, non-ferrous metals sector, and the operation of heavy trucks. a., Iron and steel sector under the BAU-solar scenario. **b.,** Iron and steel sector under the FULL-solar scenario. **c.,** Iron and steel sector under the BAU-wind scenario. **d.,** Iron and steel sector under the FULL-wind scenario. **e.,** Non-ferrous metals sector under the BAU-solar scenario. **f.,** Non-ferrous metals sector under the FULL-solar scenario. **g.,** Non-ferrous metals sector under the BAU-wind scenario. **h.,** Non-ferrous metals sector under the FULL-wind scenario. **i.,** Operation of heavy trucks based on the use of green hydrogen technologies under the BAU-solar scenario. **j.,** Operation of heavy trucks based on the use of green hydrogen technologies under the FULL-solar scenario. **k.,** Operation of heavy trucks based on the use of green hydrogen technologies under the BAU-wind scenario. **l.,** Operation of heavy trucks based on the use of green hydrogen technologies under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



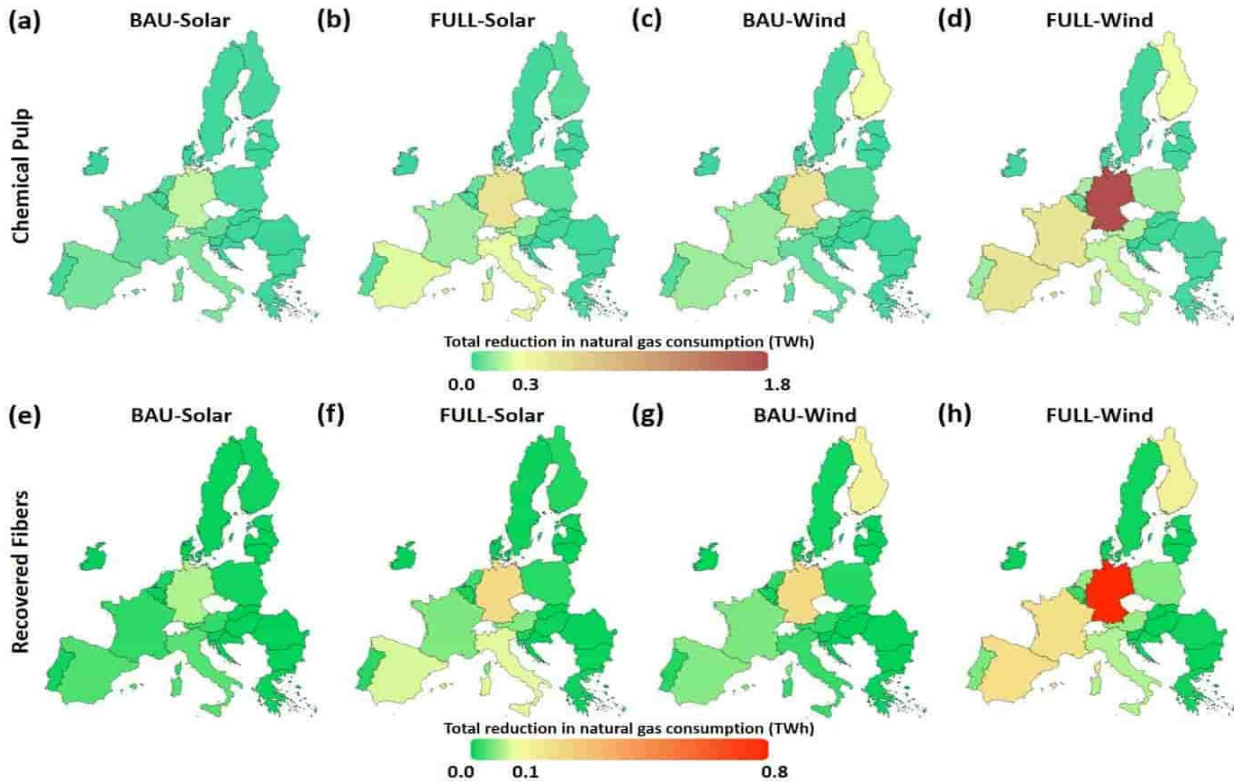
Supplementary Figure 6. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the cement/clinker sector and lime burning sector. a., Cement/clinker sector under the BAU-solar scenario. **b.,** Cement/clinker sector under the FULL-solar scenario. **c.,** Cement/clinker sector under the BAU-wind scenario. **d.,** Cement/clinker sector under the FULL-wind scenario. **e.,** Lime burning sector under the BAU-solar scenario. **f.,** Lime burning sector under the FULL-solar scenario. **g.,** Lime burning sector under the BAU-wind scenario. **h.,** Lime burning sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



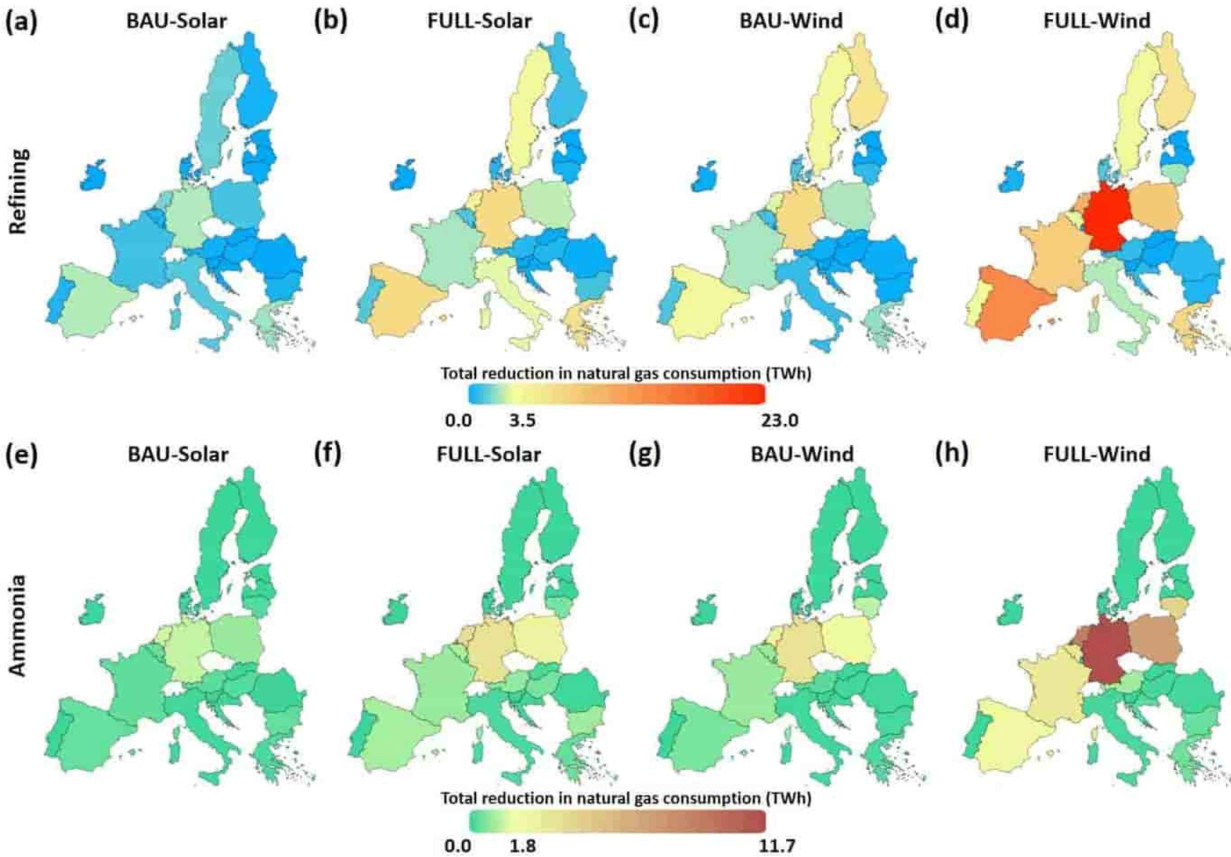
Supplementary Figure 7. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the container glass sector and flat glass sector. a., Container glass sector under the BAU-solar scenario. **b.,** Container glass sector under the FULL-solar scenario. **c.,** Container glass sector under the BAU-wind scenario. **d.,** Container glass sector under the FULL-wind scenario. **e.,** Flat glass sector under the BAU-solar scenario. **f.,** Flat glass sector under the FULL-solar scenario. **g.,** Flat glass sector under the BAU-wind scenario. **h.,** Flat glass sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



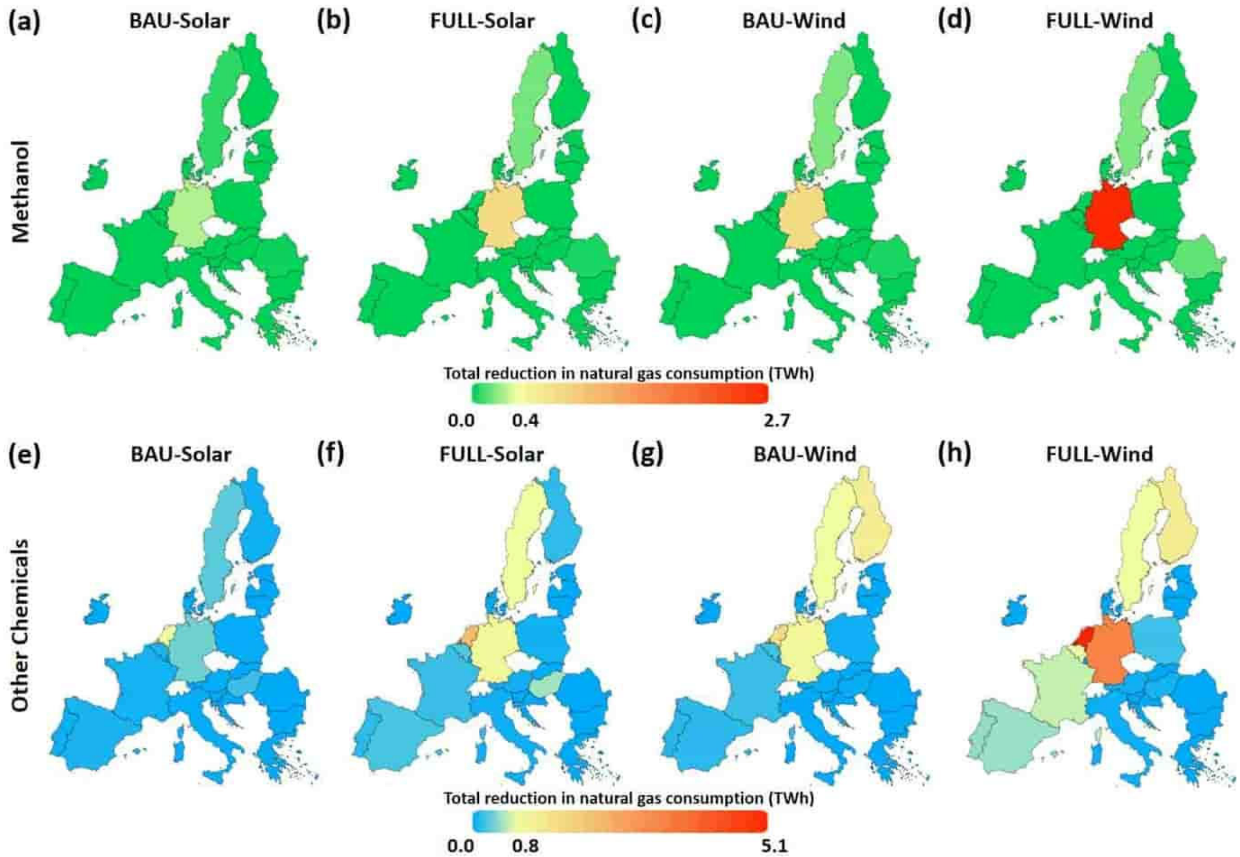
Supplementary Figure 8. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the board and packaging paper sector, graphic paper sector, and tissue paper sector. a., Board and packaging paper sector under the BAU-solar scenario. **b.,** Board and packaging paper sector under the FULL-solar scenario. **c.,** Board and packaging paper sector under the BAU-wind scenario. **d.,** Board and packaging paper sector under the FULL-wind scenario. **e.,** Graphic paper sector under the BAU-solar scenario. **f.,** Graphic paper sector under the FULL-solar scenario. **g.,** Graphic paper sector under the BAU-wind scenario. **h.,** Graphic paper sector under the FULL-wind scenario. **i.,** Tissue paper sector under the BAU-solar scenario. **j.,** Tissue paper sector under the FULL-solar scenario. **k.,** Tissue paper sector under the BAU-wind scenario. **l.,** Tissue paper sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



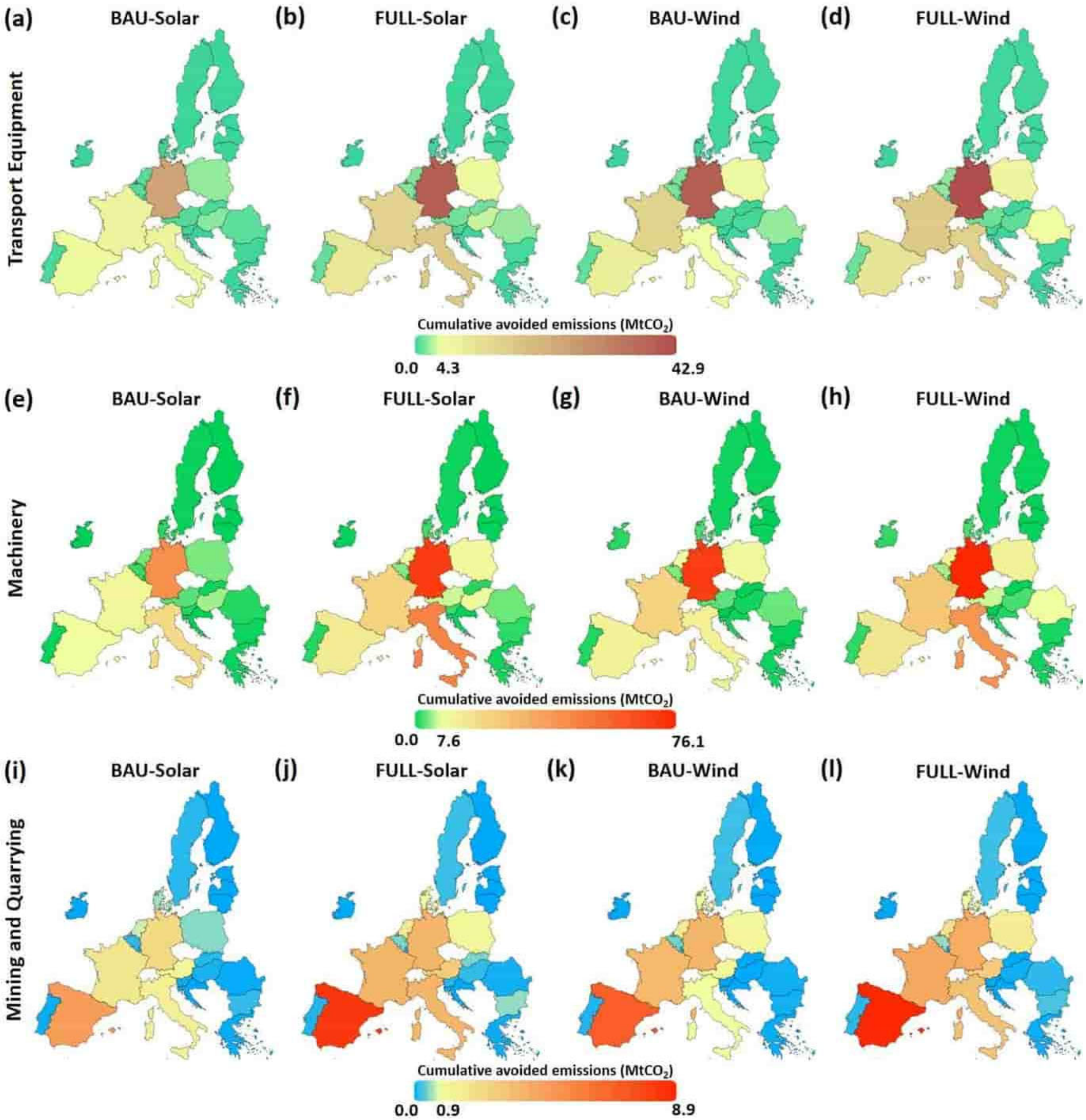
Supplementary Figure 9. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the chemical pulp sector and recovered fibers sector. a., Chemical pulp sector under the BAU-solar scenario. **b.,** Chemical pulp sector under the FULL-solar scenario. **c.,** Chemical pulp sector under the BAU-wind scenario. **d.,** Chemical pulp sector under the FULL-wind scenario. **e.,** Recovered fibers sector under the BAU-solar scenario. **f.,** Recovered fibers sector under the FULL-solar scenario. **g.,** Recovered fibers sector under the BAU-wind scenario. **h.,** Recovered fibers sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



Supplementary Figure 10. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the refining sector and ammonia sector. a., Refining sector under the BAU-solar scenario. **b.,** Refining sector under the FULL-solar scenario. **c.,** Refining sector under the BAU-wind scenario. **d.,** Refining sector under the FULL-wind scenario. **e.,** Ammonia sector under the BAU-solar scenario. **f.,** Ammonia sector under the FULL-solar scenario. **g.,** Ammonia sector under the BAU-wind scenario. **h.,** Ammonia sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

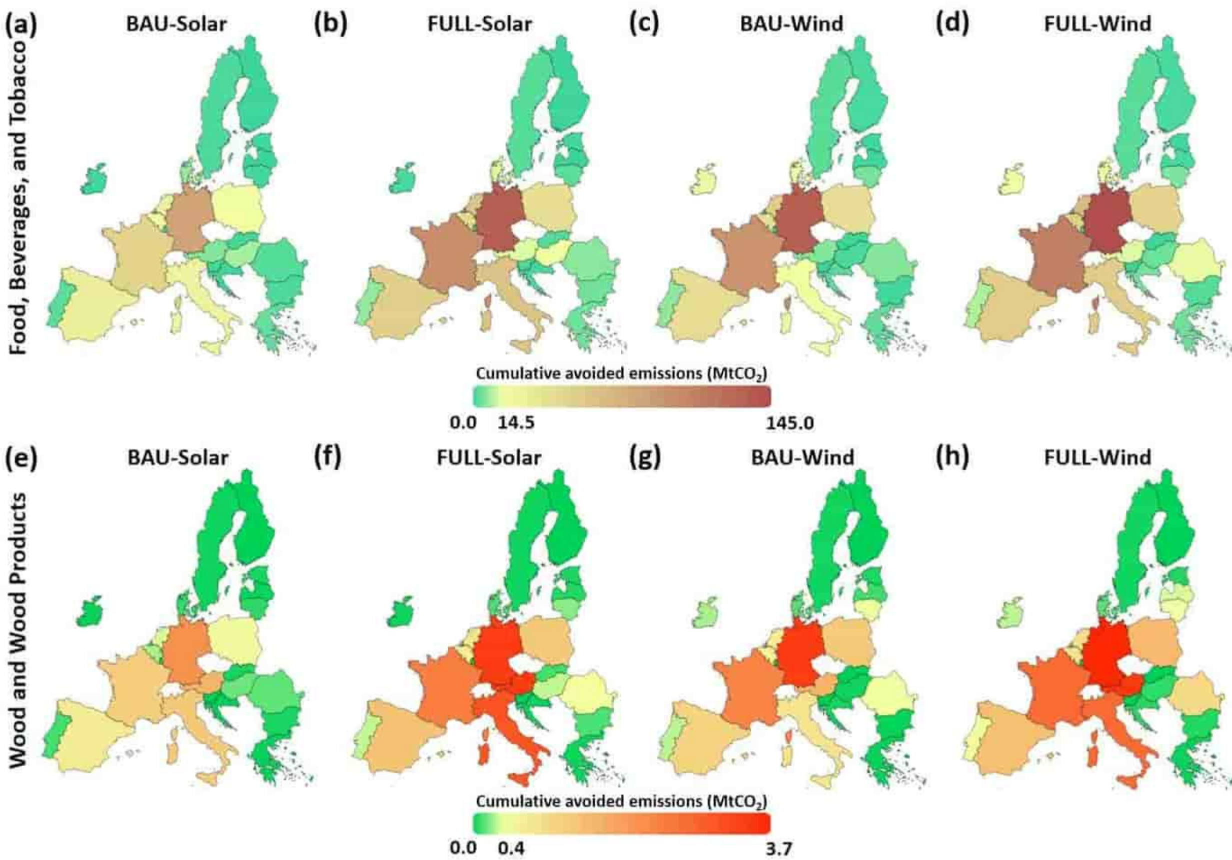


Supplementary Figure 11. Total reduction in natural gas consumption (TWh) across EU member countries by 2050 under renewable expansion scenarios in the methanol sector and other chemicals sector. a., Methanol sector under the BAU-solar scenario. **b.,** Methanol sector under the FULL-solar scenario. **c.,** Methanol sector under the BAU-wind scenario. **d.,** Methanol sector under the FULL-wind scenario. **e.,** Other chemicals sector under the BAU-solar scenario. **f.,** Other chemicals sector under the FULL-solar scenario. **g.,** Other chemicals sector under the BAU-wind scenario. **h.,** Other chemicals sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

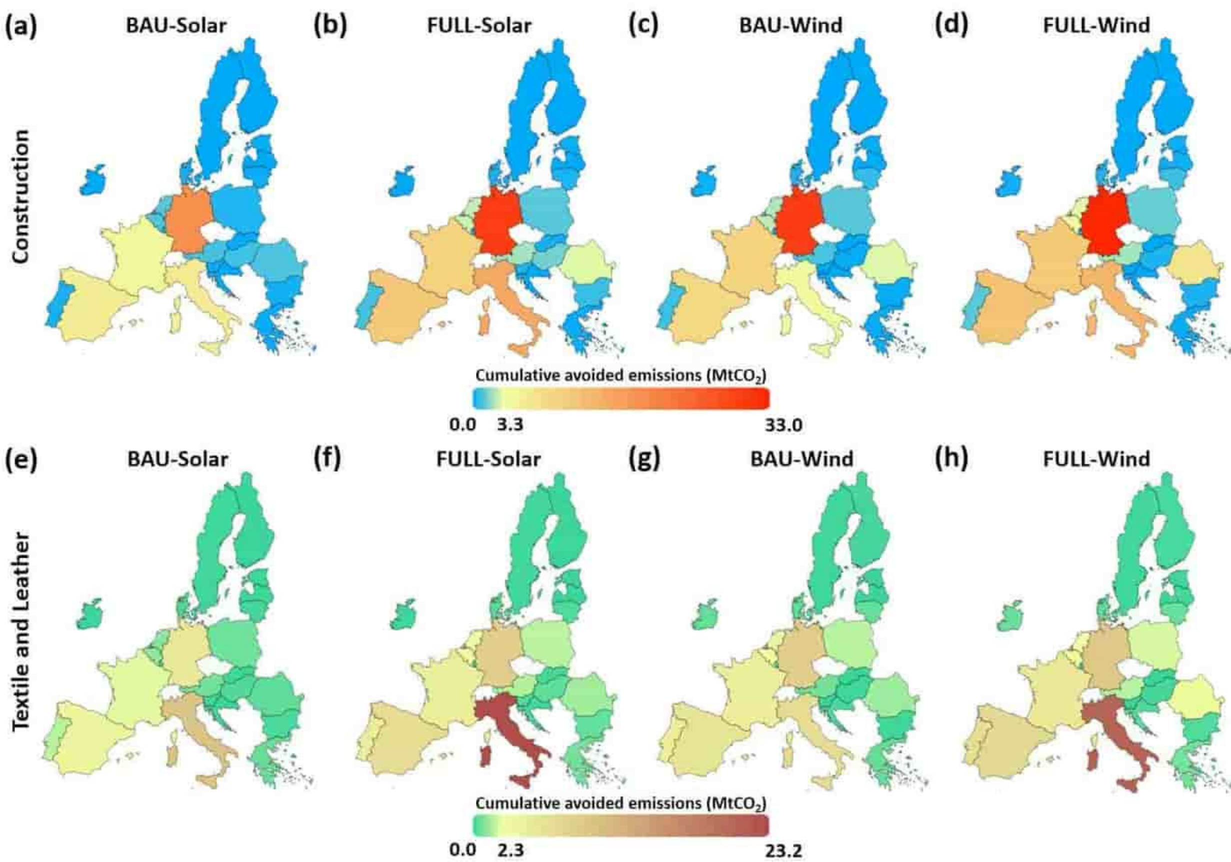


Supplementary Figure 12. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the transportation equipment sector, machinery sector, and mining and quarrying sector. a., Transportation equipment sector under the BAU-solar scenario. **b.,** Transportation equipment sector under the FULL-solar scenario. **c.,** Transportation equipment sector under the BAU-wind scenario. **d.,** Transportation equipment sector under the FULL-wind scenario. **e.,** Machinery sector under the BAU-solar scenario. **f.,** Machinery sector under the FULL-solar scenario. **g.,** Machinery sector under the BAU-wind scenario. **h.,** Machinery sector under the FULL-wind scenario. **i.,**

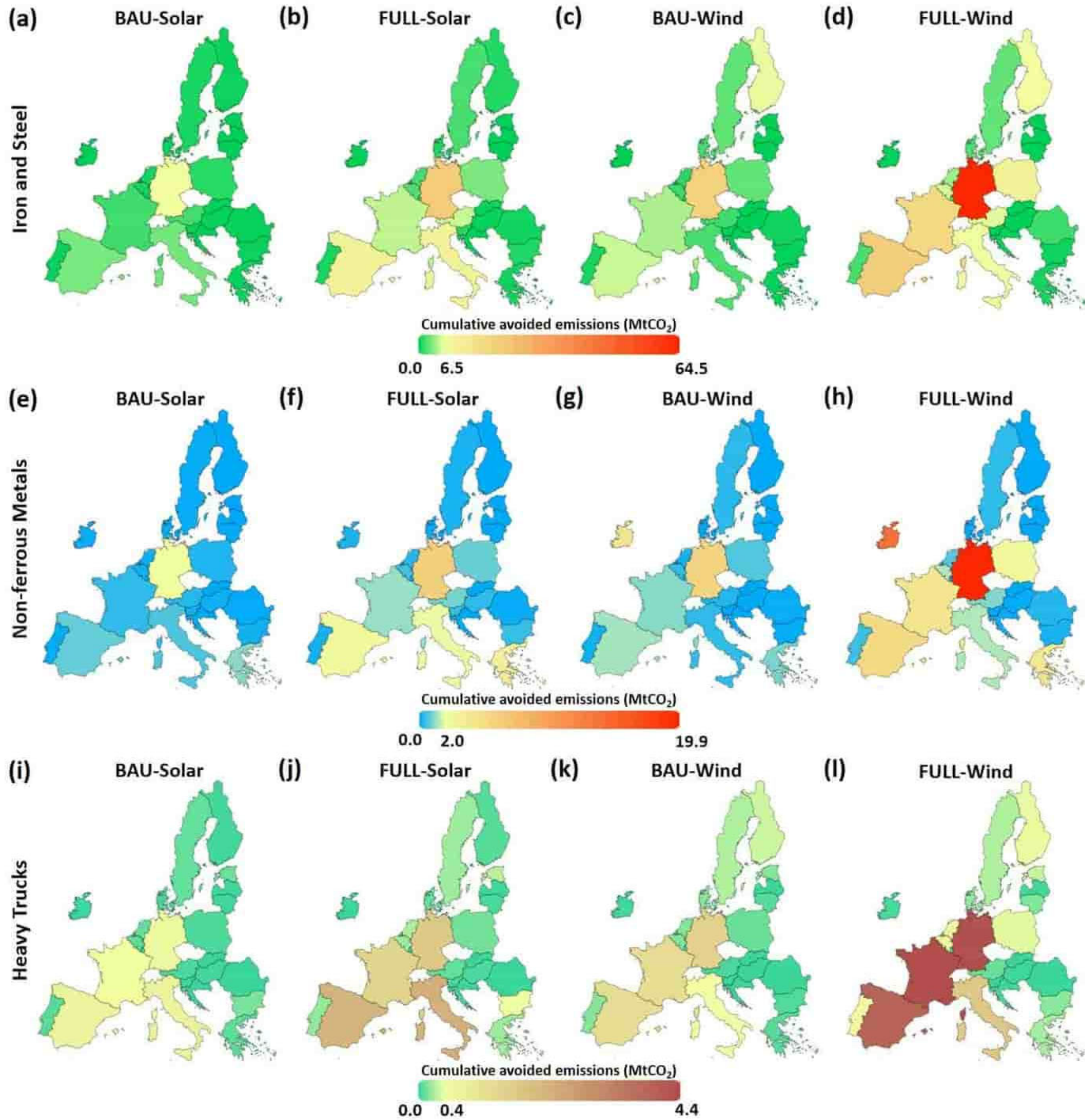
Mining and quarrying sector under the BAU-solar scenario. **j.,** Mining and quarrying sector under the FULL-solar scenario. **k.,** Mining and quarrying sector under the BAU-wind scenario. **l.,** Mining and quarrying sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



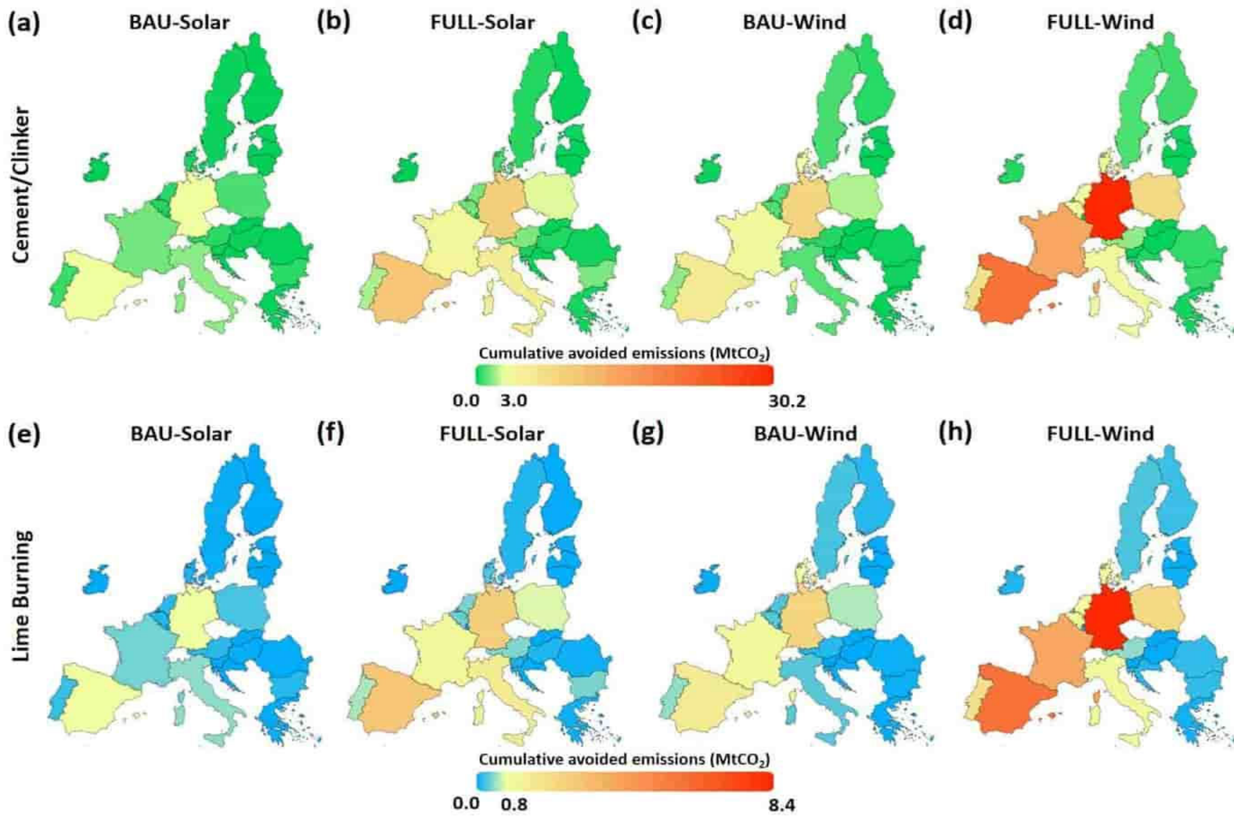
Supplementary Figure 13. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the food, beverages, and tobacco sector and the wood and wood products sector. a., Food, beverages, and tobacco sector under the BAU-solar scenario. **b.,** Food, beverages, and tobacco sector under the FULL-solar scenario. **c.,** Food, beverages, and tobacco sector under the BAU-wind scenario. **d.,** Food, beverages, and tobacco sector under the FULL-wind scenario. **e.,** Wood and wood products sector under the BAU-solar scenario. **f.,** Wood and wood products sector under the FULL-solar scenario. **g.,** Wood and wood products sector under the BAU-wind scenario. **h.,** Wood and wood products sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



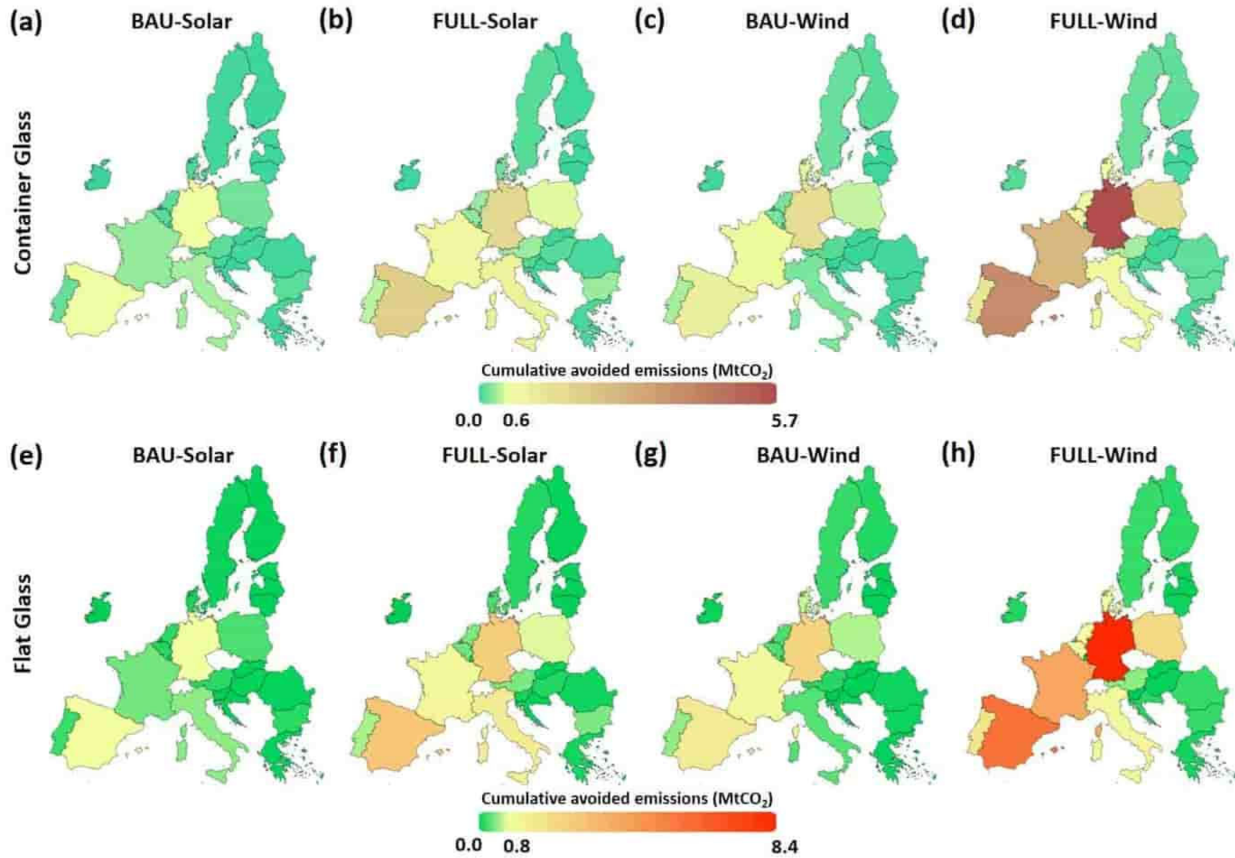
Supplementary Figure 14. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the construction sector and textile and leather sector. a., Construction sector under the BAU-solar scenario. **b.,** Construction sector under the FULL-solar scenario. **c.,** Construction sector under the BAU-wind scenario. **d.,** Construction sector under the FULL-wind scenario. **e.,** Textile and leather sector under the BAU-solar scenario. **f.,** Textile and leather sector under the FULL-solar scenario. **g.,** Textile and leather sector under the BAU-wind scenario. **h.,** Textile and leather sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



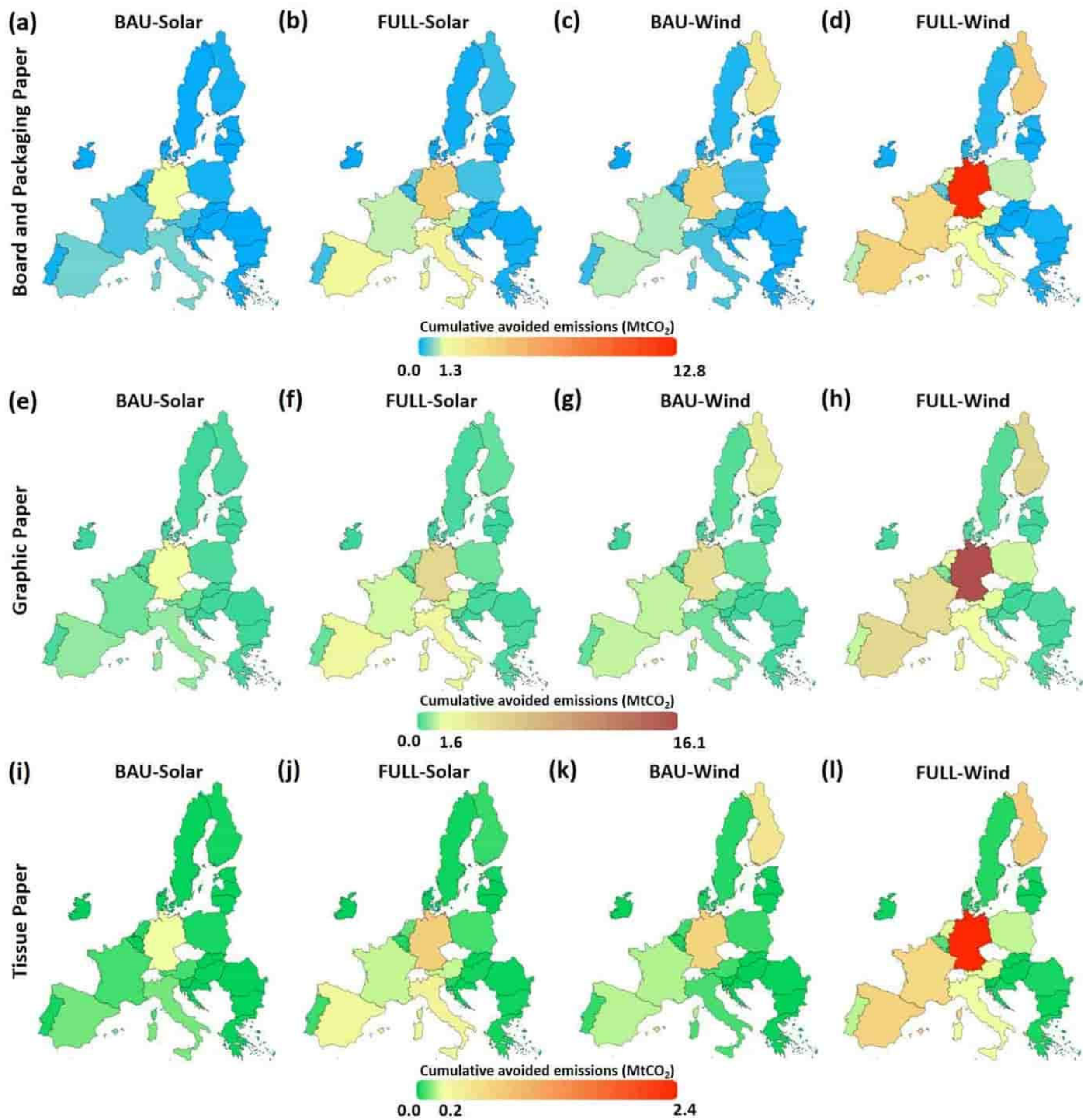
Supplementary Figure 15. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the iron and steel sector, non-ferrous metals sector, and the operation of heavy trucks. a., Iron and steel sector under the BAU-solar scenario. **b.,** Iron and steel sector under the FULL-solar scenario. **c.,** Iron and steel sector under the BAU-wind scenario. **d.,** Iron and steel sector under the FULL-wind scenario. **e.,** Non-ferrous metals sector under the BAU-solar scenario. **f.,** Non-ferrous metals sector under the FULL-solar scenario. **g.,** Non-ferrous metals sector under the BAU-wind scenario. **h.,** Non-ferrous metals sector under the FULL-wind scenario. **i.,** Operation of heavy trucks based on the use of green hydrogen technologies under the BAU-solar scenario. **j.,** Operation of heavy trucks based on the use of green hydrogen technologies under the FULL-solar scenario. **k.,** Operation of heavy trucks based on the use of green hydrogen technologies under the BAU-wind scenario. **l.,** Operation of heavy trucks based on the use of green hydrogen technologies under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



Supplementary Figure 16. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the cement/clinker sector and lime burning sector. a., Cement/clinker sector under the BAU-solar scenario. **b.,** Cement/clinker sector under the FULL-solar scenario. **c.,** Cement/clinker sector under the BAU-wind scenario. **d.,** Cement/clinker sector under the FULL-wind scenario. **e.,** Lime burning sector under the BAU-solar scenario. **f.,** Lime burning sector under the FULL-solar scenario. **g.,** Lime burning sector under the BAU-wind scenario. **h.,** Lime burning sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

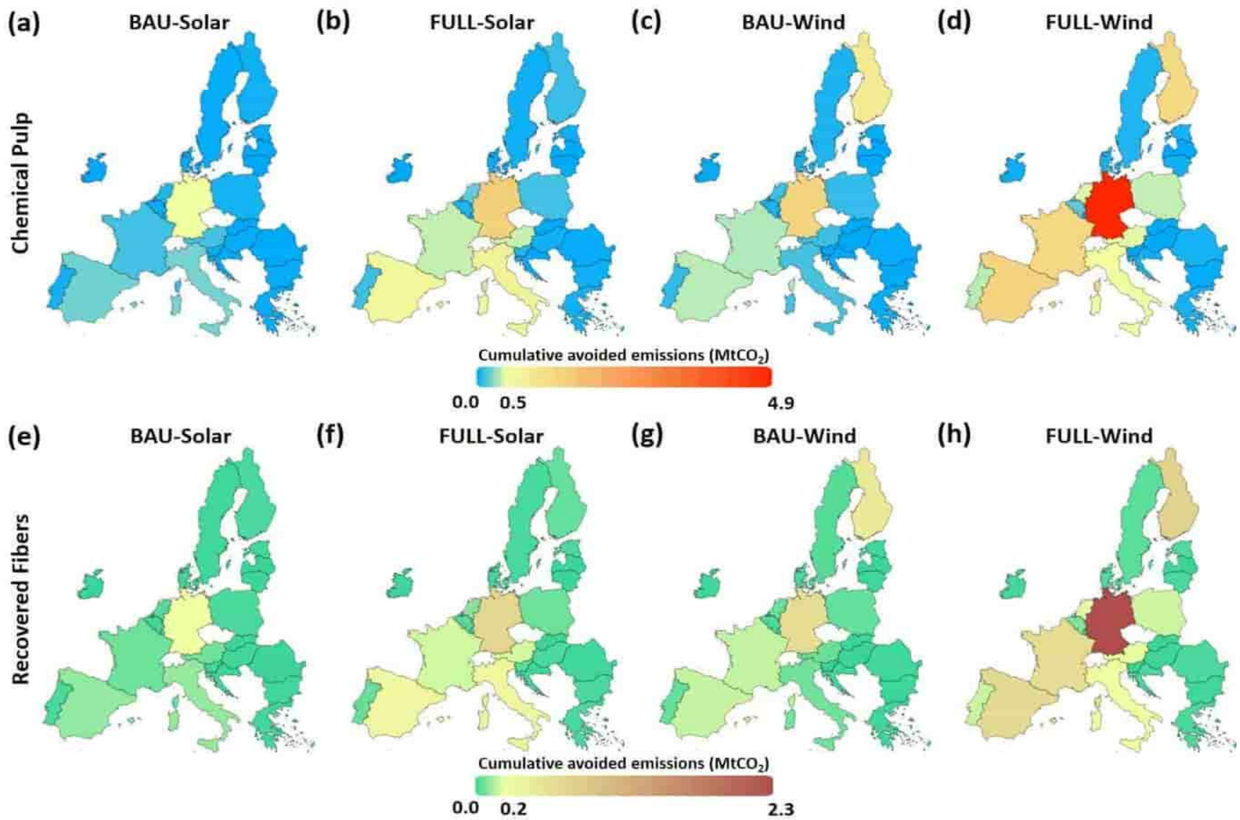


Supplementary Figure 17. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the container glass sector and flat glass sector. a., Container glass sector under the BAU-solar scenario. **b.,** Container glass sector under the FULL-solar scenario. **c.,** Container glass sector under the BAU-wind scenario. **d.,** Container glass sector under the FULL-wind scenario. **e.,** Flat glass sector under the BAU-solar scenario. **f.,** Flat glass sector under the FULL-solar scenario. **g.,** Flat glass sector under the BAU-wind scenario. **h.,** Flat glass sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

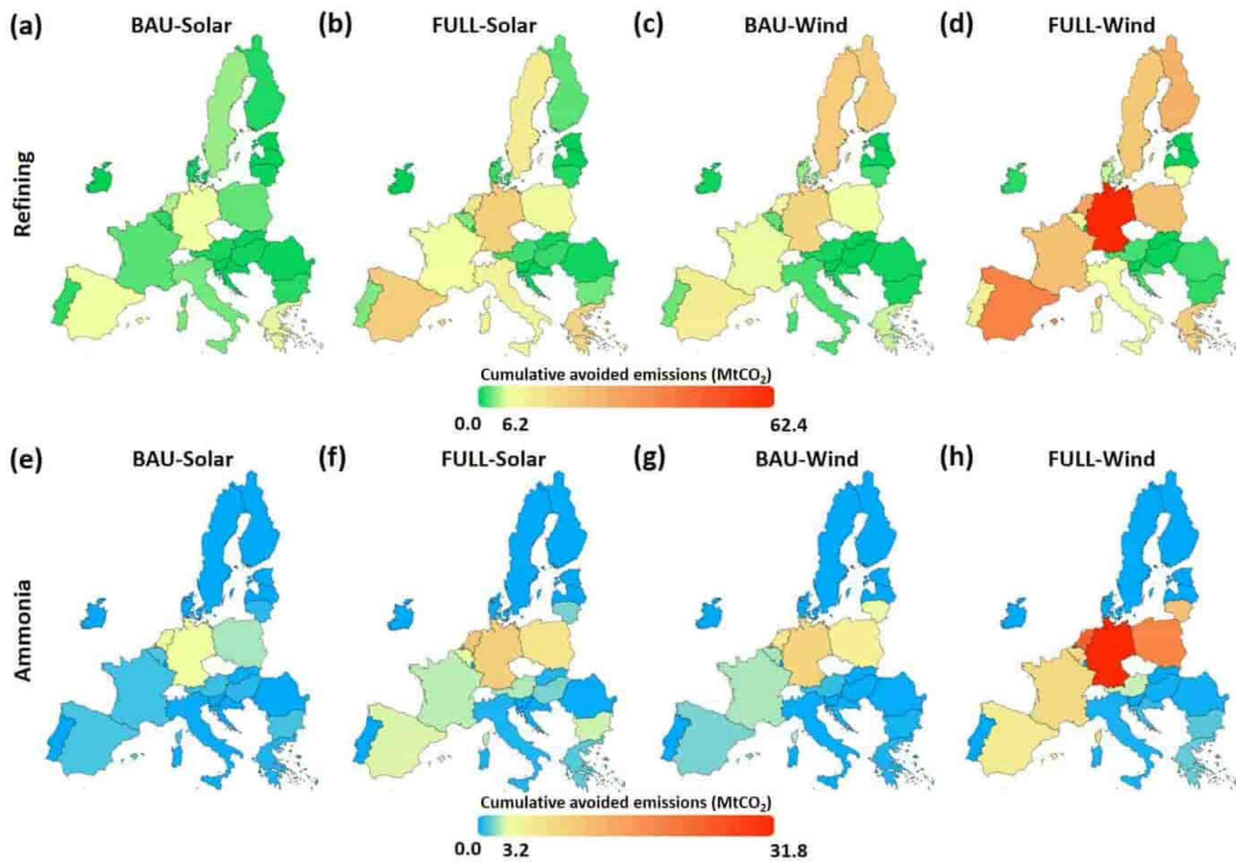


Supplementary Figure 18. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the board and packaging paper sector, graphic paper sector, and tissue paper sector. a., Board and packaging paper sector under the BAU-solar scenario. **b.,** Board and packaging paper sector under the FULL-solar scenario. **c.,** Board and packaging paper sector under the BAU-wind scenario. **d.,** Board and packaging paper sector under the FULL-wind scenario. **e.,** Graphic paper sector under the BAU-solar scenario. **f.,** Graphic paper sector under the FULL-solar scenario. **g.,** Graphic paper sector under the BAU-wind scenario. **h.,** Graphic paper sector under the FULL-wind scenario.

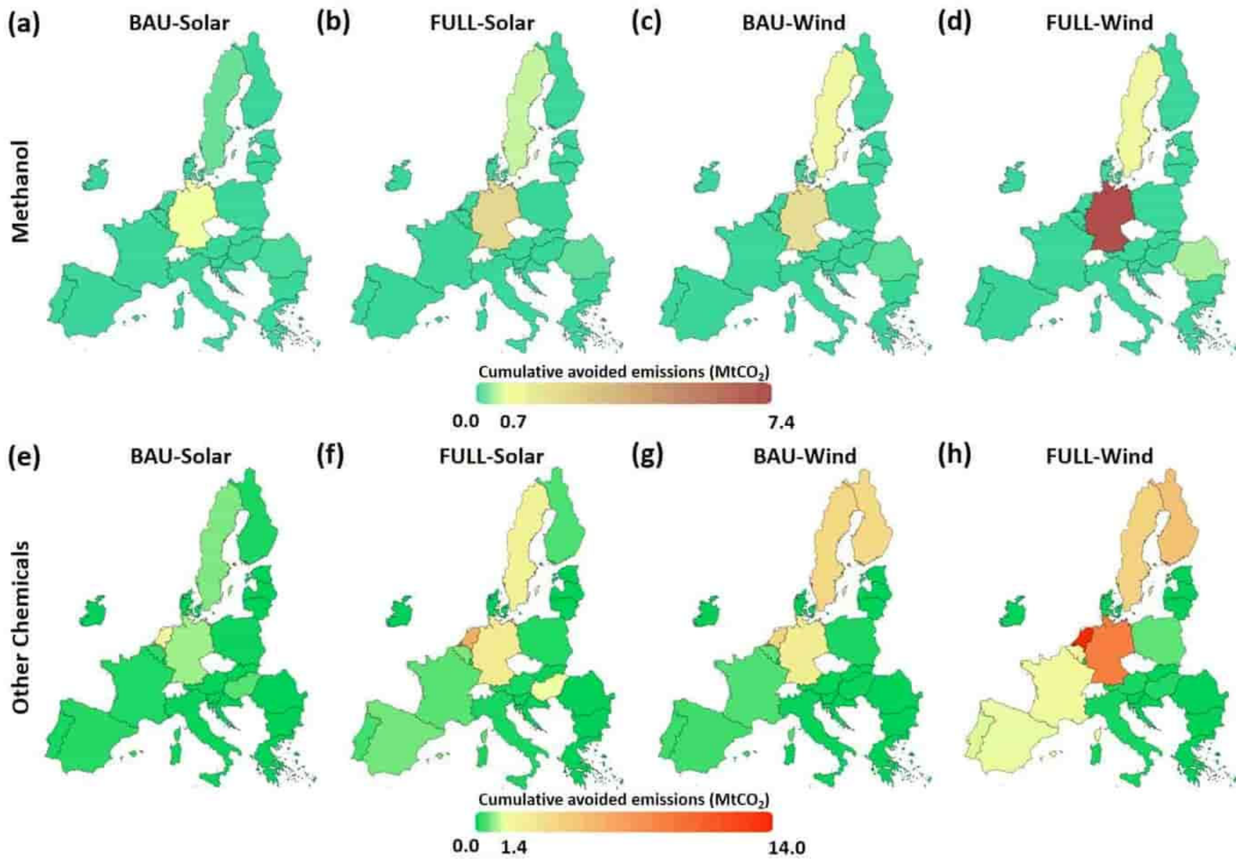
i., Tissue paper sector under the BAU-solar scenario. **j.,** Tissue paper sector under the FULL-solar scenario. **k.,** Tissue paper sector under the BAU-wind scenario. **l.,** Tissue paper sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



Supplementary Figure 19. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the chemical pulp sector and recovered fibers sector. a., Chemical pulp sector under the BAU-solar scenario. **b.,** Chemical pulp sector under the FULL-solar scenario. **c.,** Chemical pulp sector under the BAU-wind scenario. **d.,** Chemical pulp sector under the FULL-wind scenario. **e.,** Recovered fibers sector under the BAU-solar scenario. **f.,** Recovered fibers sector under the FULL-solar scenario. **g.,** Recovered fibers sector under the BAU-wind scenario. **h.,** Recovered fibers sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

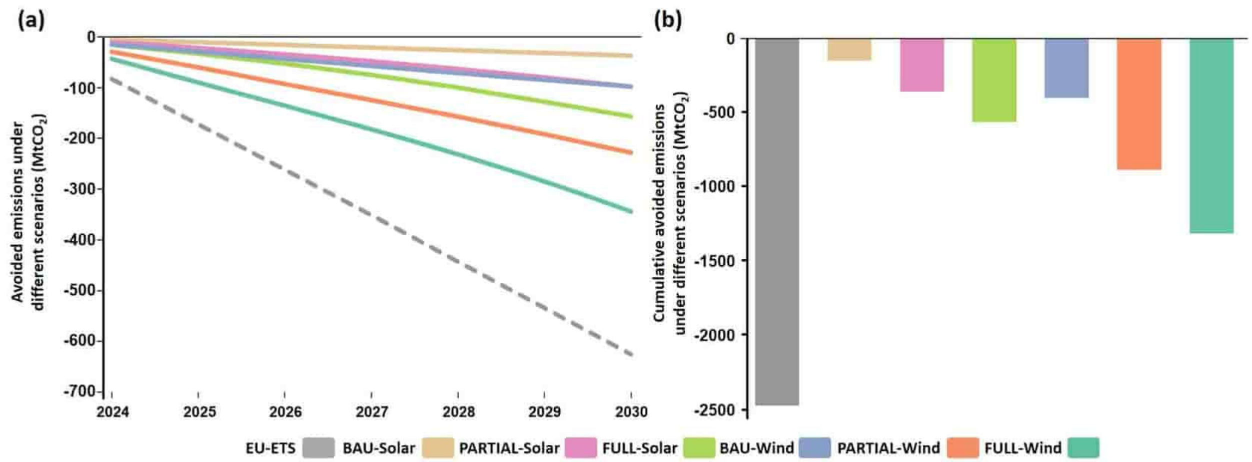


Supplementary Figure 20. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the refining sector and ammonia sector. a., Refining sector under the BAU-solar scenario. **b.,** Refining sector under the FULL-solar scenario. **c.,** Refining sector under the BAU-wind scenario. **d.,** Refining sector under the FULL-wind scenario. **e.,** Ammonia sector under the BAU-solar scenario. **f.,** Ammonia sector under the FULL-solar scenario. **g.,** Ammonia sector under the BAU-wind scenario. **h.,** Ammonia sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



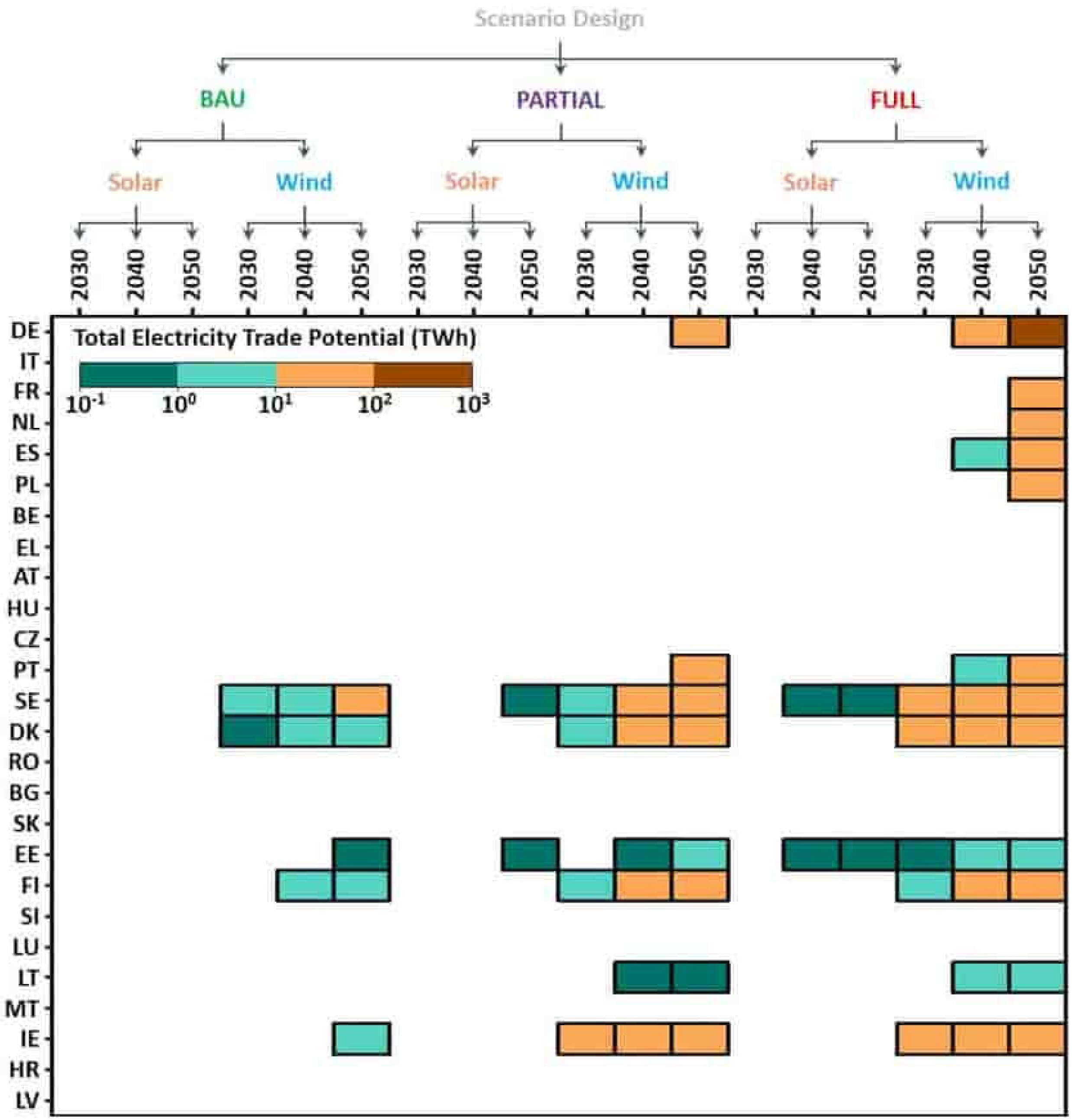
Supplementary Figure 21. Cumulative avoided emissions ($MtCO_2$) across EU member countries by 2050 under renewable expansion scenarios in the methanol sector and other chemicals sector. a., Methanol sector under the BAU-solar scenario. **b.,** Methanol sector under the FULL-solar scenario. **c.,** Methanol sector under the BAU-wind scenario. **d.,** Methanol sector under the FULL-wind scenario. **e.,** Other chemicals sector under the BAU-solar scenario. **f.,** Other chemicals sector under the FULL-solar scenario. **g.,** Other chemicals sector under the BAU-wind scenario. **h.,** Other chemicals sector under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

The EU Emissions Trading System (ETS) targets a progressive reduction in emissions through an annually declining cap on allowances, which stood at 1,469 $MtCO_2$ in 2023[1], decreased to 1,386 $MtCO_2$ in 2024 as informed by the Commission[2], and continues to decline via a linear reduction factor of 4.3% from 2024 to 2027 and 4.4% from 2028 onward. The reduction factor is applied to a fixed reference cap value, i.e. the average annual volume of allowances issued under the system over the 2008-2012 period[3], where each allowance corresponds to one tonne of CO_2. **Supplementary Fig. 22**a illustrates the required annual emissions reductions under the ETS and benchmarks them against the BAU, PARTIAL, and FULL scenarios for wind and solar power expansion, incorporating electrification, green hydrogen, and carbon offsetting strategies. Notably, the FULL-wind scenario achieves the greatest reduction, reaching 344.2 $MtCO_2$ by 2030. In contrast, the BAU-solar scenario shows the slowest decarbonization progress, trailing the 2030 total ETS reduction benchmark by 94.0%. **Supplementary Fig. 22**b presents the cumulative avoided emissions from 2024 to 2030 for each scenario, contextualized against the ETS-aligned reduction target over the same period. While the PARTIAL and BAU scenarios contribute to overall decarbonization efforts, the results indicate substantial shortfalls compared to the ETS baseline, emphasizing the need for more robust policy and technological interventions.



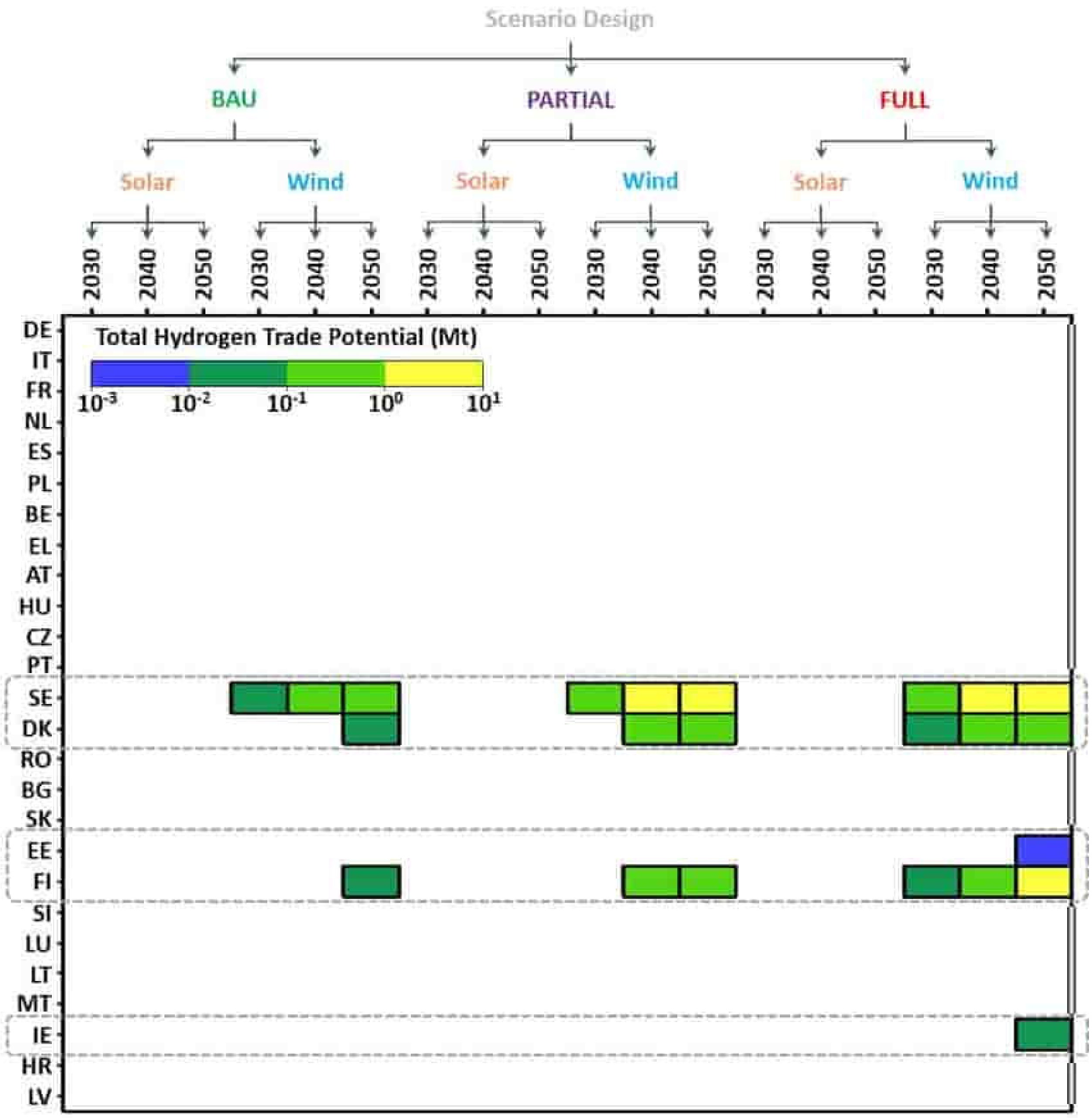
Supplementary Figure 22. Comparison of emissions reductions from renewable expansion scenarios with EU-ETS requirements. a., Annual emissions reductions ($MtCO_2$) under the EU-ETS cap trajectory and the BAU, PARTIAL, and FULL scenarios for solar and wind power expansion, incorporating electrification, hydrogen, and carbon offsetting strategies. **b.,** Cumulative avoided emissions ($MtCO_2$) under the BAU, PARTIAL, and FULL scenarios for wind and solar power expansion, benchmarked against the total emissions reduction required under the ETS over the same period.

In order to complement domestic strategic interventions for reducing natural gas consumption in the investigated scenarios, this work evaluates the role of both intra-EU integration and international trade opportunities across sectors and time horizons. The results presented in **Supplementary Figs. 23-25** illustrate a multi-layered analysis of how clean electricity and green hydrogen trade can strengthen EU-wide energy security. Specifically, **Supplementary Figs. 23-24** assess intra-regional trade potential within the EU, based on modeled projections of excess supply after substituting country-specific natural gas use in targeted sectors. **Supplementary Fig. 23** presents the clean electricity trade opportunity across EU member states in the BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind scenarios for 2030, 2040, and 2050. The results highlight emerging surpluses in selected countries that can be shared through regional integration and cross-border cooperation. Similarly, **Supplementary Fig. 24** shows the corresponding trade potential for green hydrogen under the same scenarios and timeframes, focusing on volumes available beyond domestic substitution needs. Building upon this intra-regional dimension, **Supplementary Fig. 25** explores the complementary role of international trade in reducing EU natural gas reliance. In this regard, **Supplementary Fig. 25**a illustrates the percentage reduction in gross inland natural gas consumption under different scenarios, while **Supplementary Figs. 25**b-d present sector-specific opportunities for international trade. These include clean electricity supply corridors for the electricity and heating sector, green fuels for industrial applications, and a combination of electricity and hydrogen-based fuels for the road transport sector.

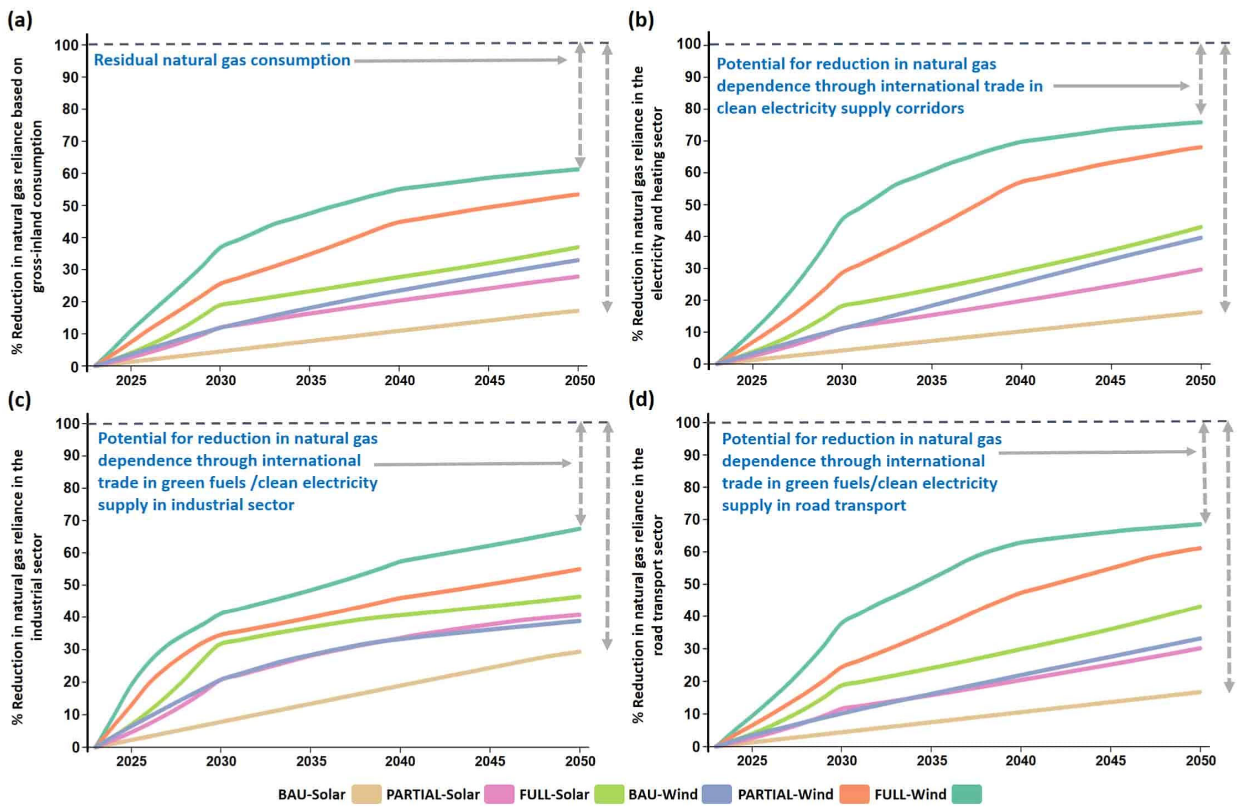


Supplementary Figure 23. Comparative assessment of intra-regional clean electricity trade opportunities among EU countries across BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind scenarios over varying time horizons (2030, 2040, and 2050). The analysis is based on excess electricity supply potential after substituting country-specific sectoral natural gas consumption, indicating opportunities for cross-border integration. Acronyms for the EU member states follow the glossary by the European Commission: Germany (DE); Italy (IT); France (FR); Netherlands (NL); Spain (ES);

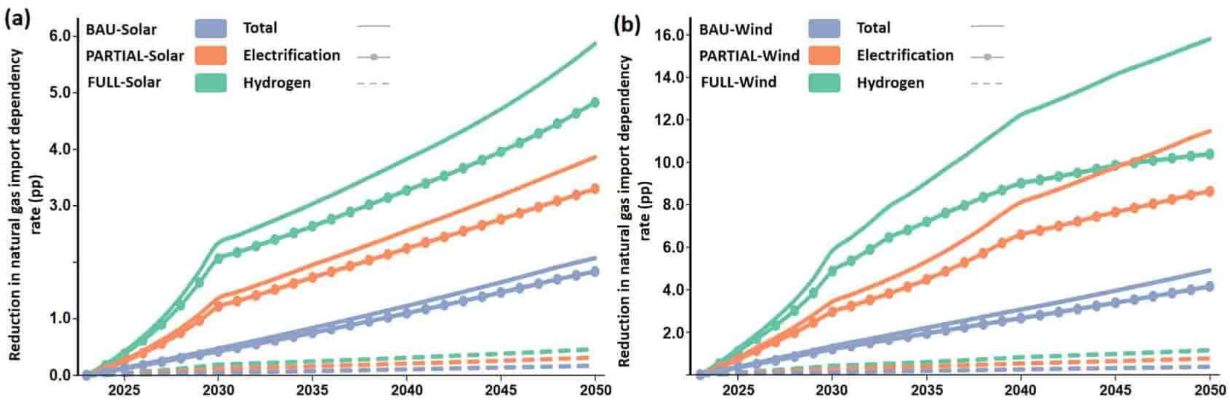
Poland (PL); Belgium (BE); Greece (EL); Austria (AT); Hungary (HU); Czechia (CZ); Portugal (PT); Sweden (SE); Denmark (DK); Romania (RO); Bulgaria (BG); Slovakia (SK); Estonia (EE); Finland (FI); Slovenia (SI); Luxembourg (LU); Lithuania (LT); Malta (MT); Ireland (IE); Croatia (HR); Latvia (LV).



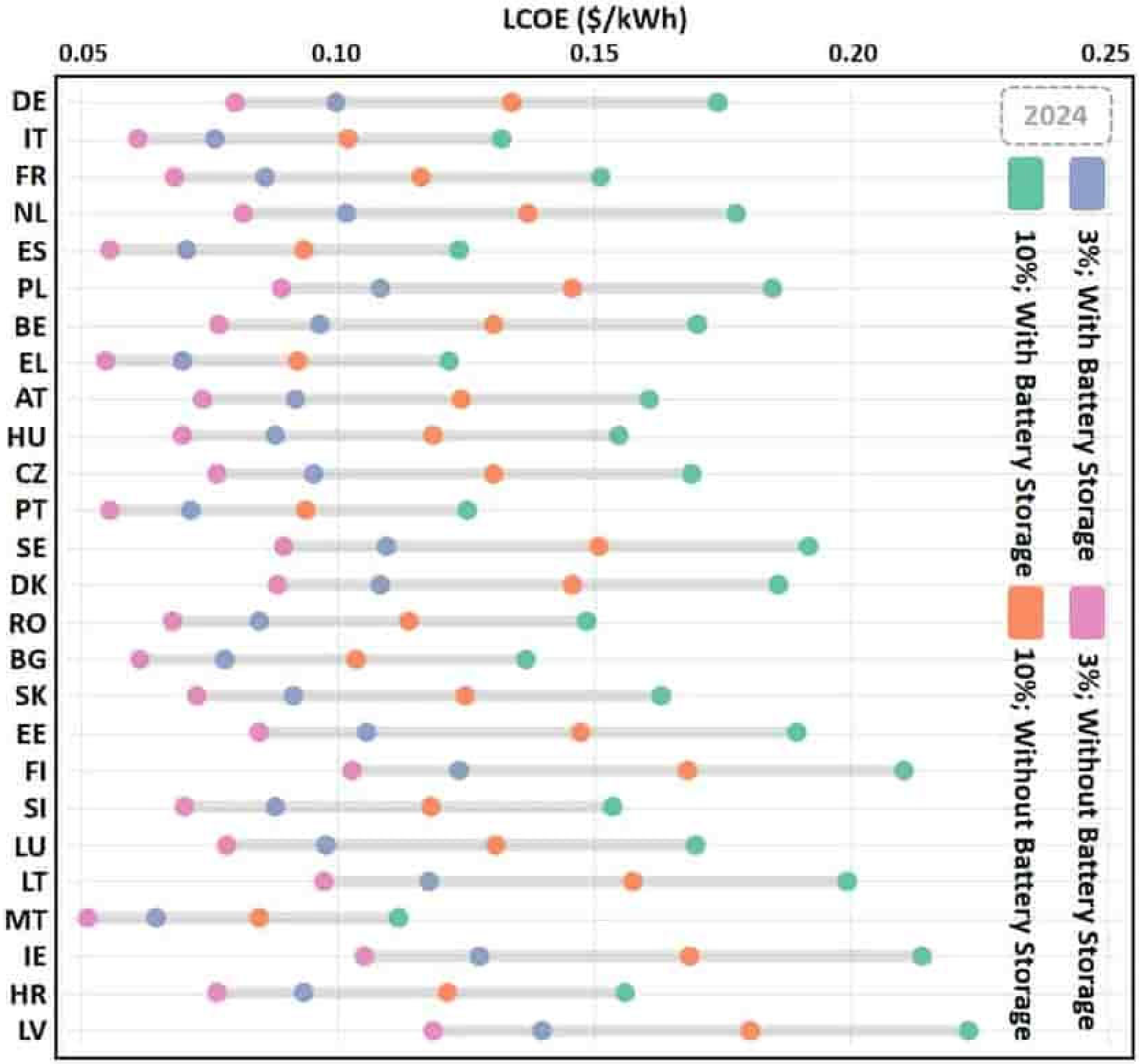
Supplementary Figure 24. Comparative assessment of intra-regional green hydrogen trade opportunities among EU countries across BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind scenarios over varying time horizons (2030, 2040, and 2050). The analysis is based on excess green hydrogen supply potential after meeting country-specific natural gas substitution needs in hard-to-abate sectors, highlighting the potential for cross-border hydrogen distribution. Acronyms for the EU member states follow the glossary by the European Commission: Germany (DE); Italy (IT); France (FR); Netherlands (NL); Spain (ES); Poland (PL); Belgium (BE); Greece (EL); Austria (AT); Hungary (HU); Czechia (CZ); Portugal (PT); Sweden (SE); Denmark (DK); Romania (RO); Bulgaria (BG); Slovakia (SK); Estonia (EE); Finland (FI); Slovenia (SI); Luxembourg (LU); Lithuania (LT); Malta (MT); Ireland (IE); Croatia (HR); Latvia (LV).



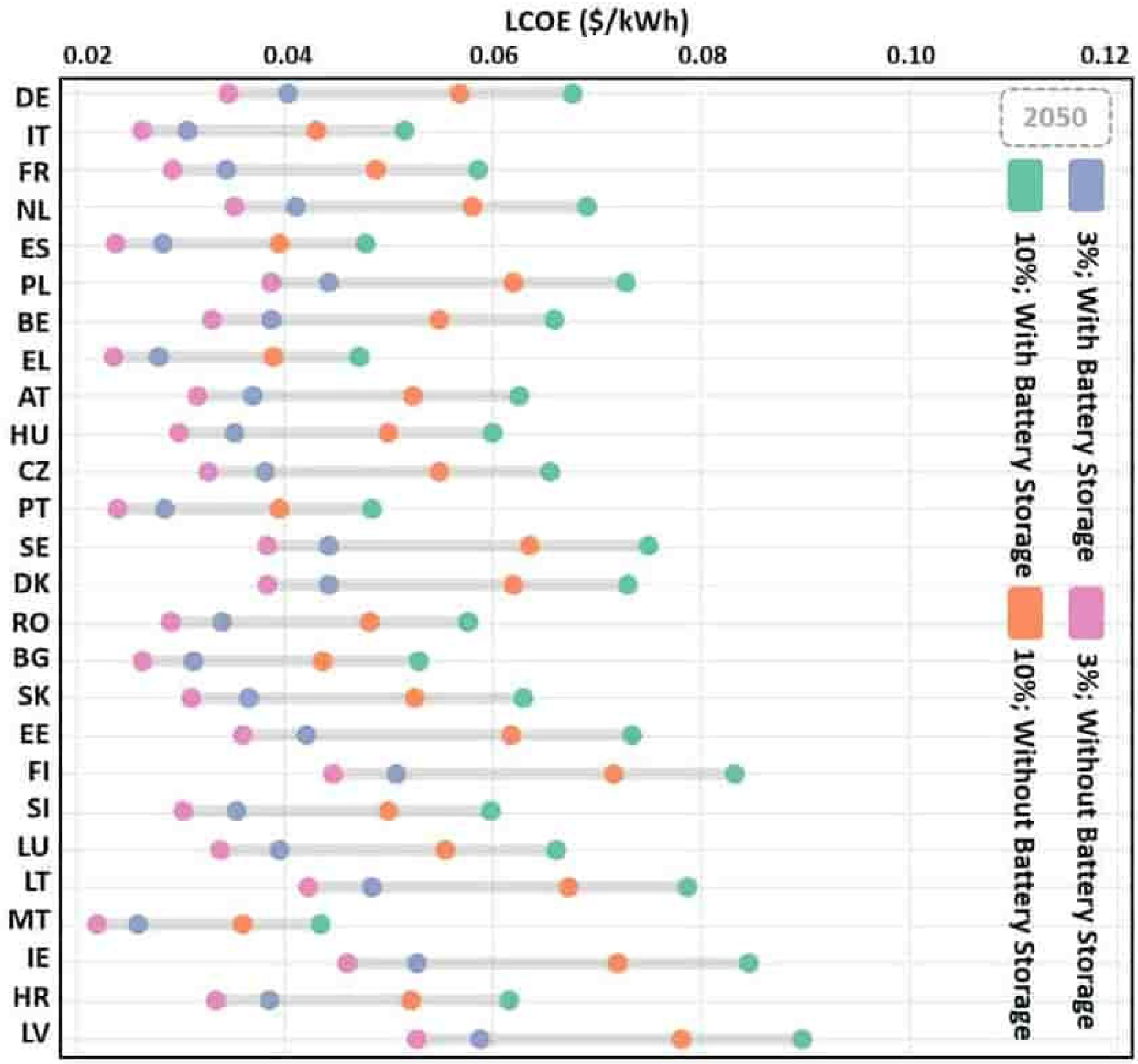
Supplementary Figure 25. Sectoral reductions in EU natural gas reliance under renewable expansion scenarios and associated opportunities for international clean electricity corridors and green fuel trade. a., Percentage reduction (%) in the EU natural gas reliance based on gross inland consumption across different scenarios. **b.,** Percentage reduction (%) in natural gas reliance in the electricity and heating sector, illustrating the potential opportunity for international trade in clean electricity supply corridors as a complementary strategy to further enhance energy security. **c.,** Percentage reduction (%) in natural gas reliance in the industrial sector, illustrating the potential opportunity for international trade in green fuels for heavy industries and clean electricity supply for light industries as complementary strategies to further enhance energy security. **d.,** Percentage reduction (%) in natural gas reliance in the road transportation sector, illustrating the potential opportunity for international trade in clean electricity supply for passenger cars, light commercial vehicles, buses, and coaches, and green fuels for heavy trucks as complementary strategies to further enhance energy security.



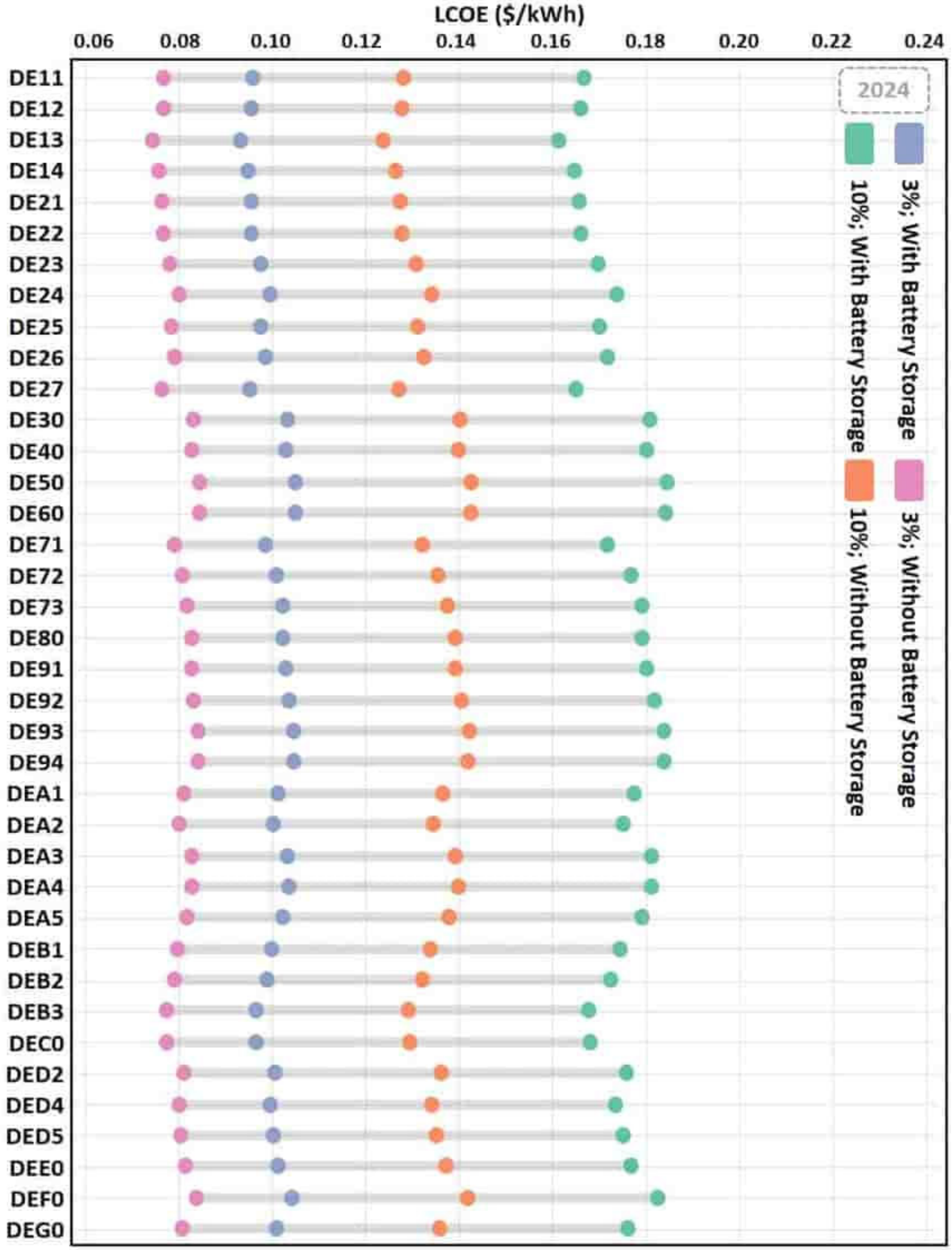
Supplementary Figure 26. Reductions in EU natural gas import dependency under renewable expansion scenarios. a., Total reduction in natural gas import dependency rate (percentage points) across the BAU-Solar, PARTIAL-Solar, and FULL-Solar scenarios through 2050, disaggregated by the individual impact from electrification and green hydrogen deployment. **b.,** Total reduction in natural gas import dependency rate (percentage points) across the BAU-Wind, PARTIAL-Wind, and FULL-Wind scenarios through 2050, disaggregated by the individual impact from electrification and green hydrogen deployment.



Supplementary Figure 27. Comparative assessment of solar PV LCOE for EU countries in 2024 under different assumptions for battery storage inclusion and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. Acronyms for the EU member states follow the glossary by the European Commission: Germany (DE); Italy (IT); France (FR); Netherlands (NL); Spain (ES); Poland (PL); Belgium (BE); Greece (EL); Austria (AT); Hungary (HU); Czechia (CZ); Portugal (PT); Sweden (SE); Denmark (DK); Romania (RO); Bulgaria (BG); Slovakia (SK); Estonia (EE); Finland (FI); Slovenia (SI); Luxembourg (LU); Lithuania (LT); Malta (MT); Ireland (IE); Croatia (HR); Latvia (LV).

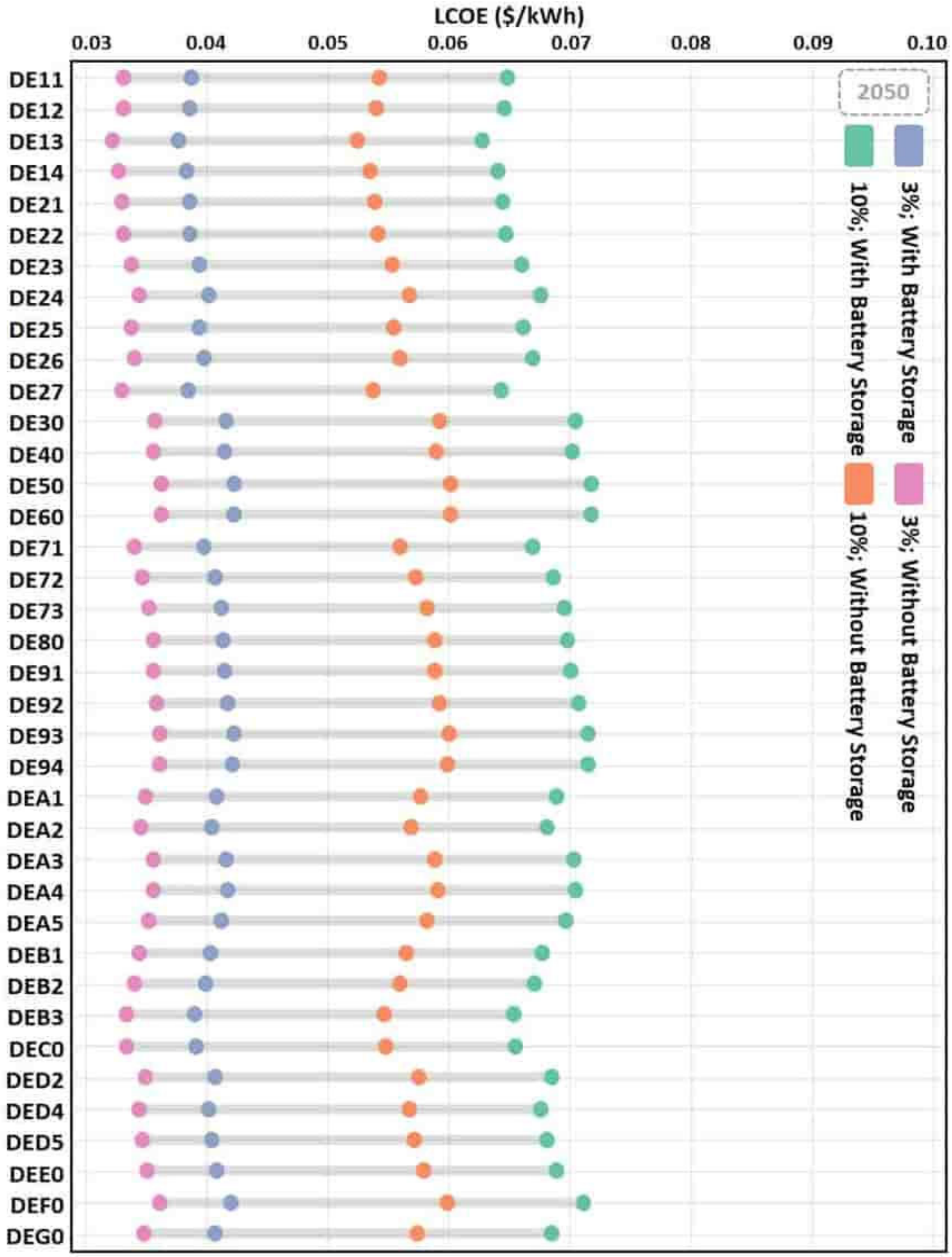


Supplementary Figure 28. Comparative assessment of solar PV LCOE for EU countries in 2050 under different assumptions for battery storage inclusion and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. Acronyms for the EU member states follow the glossary by the European Commission: Germany (DE); Italy (IT); France (FR); Netherlands (NL); Spain (ES); Poland (PL); Belgium (BE); Greece (EL); Austria (AT); Hungary (HU); Czechia (CZ); Portugal (PT); Sweden (SE); Denmark (DK); Romania (RO); Bulgaria (BG); Slovakia (SK); Estonia (EE); Finland (FI); Slovenia (SI); Luxembourg (LU); Lithuania (LT); Malta (MT); Ireland (IE); Croatia (HR); Latvia (LV).



Supplementary Figure 29. Comparative assessment of solar PV LCOE across NUTS-2 regions in Germany for 2024 under different assumptions for battery storage inclusion

and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. Acronyms for the NUTS-2 regional codes follow the classification by Eurostat: Stuttgart (DE11); Karlsruhe (DE12); Freiburg (DE13); Tübingen (DE14); Oberbayern (DE21); Niederbayern (DE22); Oberpfalz (DE23); Oberfranken (DE24); Mittelfranken (DE25); Unterfranken (DE26); Schwaben (DE27); Berlin (DE30); Brandenburg (DE40); Bremen (DE50); Hamburg (DE60); Darmstadt (D71); Gießen (D72); Kassel (D73); Mecklenburg-Vorpommern (D80); Braunschweig (DE91); Hannover (DE92); Lüneburg (DE93); Weser-Ems (DE94); Düsseldorf (DEA1); Köln (DEA2); Münster (DEA3); Detmold (DEA4); Arnsberg (DEA5); Koblenz (DEB1); Trier (DEB2); Rheinhessen-Pfalz (DEB3); Saarland (DEC0); Dresden (DED2); Chemnitz (DED4); Leipzig (DED5); Sachsen-Anhalt (DEE0); Schleswig-Holstein (DEF0); Thüringen (DEG0).



Supplementary Figure 30. Comparative assessment of solar PV LCOE across NUTS-2 regions in Germany for 2024 under different assumptions for battery storage inclusion

and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. Acronyms for the NUTS-2 regional codes follow the classification by Eurostat: Stuttgart (DE11); Karlsruhe (DE12); Freiburg (DE13); Tübingen (DE14); Oberbayern (DE21); Niederbayern (DE22); Oberpfalz (DE23); Oberfranken (DE24); Mittelfranken (DE25); Unterfranken (DE26); Schwaben (DE27); Berlin (DE30); Brandenburg (DE40); Bremen (DE50); Hamburg (DE60); Darmstadt (D71); Gießen (D72); Kassel (D73); Mecklenburg-Vorpommern (D80); Braunschweig (DE91); Hannover (DE92); Lüneburg (DE93); Weser-Ems (DE94); Düsseldorf (DEA1); Köln (DEA2); Münster (DEA3); Detmold (DEA4); Arnsberg (DEA5); Koblenz (DEB1); Trier (DEB2); Rheinhessen-Pfalz (DEB3); Saarland (DEC0); Dresden (DED2); Chemnitz (DED4); Leipzig (DED5); Sachsen-Anhalt (DEE0); Schleswig-Holstein (DEF0); Thüringen (DEG0).

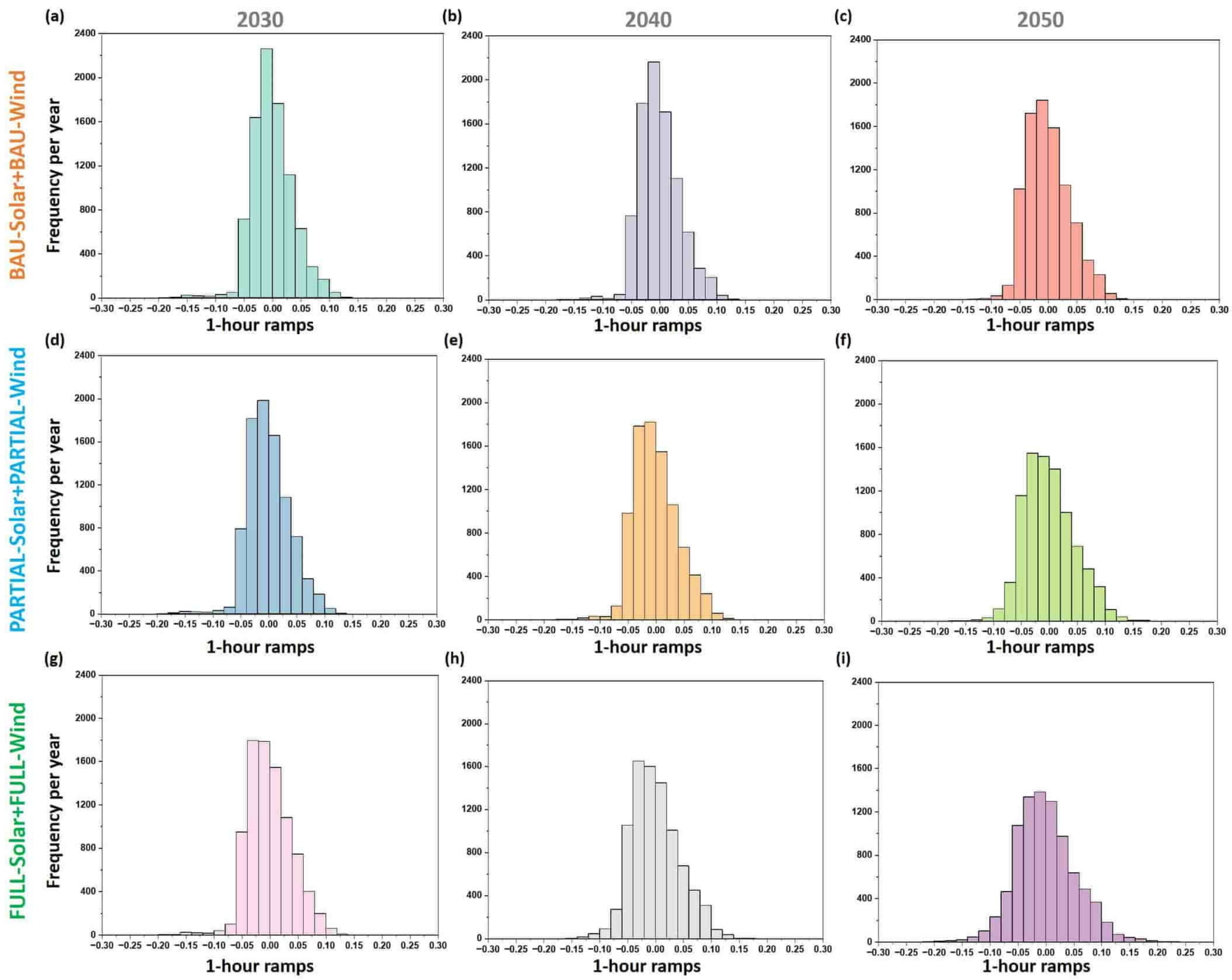
Supplementary Table 1. Comparison summary of key focus areas, insights from prior literature, and corresponding contributions of this study.

Focus Area	Citations	Insights from Prior Literature	Contribution of This Study
Energy Security and Import Substitution	[4, 5, 6]	Empirical assessment and analysis show that renewable energy deployment, diversification of primary energy sources, and sufficiency measures can reduce import dependency.	Develops renewable expansion scenarios with sector-specific gross inland natural gas reductions as a central metric to evaluate energy security gains and decreases in import dependency rates.
Energy Systems Analysis	[7, 8, 9, 10]	Utilize least-cost energy system or transmission-level analyses to explore feasible system designs, societal coordination, multi-sector integration, and grid constraints.	Proposes a scenario-based framework with sectoral disaggregation to assess the impact of renewable deployment on aligning energy security and emissions reduction, while capturing cost, technological penetration, and flexibility

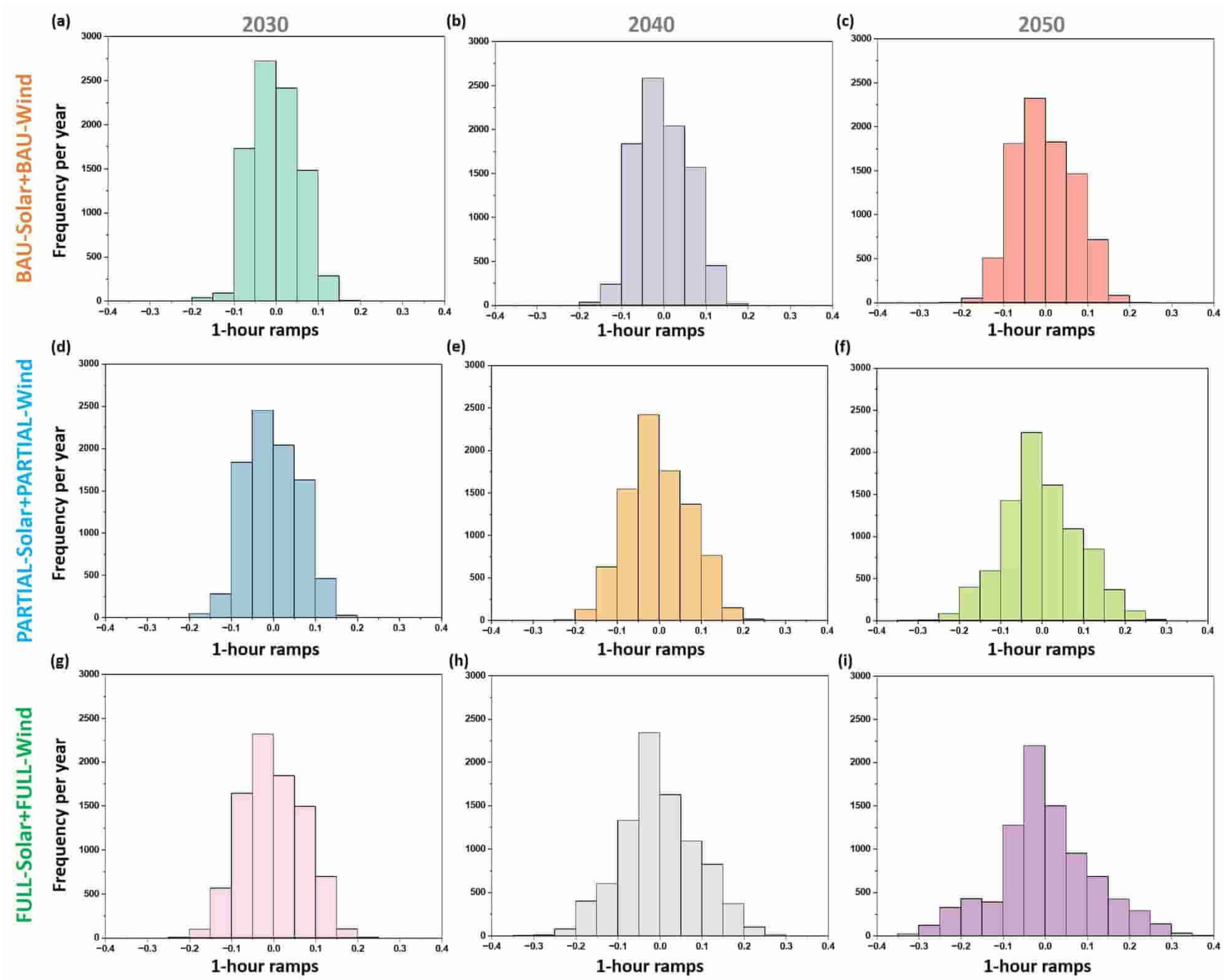
			requirements across spatial and temporal dimensions.
Individual Energy Pathways and Regional Assessments	[11, 12, 13, 14, 15, 16, 17, 18]	Explore individual energy pathways such as renewable investments, hydrogen infrastructure, or region-specific crisis responses, with limited emphasis on aligning energy security and climate goals.	Bridges EU-wide renewable expansion targets with targeted interventions (electrification, green hydrogen, and carbon offsetting) to evaluate regional feasibility under cost uncertainties and assess contributions to energy security and decarbonization.

Supplementary Discussion 2: Grid Integration of Renewable Energy Expansion

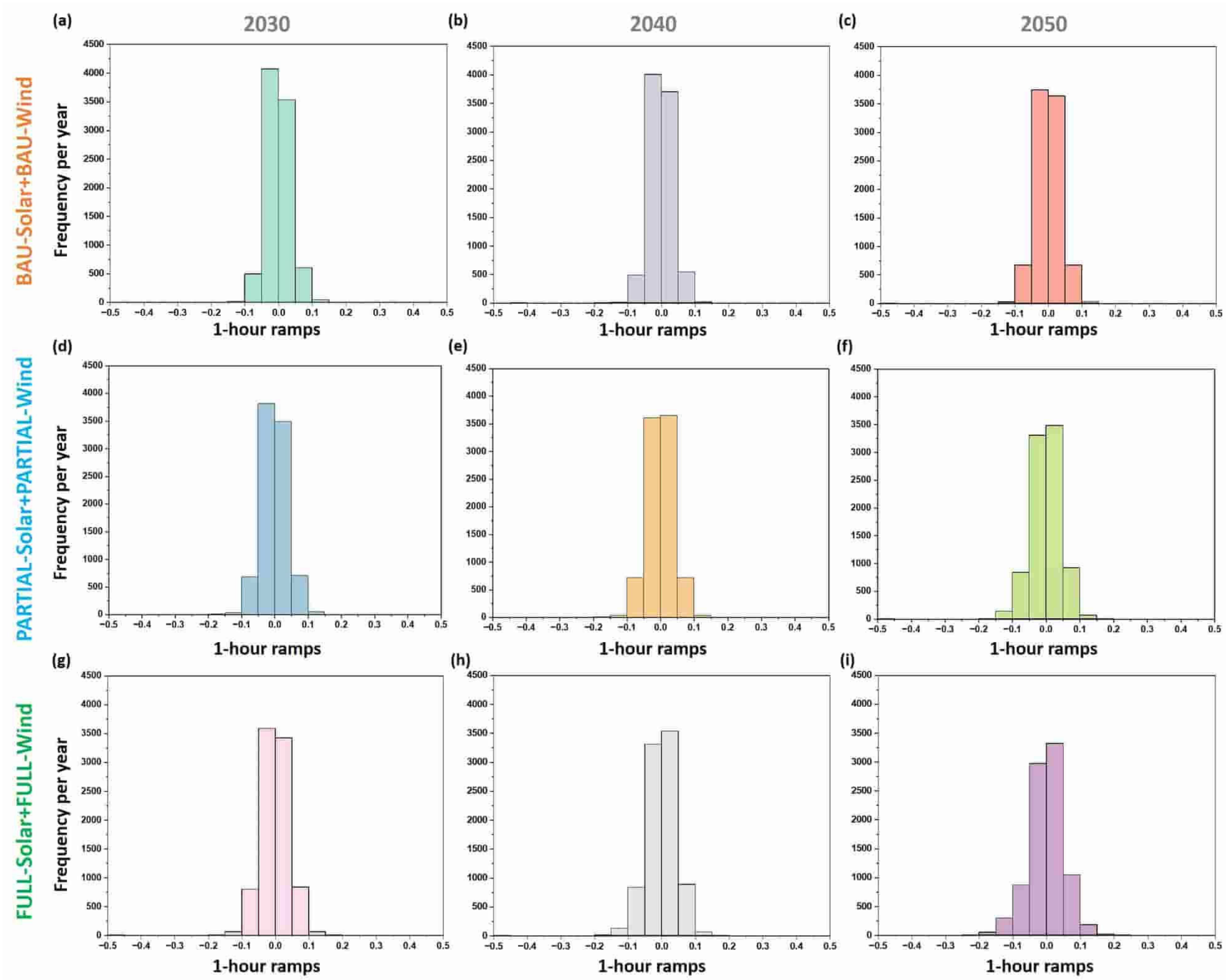
This work evaluates the frequency distribution of normalized net-load ramp rates at hourly resolution as a metric to assess grid integration challenges associated with increasing shares of variable renewable energy sources. The analysis covers the implementation scenarios, BAU-solar with BAU-wind, PARTIAL-solar with PARTIAL-wind, and FULL-solar with FULL-wind across the time horizons of 2030, 2040, and 2050, as illustrated in **Supplementary Figs. 31-55**. The results show that higher renewable penetration broadens the distribution of net-load ramps, indicating a greater frequency of large ramping events, especially by 2050. This trend is particularly pronounced in countries like Germany and Spain under the FULL-solar with FULL-wind scenario, where the distribution widens notably, reflecting more frequent and larger positive and negative ramps. These shifts underscore the increasing operational variability introduced by high shares of intermittent renewables, highlighting the need for enhanced flexibility requirements and balancing resources to maintain reliability. In contrast, countries like Sweden and Finland depict relatively narrower ramp distributions. The comparison across the BAU, PARTIAL, and FULL scenarios for each country further reveals the importance of strategic interventions in managing grid reliability. In this regard, the PARTIAL-solar with PARTIAL-wind scenario exhibits a moderate level of ramping events, with distributions that fall between the BAU and FULL cases. For example, in Italy and Spain, the PARTIAL-solar with PARTIAL-wind scenario in 2050 leads to less severe ramping events than the FULL case, reflecting the trade-off between pursuing ambitious renewable targets for energy security and decarbonization and ensuring operational adequacy and reliability.



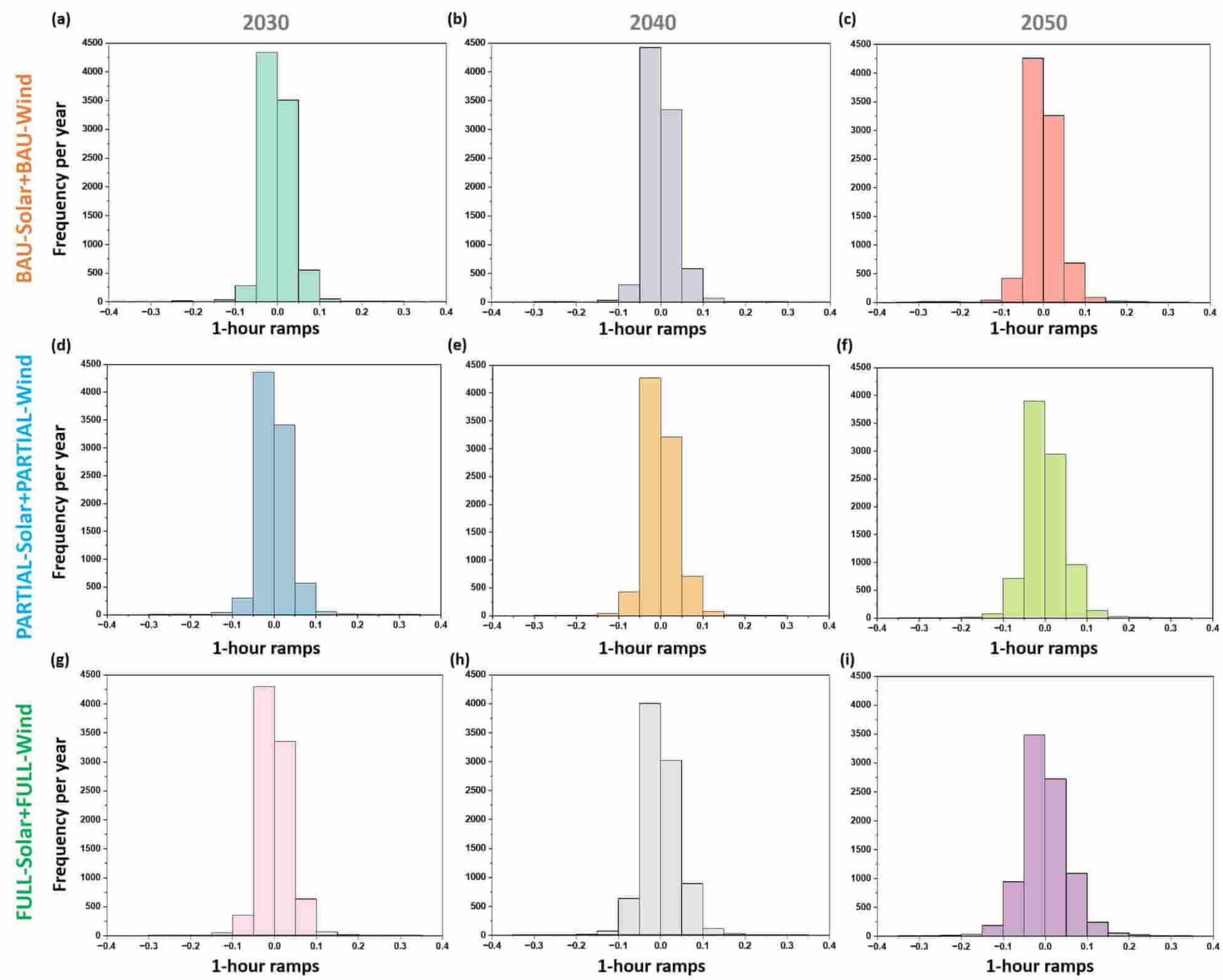
Supplementary Figure 31. Frequency distribution for hourly net-load ramps normalized to the peak load in Germany. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



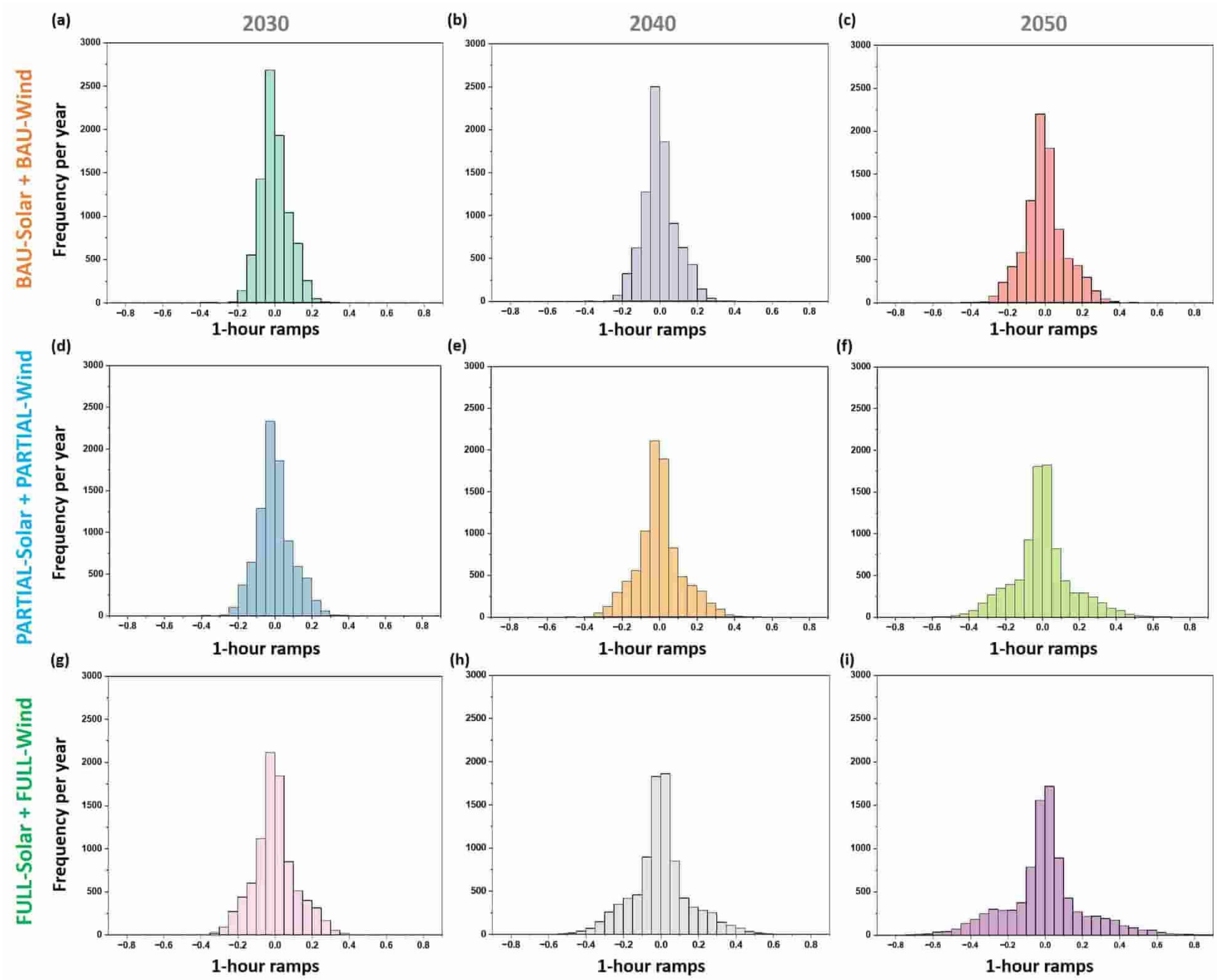
Supplementary Figure 32. Frequency distribution for hourly net-load ramps normalized to the peak load in Italy. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



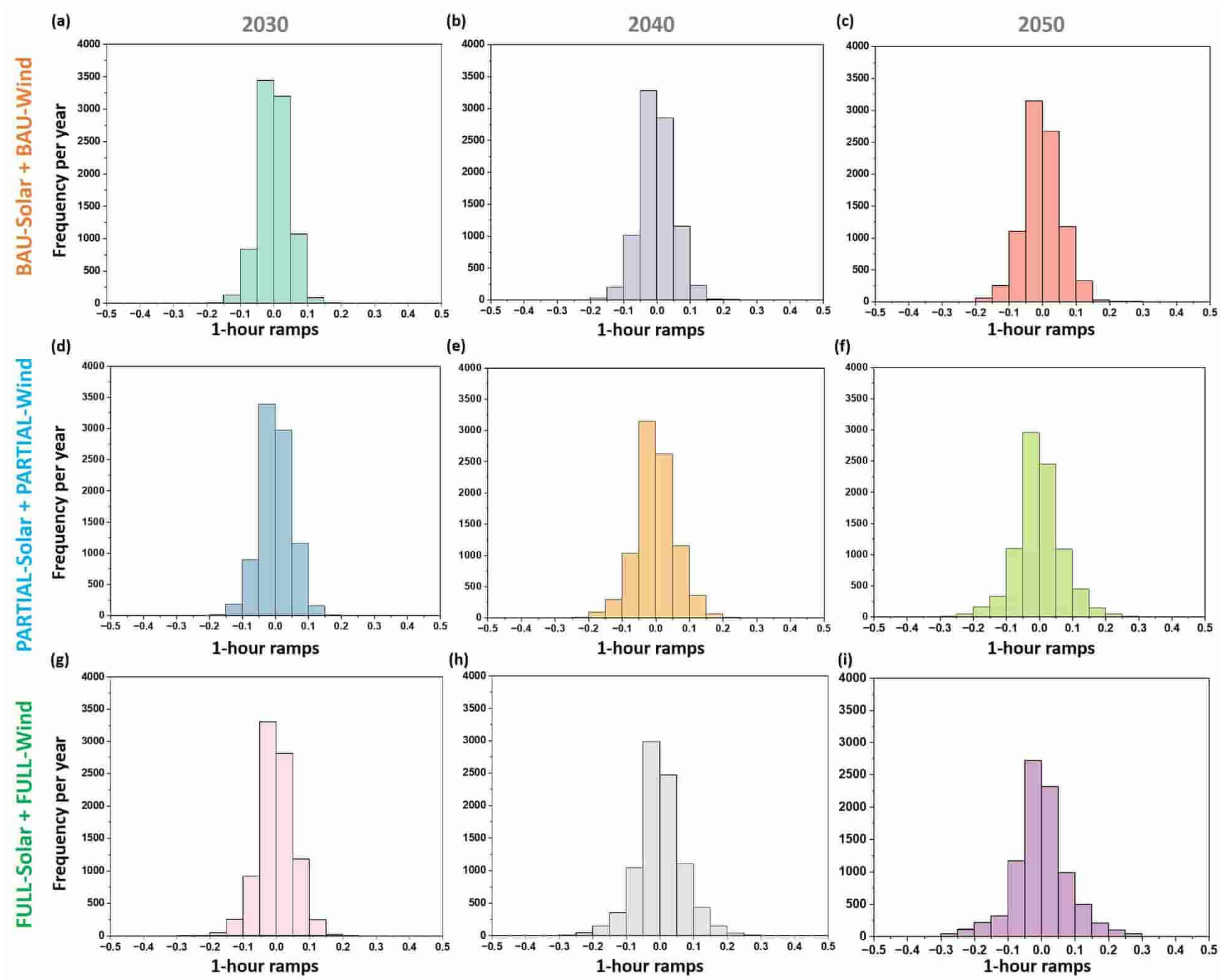
Supplementary Figure 33. Frequency distribution for hourly net-load ramps normalized to the peak load in France. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



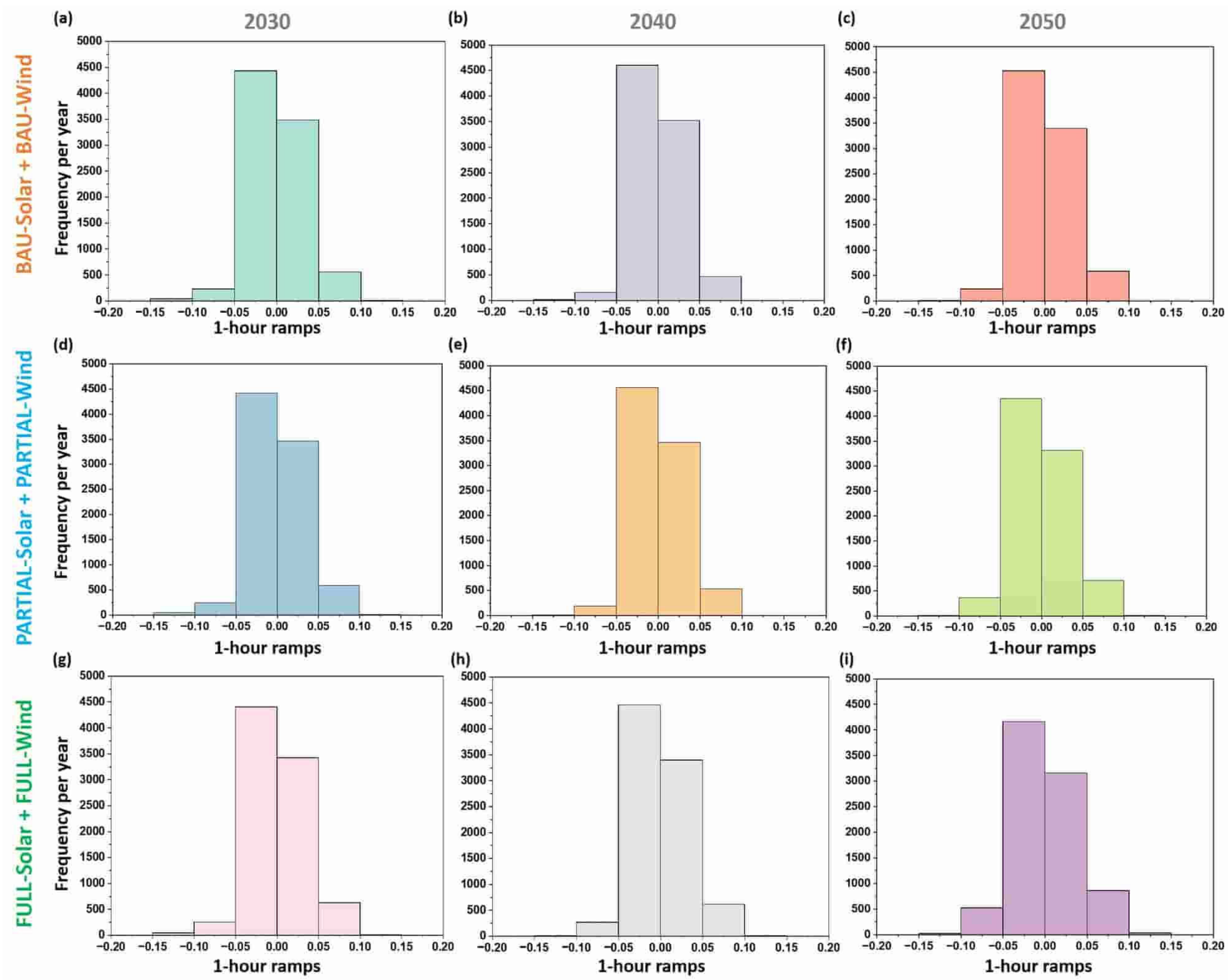
Supplementary Figure 34. Frequency distribution for hourly net-load ramps normalized to the peak load in the Netherlands. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



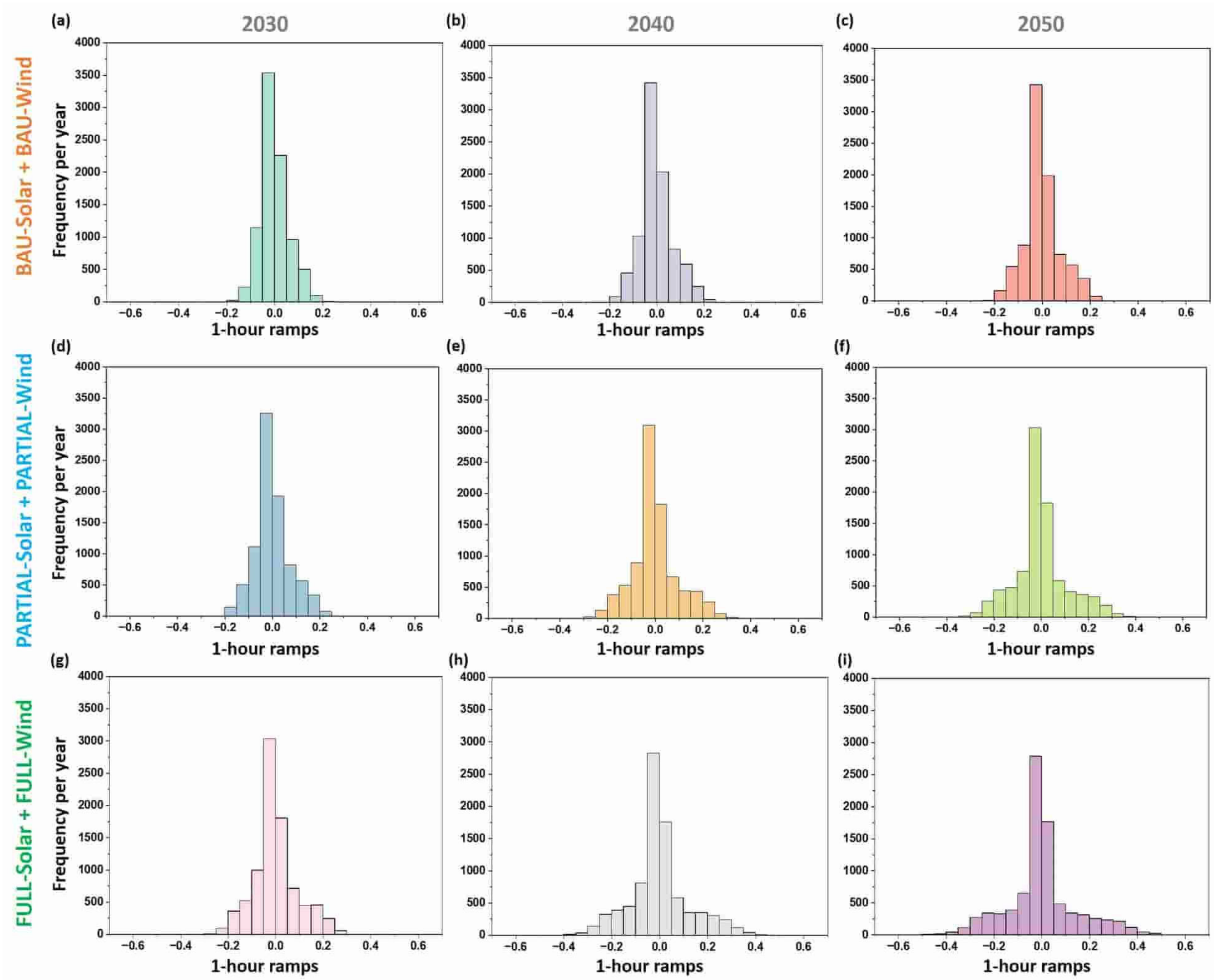
Supplementary Figure 35. Frequency distribution for hourly net-load ramps normalized to the peak load in Spain. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



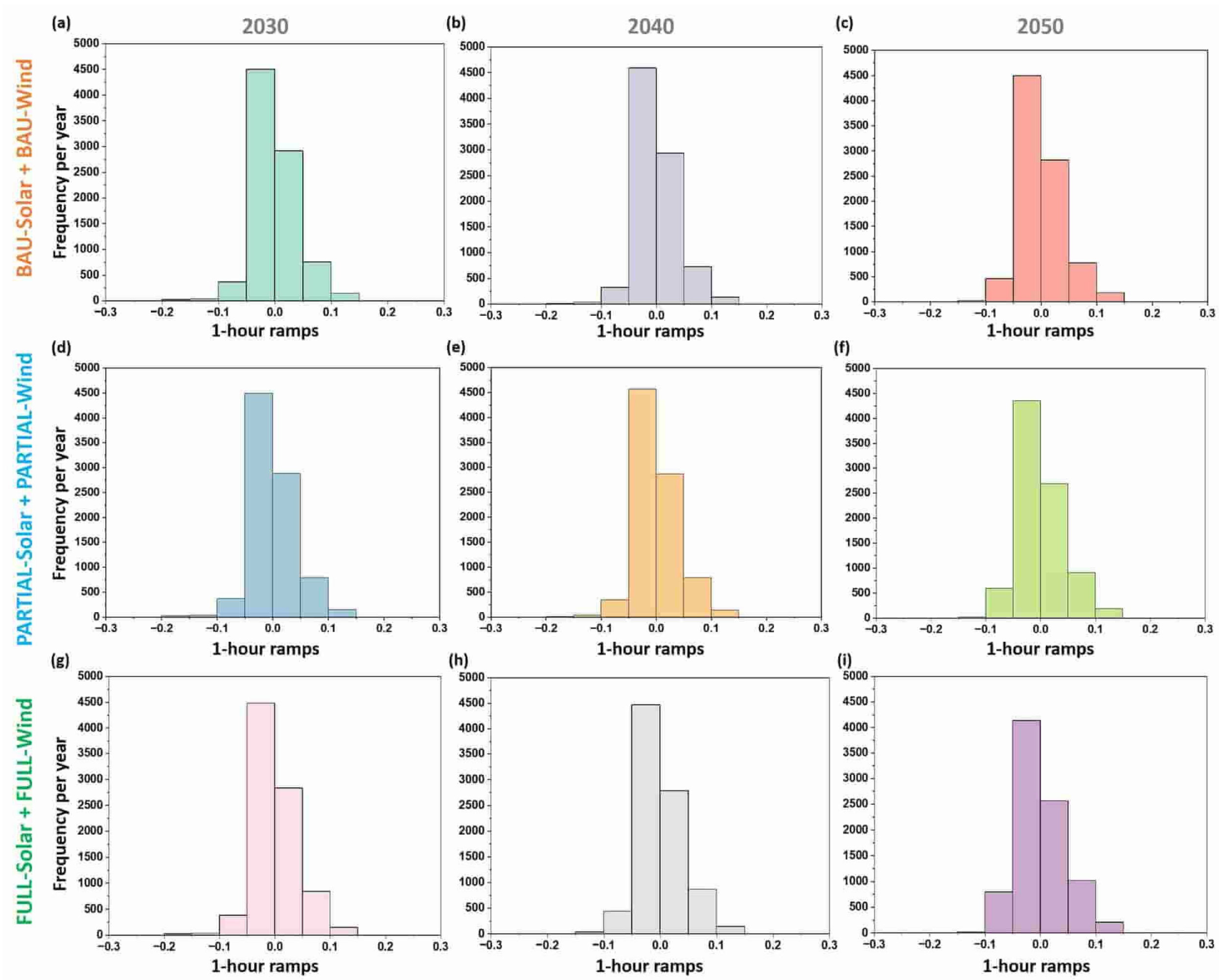
Supplementary Figure 36. Frequency distribution for hourly net-load ramps normalized to the peak load in Poland. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



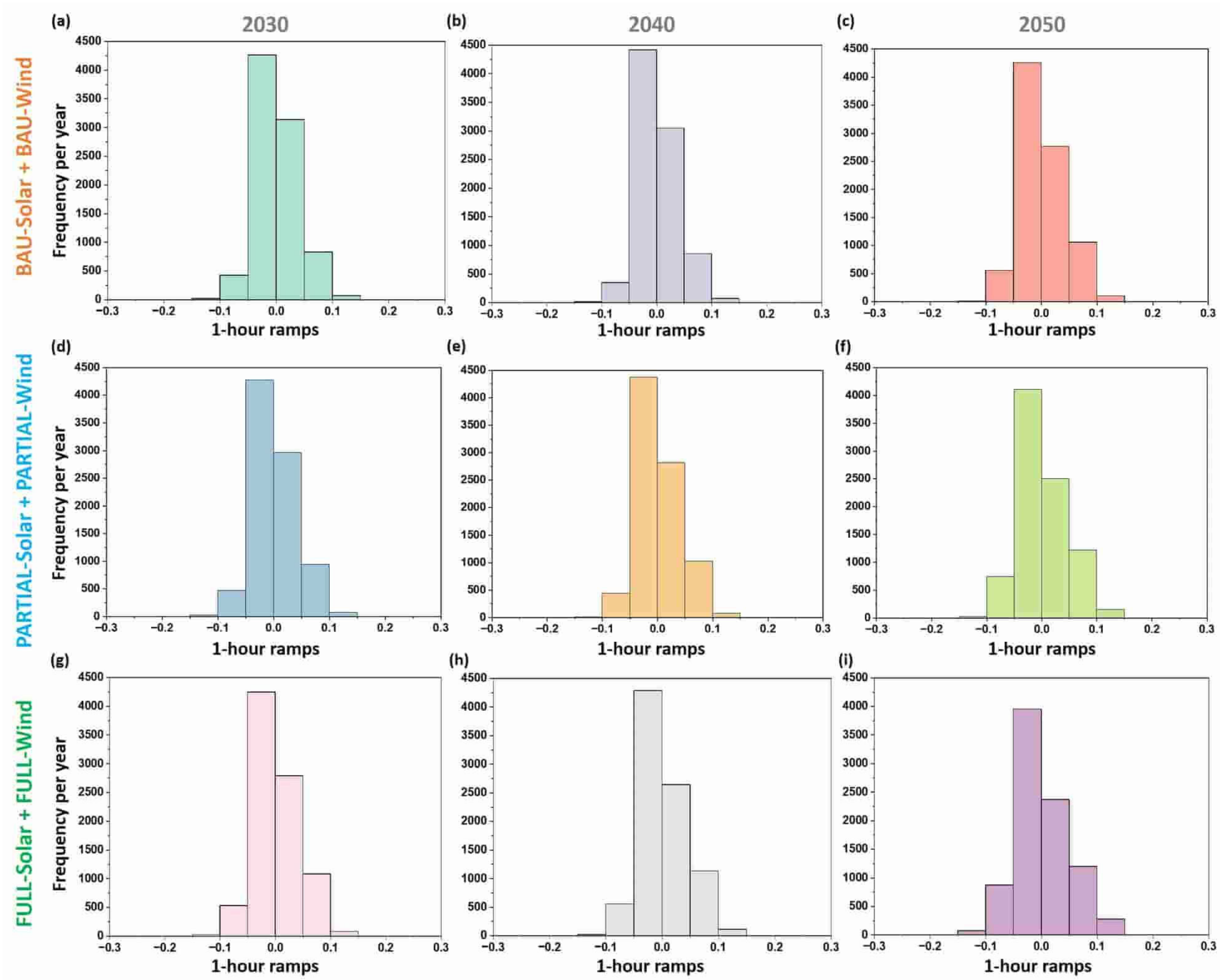
Supplementary Figure 37. Frequency distribution for hourly net-load ramps normalized to the peak load in Belgium. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



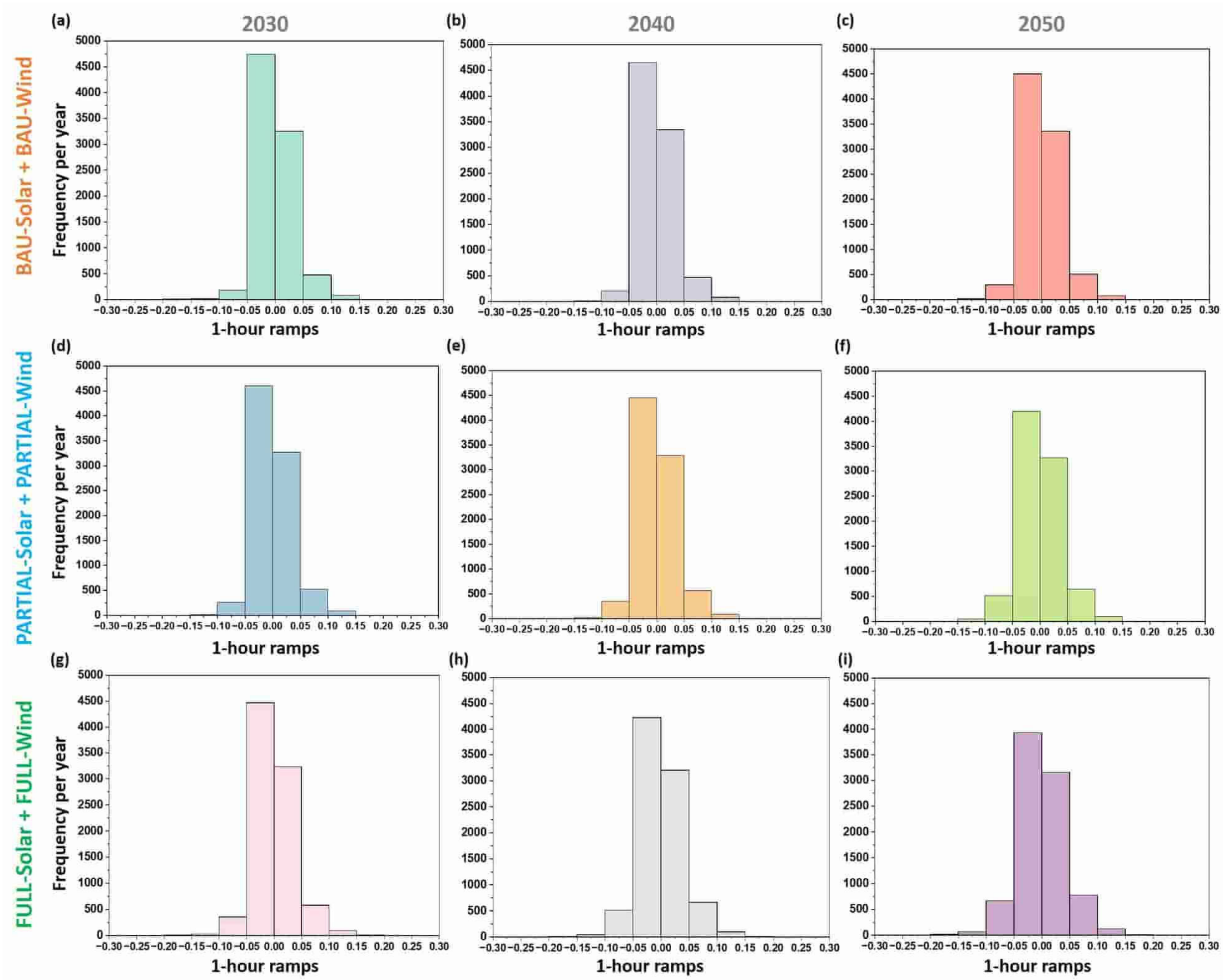
Supplementary Figure 38. Frequency distribution for hourly net-load ramps normalized to the peak load in Greece. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



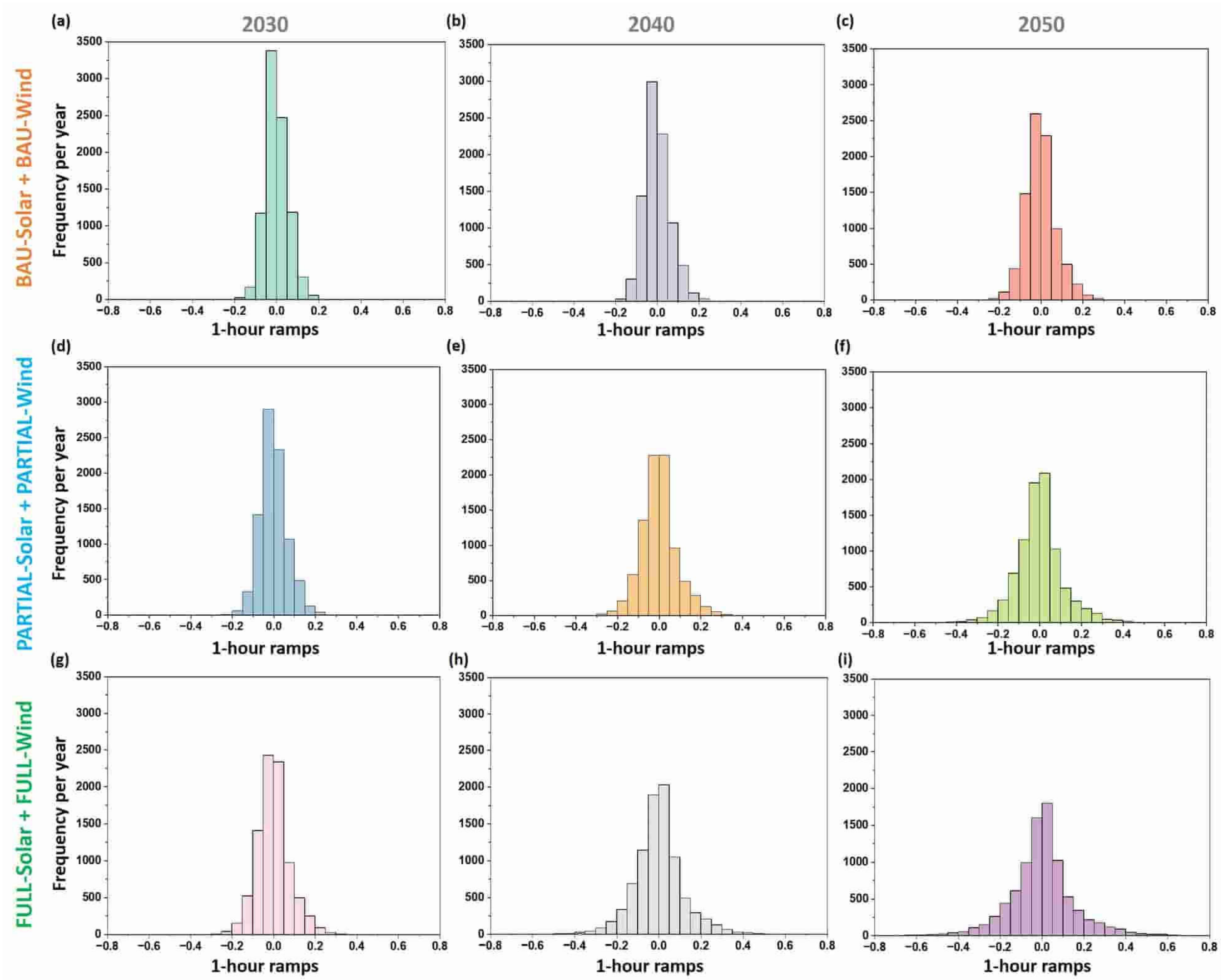
Supplementary Figure 39. Frequency distribution for hourly net-load ramps normalized to the peak load in Austria. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



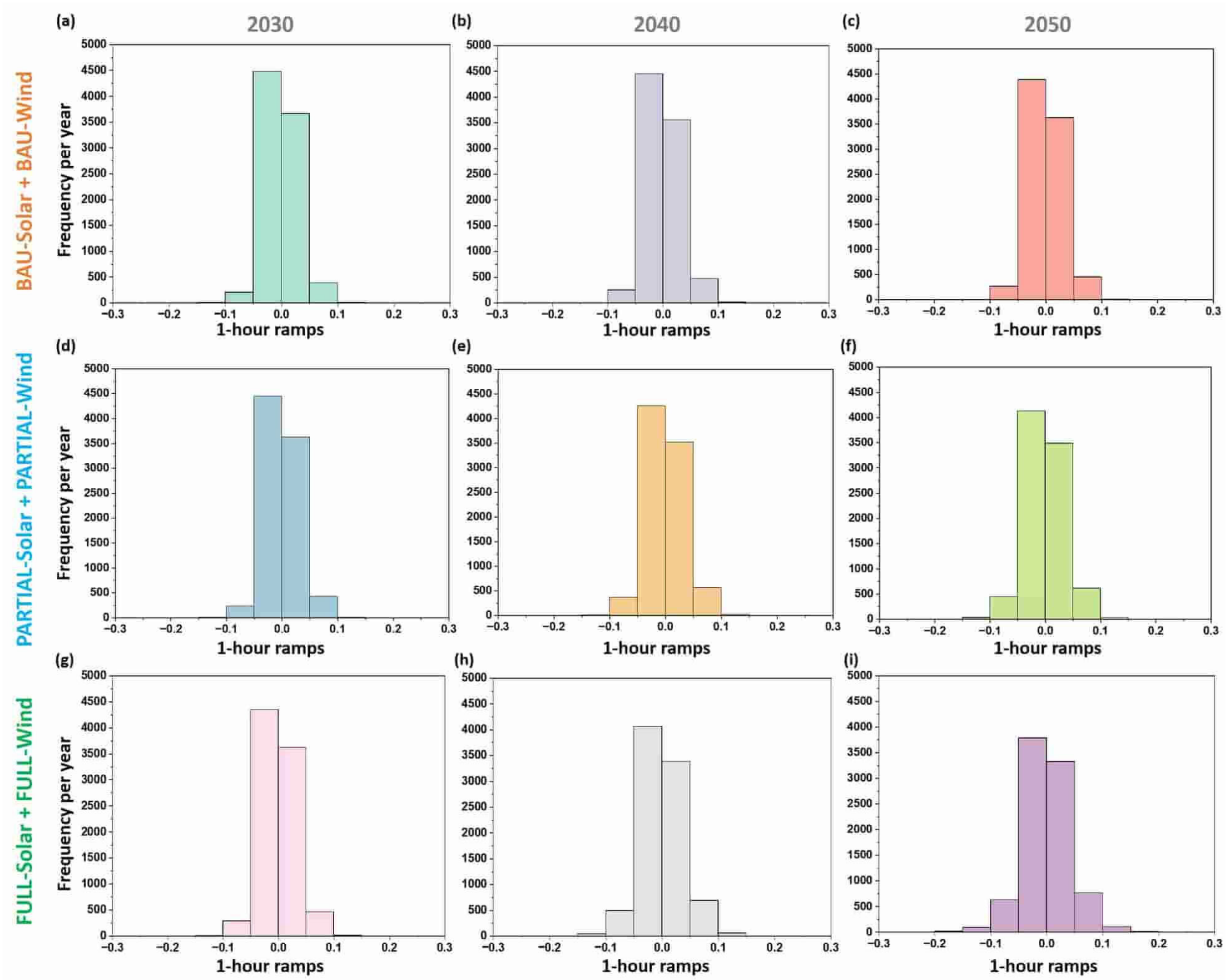
Supplementary Figure 40. Frequency distribution for hourly net-load ramps normalized to the peak load in Hungary. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



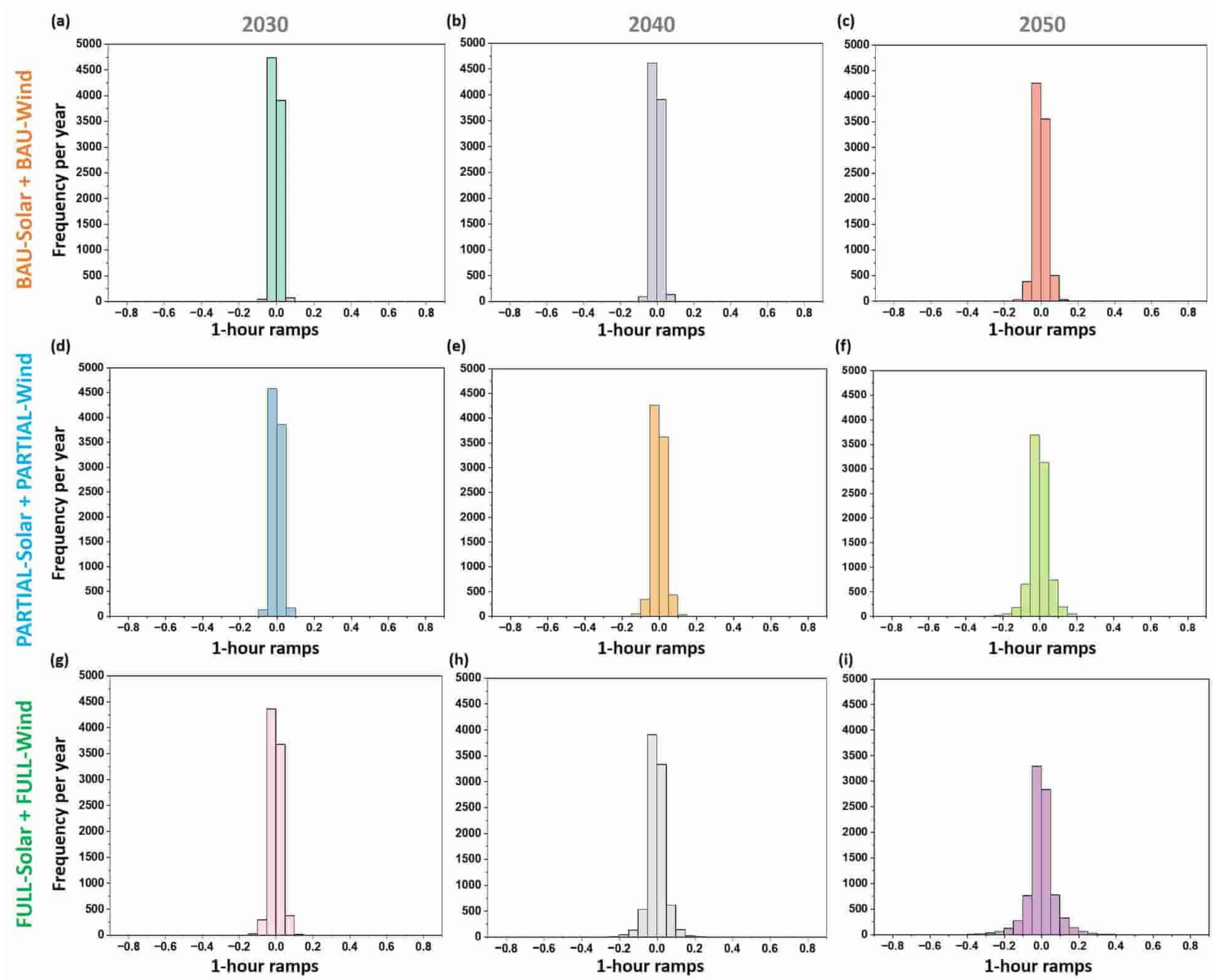
Supplementary Figure 41. Frequency distribution for hourly net-load ramps normalized to the peak load in Czechia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



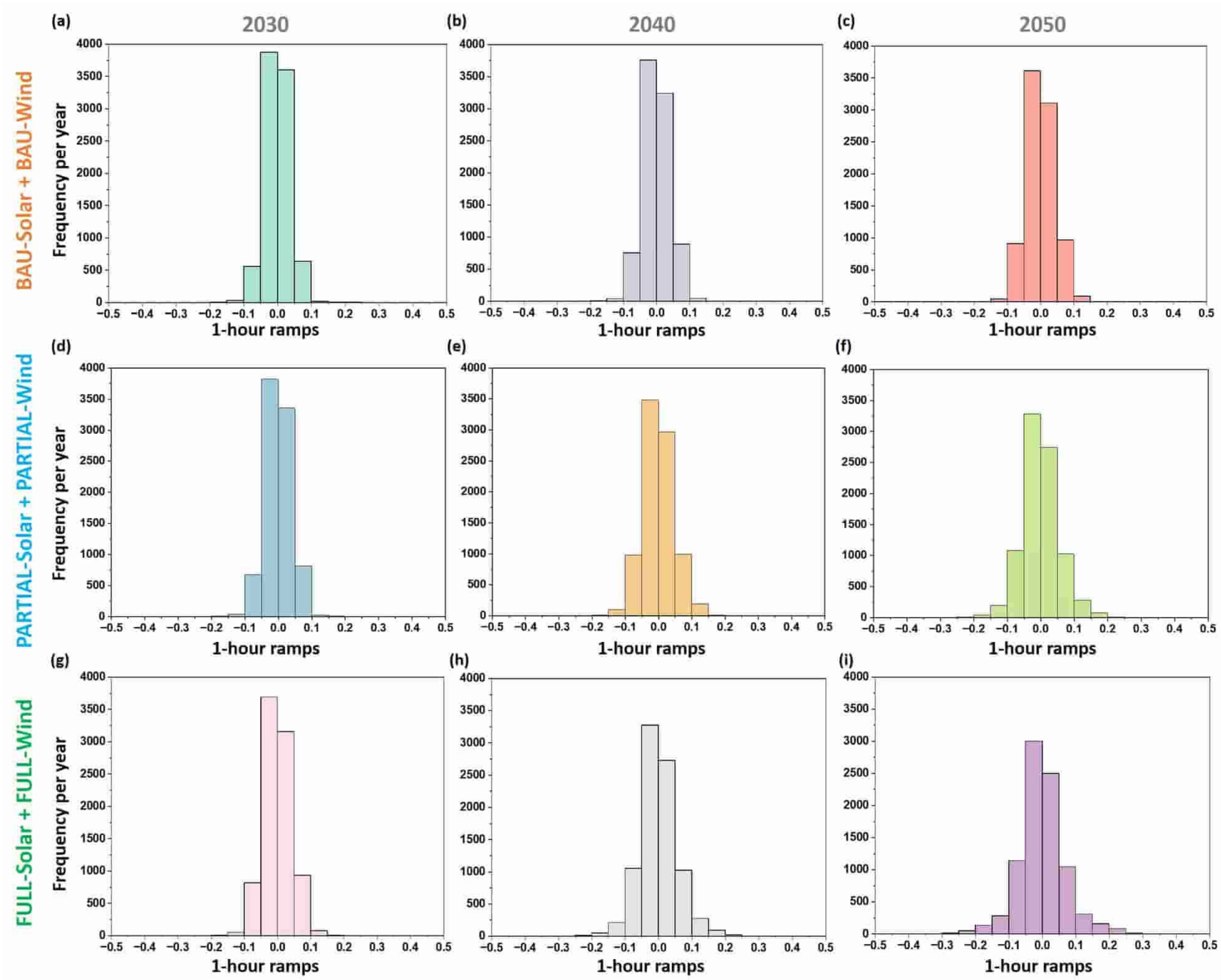
Supplementary Figure 42. Frequency distribution for hourly net-load ramps normalized to the peak load in Portugal. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



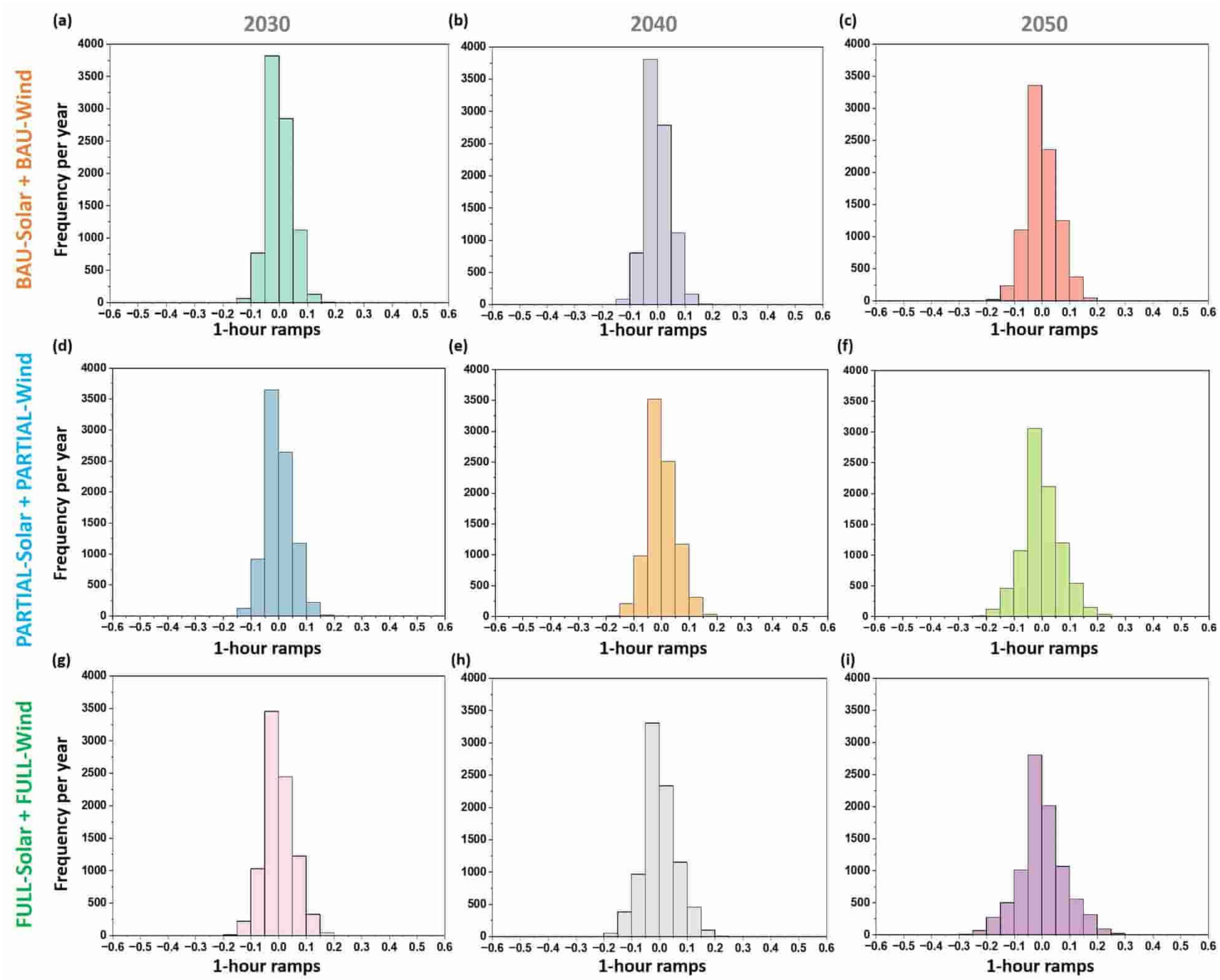
Supplementary Figure 43. Frequency distribution for hourly net-load ramps normalized to the peak load in Sweden. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



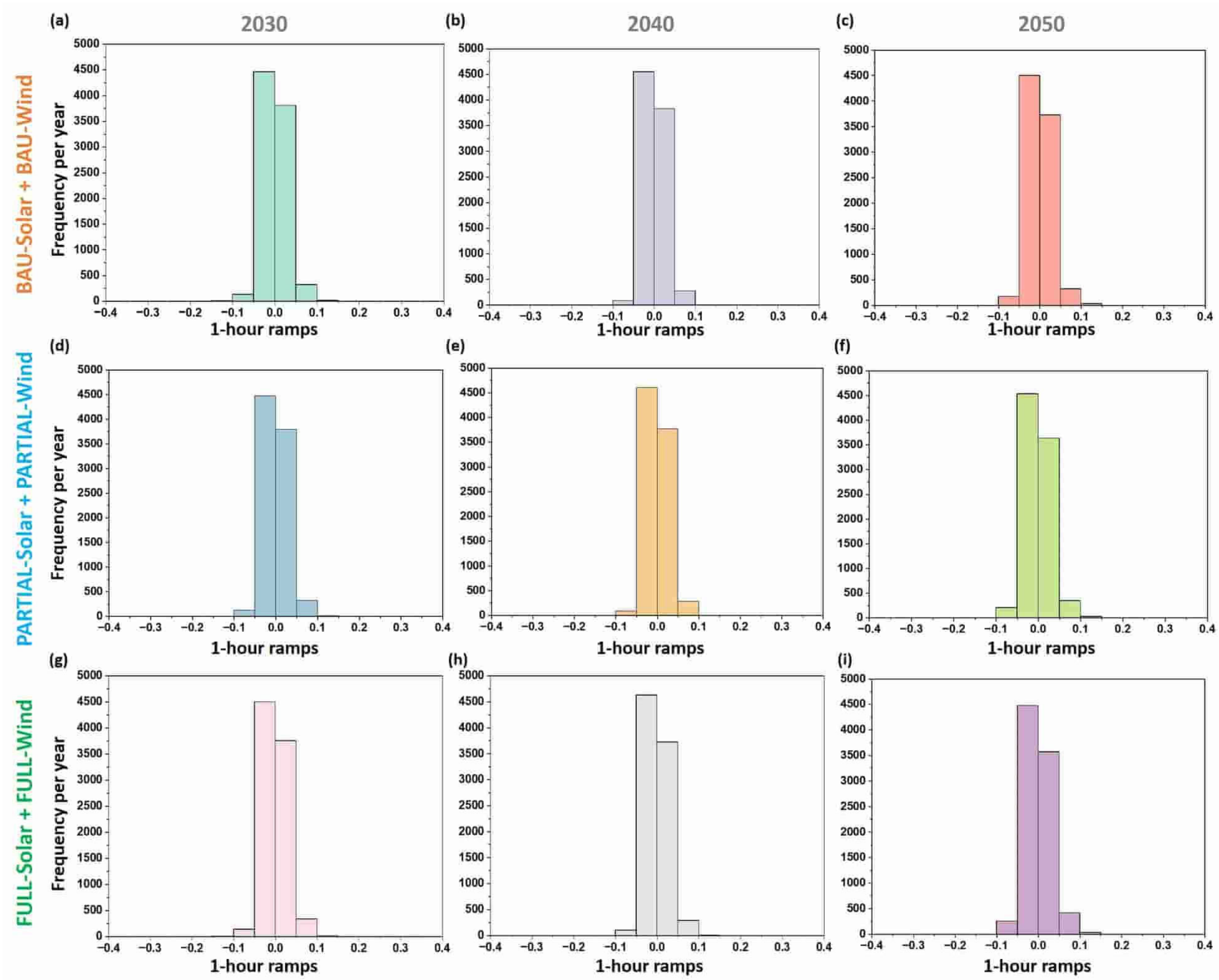
Supplementary Figure 44. Frequency distribution for hourly net-load ramps normalized to the peak load in Denmark. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



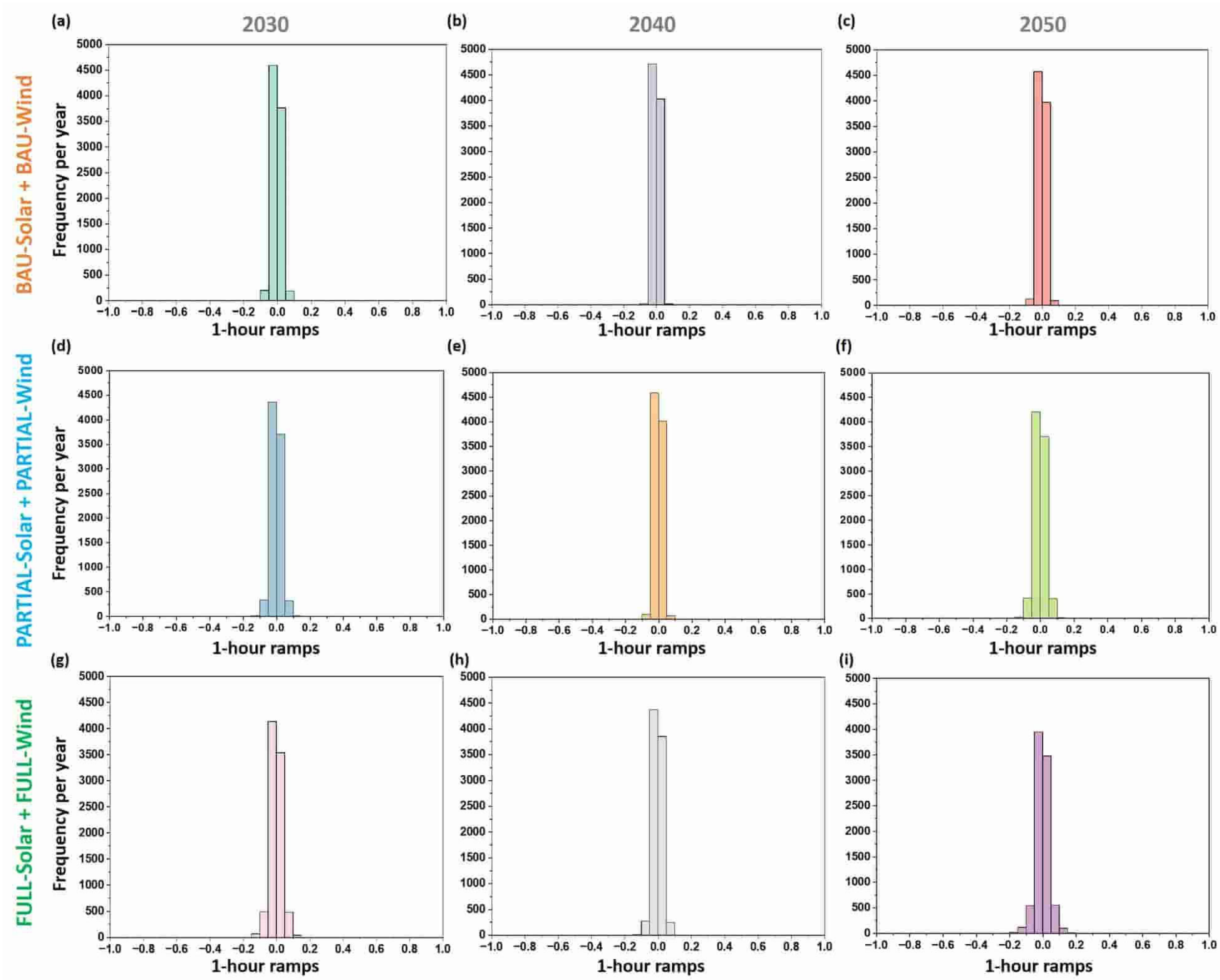
Supplementary Figure 45. Frequency distribution for hourly net-load ramps normalized to the peak load in Romania. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



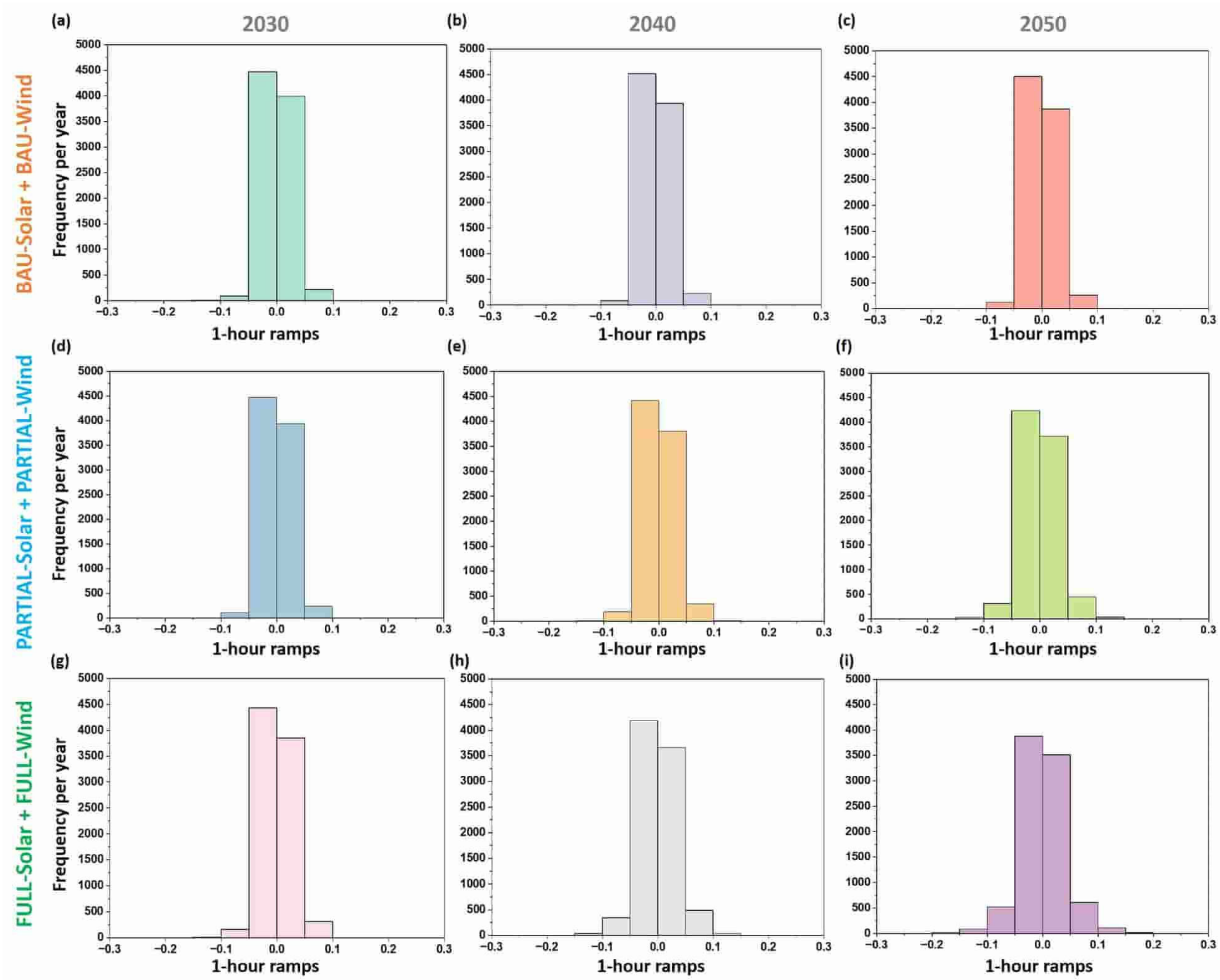
Supplementary Figure 46. Frequency distribution for hourly net-load ramps normalized to the peak load in Bulgaria. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



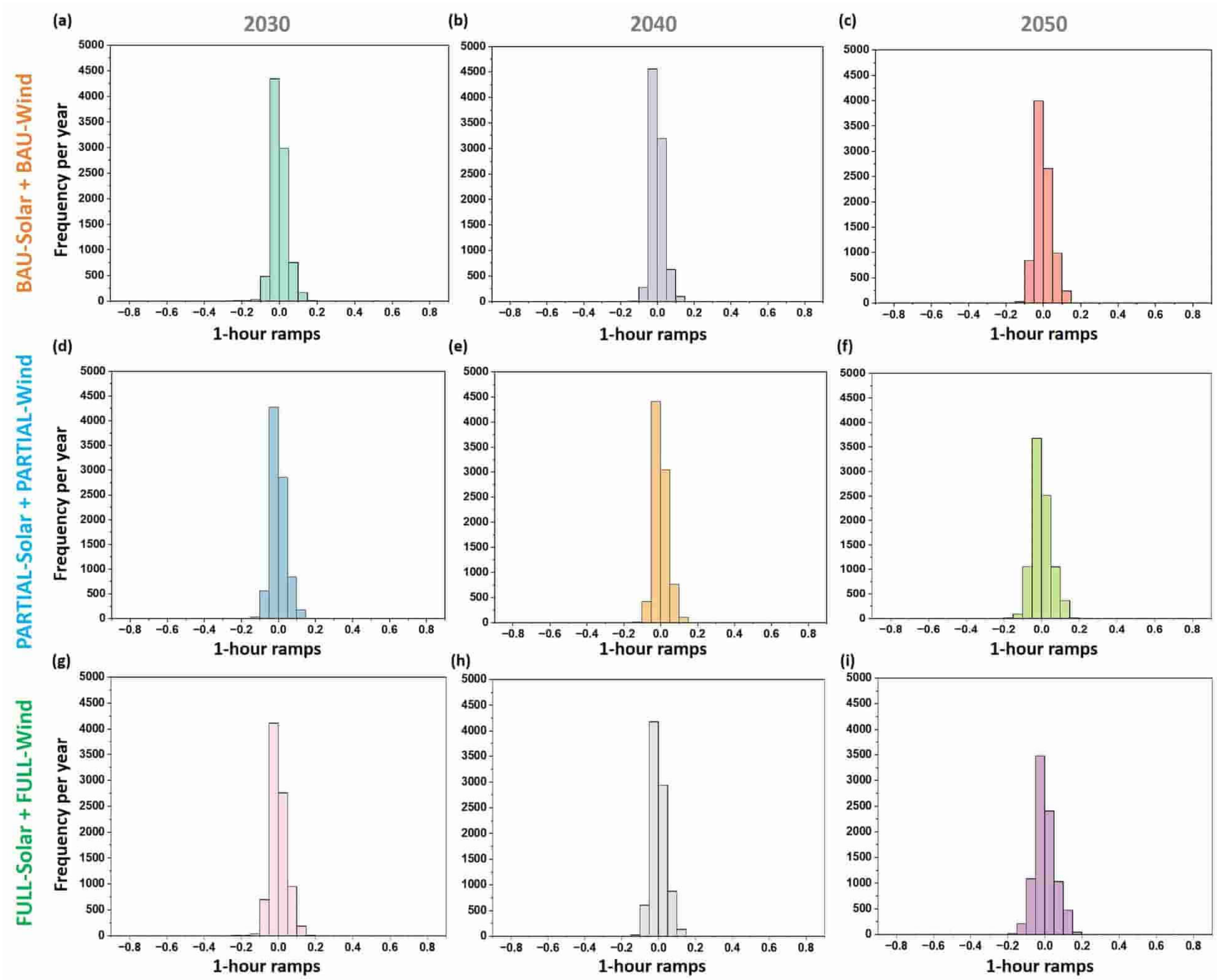
Supplementary Figure 47. Frequency distribution for hourly net-load ramps normalized to the peak load in Slovakia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



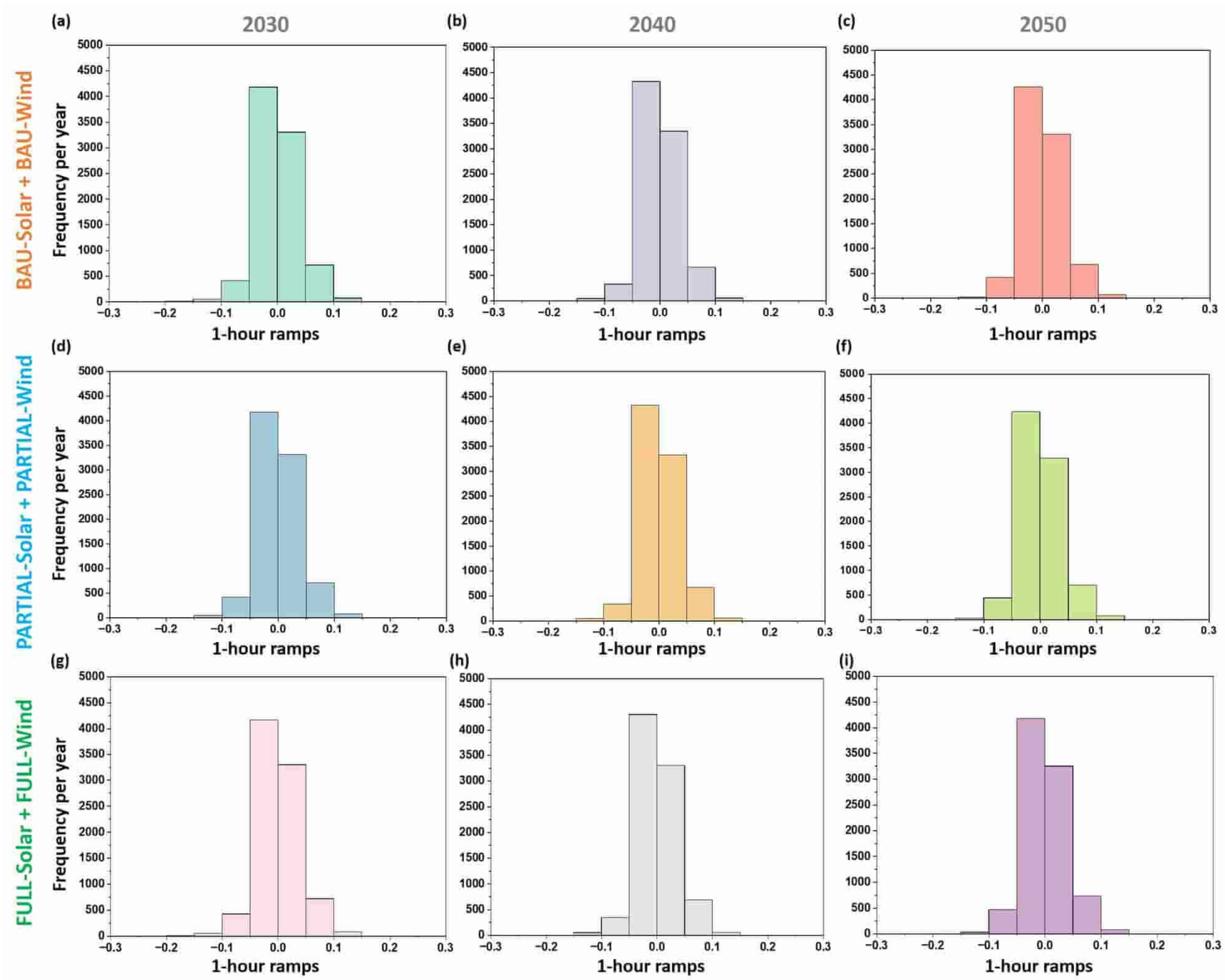
Supplementary Figure 48. Frequency distribution for hourly net-load ramps normalized to the peak load in Estonia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



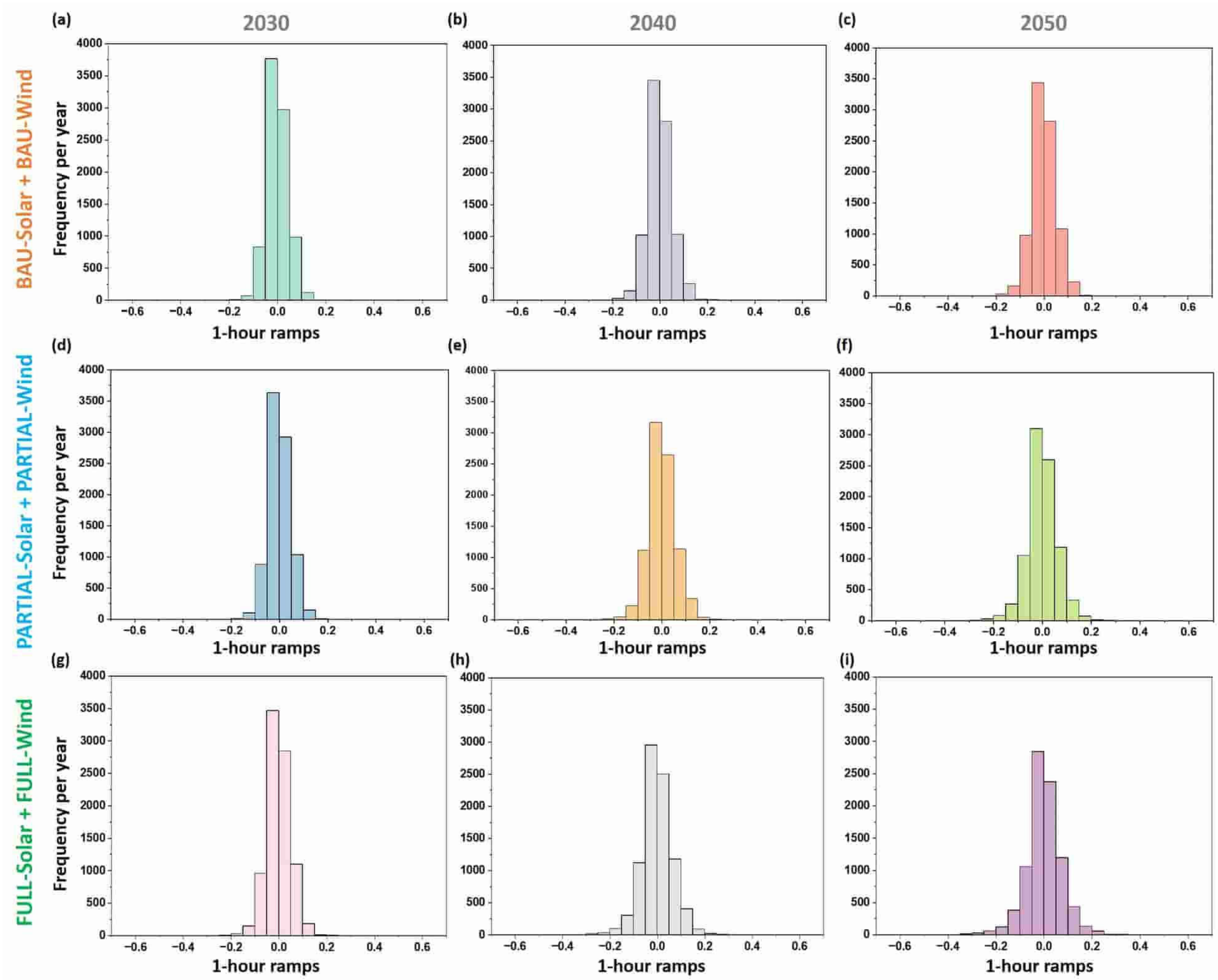
Supplementary Figure 49. Frequency distribution for hourly net-load ramps normalized to the peak load in Finland. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



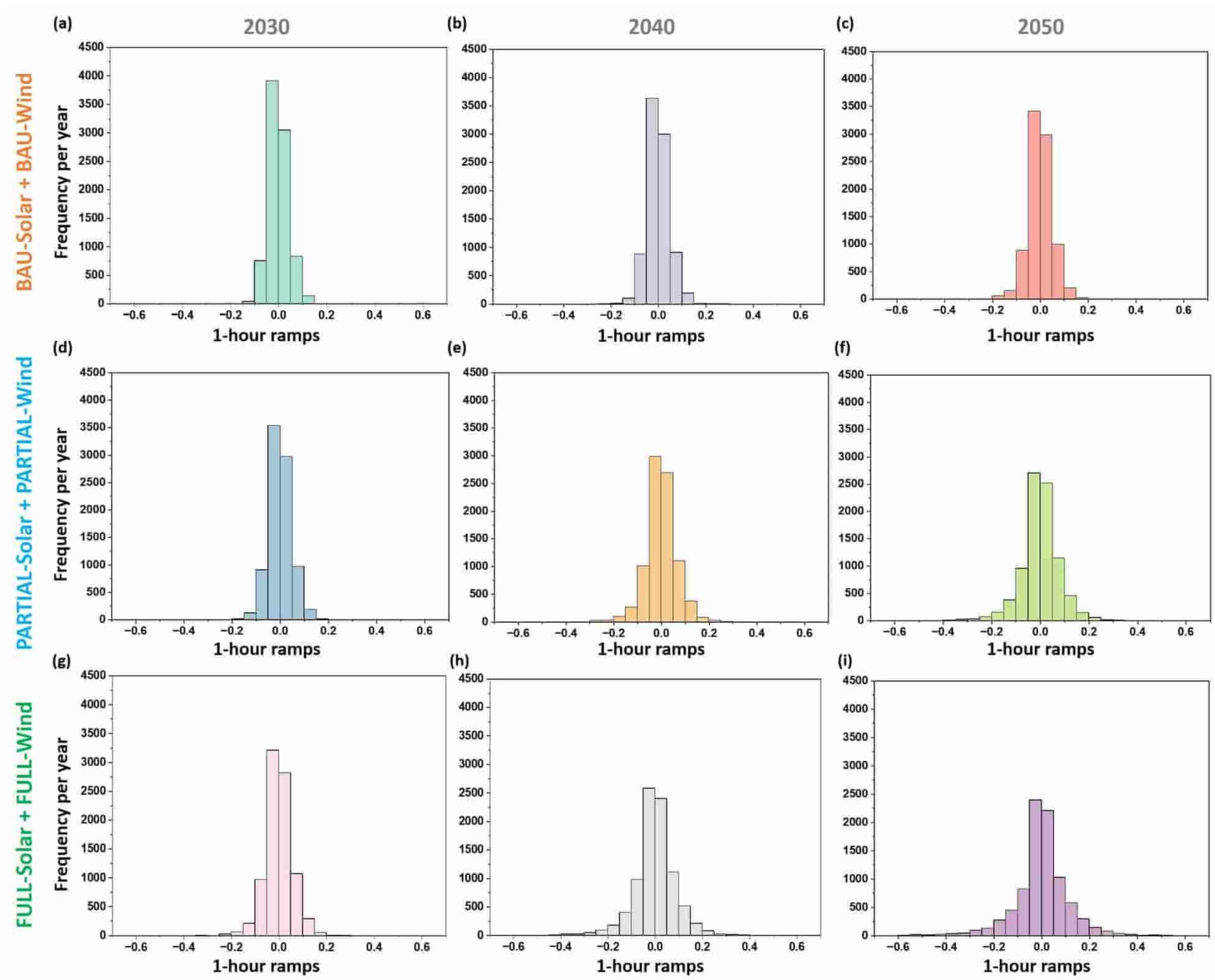
Supplementary Figure 50. Frequency distribution for hourly net-load ramps normalized to the peak load in Slovenia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



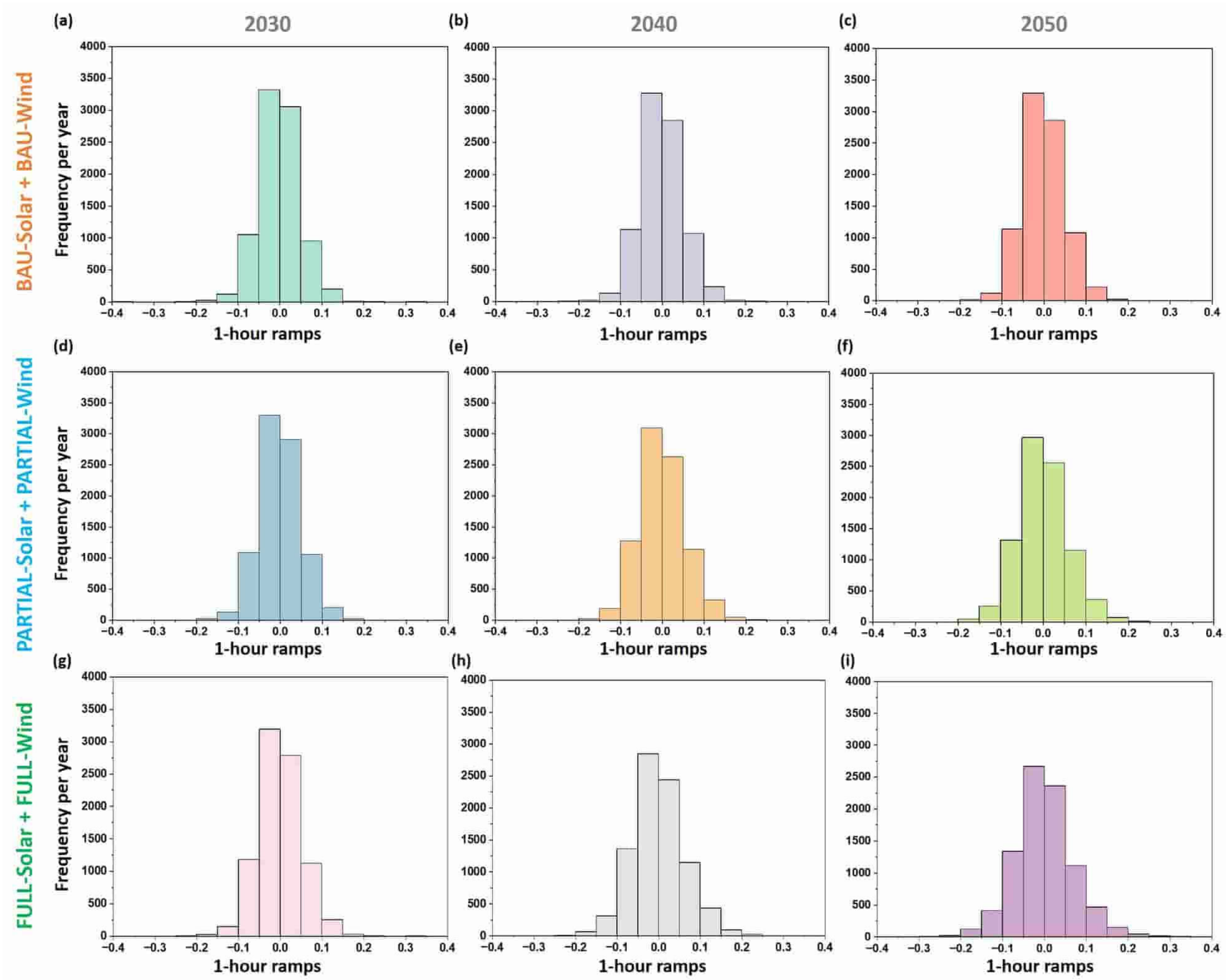
Supplementary Figure 51. Frequency distribution for hourly net-load ramps normalized to the peak load in Luxembourg. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



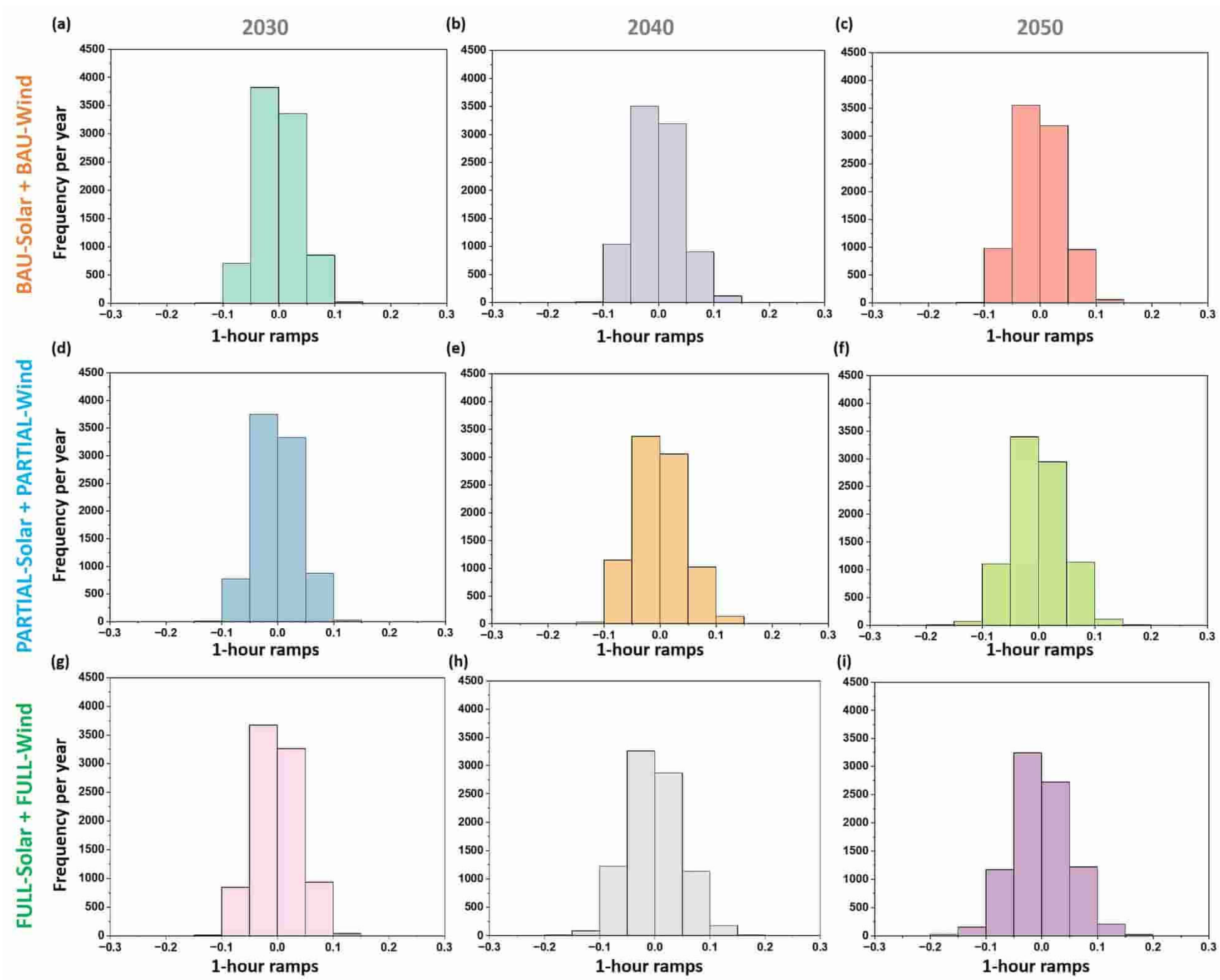
Supplementary Figure 52. Frequency distribution for hourly net-load ramps normalized to the peak load in Lithuania. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



Supplementary Figure 53. Frequency distribution for hourly net-load ramps normalized to the peak load in Ireland. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



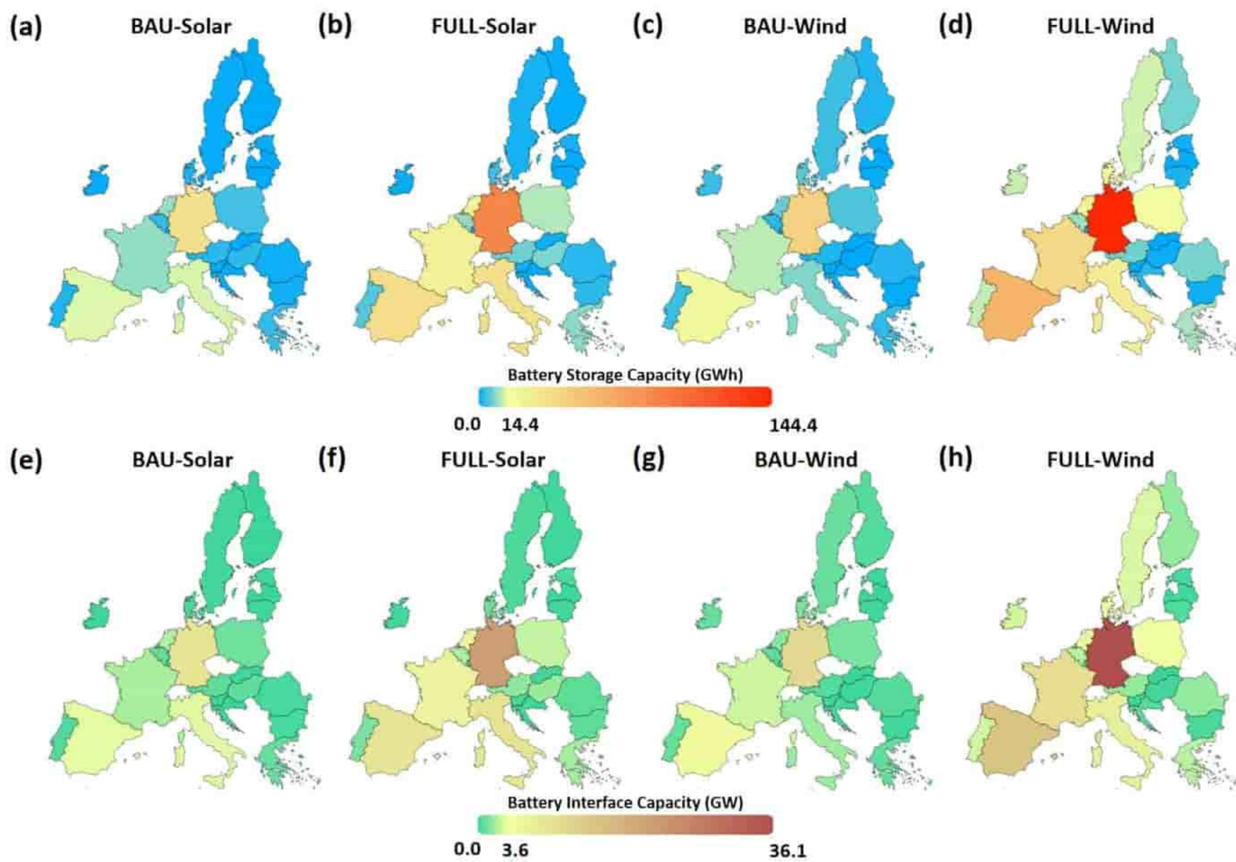
Supplementary Figure 54. Frequency distribution for hourly net-load ramps normalized to the peak load in Croatia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.



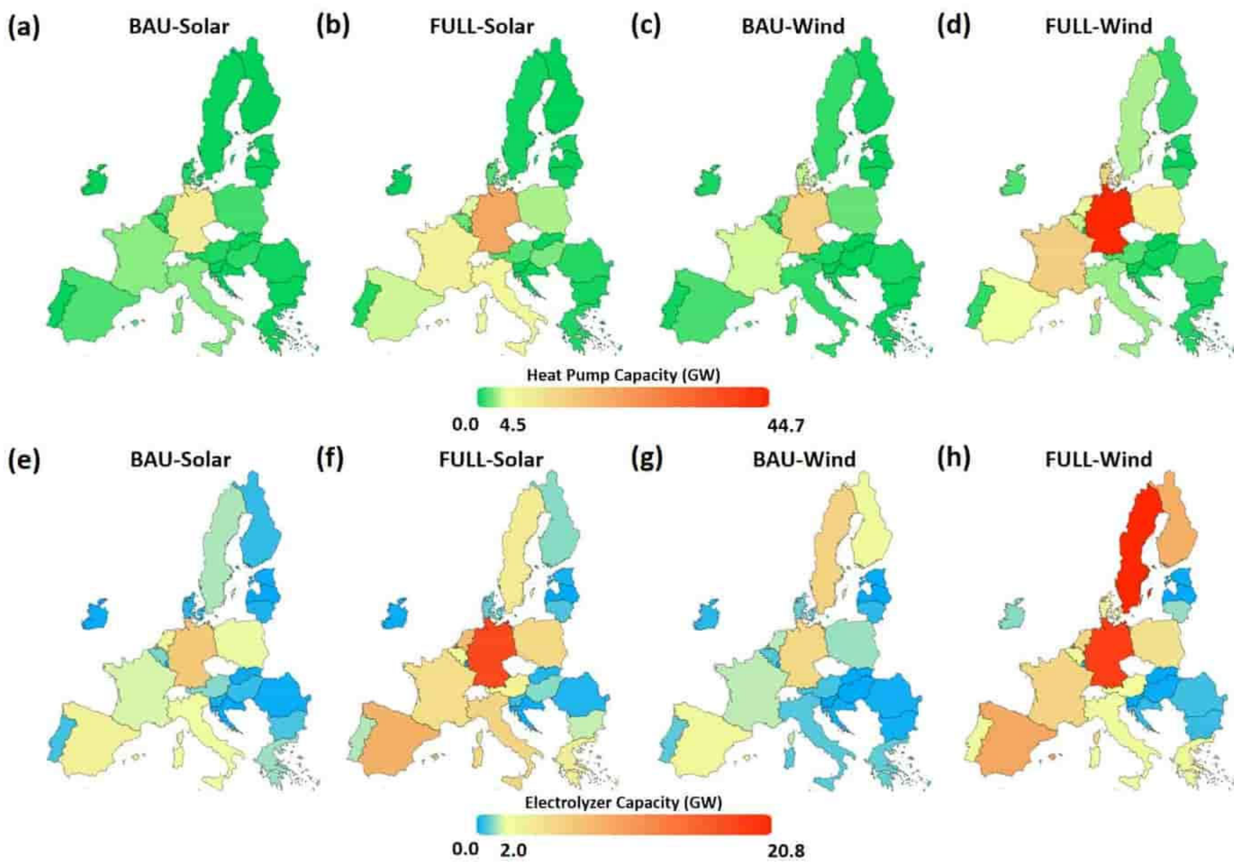
Supplementary Figure 55. Frequency distribution for hourly net-load ramps normalized to the peak load in Latvia. a., BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** PARTIAL implementation scenario in 2040. **f.,** PARTIAL implementation scenario in 2050. **g.,** FULL implementation scenario in 2030. **h.,** FULL implementation scenario in 2040. **i.,** FULL implementation scenario in 2050.

Supplementary Discussion 3: Technological Penetration for EU Energy Landscape

This section highlights the technological infrastructure required across the EU to achieve electrification, hydrogen, and carbon offsetting strategies under various scenarios of renewable energy expansion. **Supplementary Figs. 56-57** focus on the battery storage and interface, heat pumps, and electrolyzer capacities. Notably, Germany and Spain emerge as dominant players, requiring the highest battery storage capacities to meet their electrification potential. Under the FULL-wind scenario, battery storage needs in Germany reach over 144.4 GWh, with a similar high requirement of up to 59.1 GWh in Spain. In contrast, countries like Italy also show significant storage needs under solar power-driven scenarios, with storage capacities exceeding 34.0 GWh, reflecting the critical interplay between regional renewable potential and energy storage requirements. In addition to battery storage capacities, heat pump deployment is pivotal in supporting the electrification strategy across the EU. Under the FULL-solar and FULL-wind scenarios, heat pump capacity in Germany reaches up to 20.8 GW and 44.7 GW, respectively, to reduce natural gas reliance in the heating sector. Electrolyzer infrastructure is equally crucial for green hydrogen supply under the investigated scenarios. In this regard, countries like Sweden also require up to 20.8 GW in the FULL-wind scenario. These results underscore the critical role of scaling sector-specific technological infrastructure to accommodate the increasing role of renewable energy expansion across the EU in various scenarios.

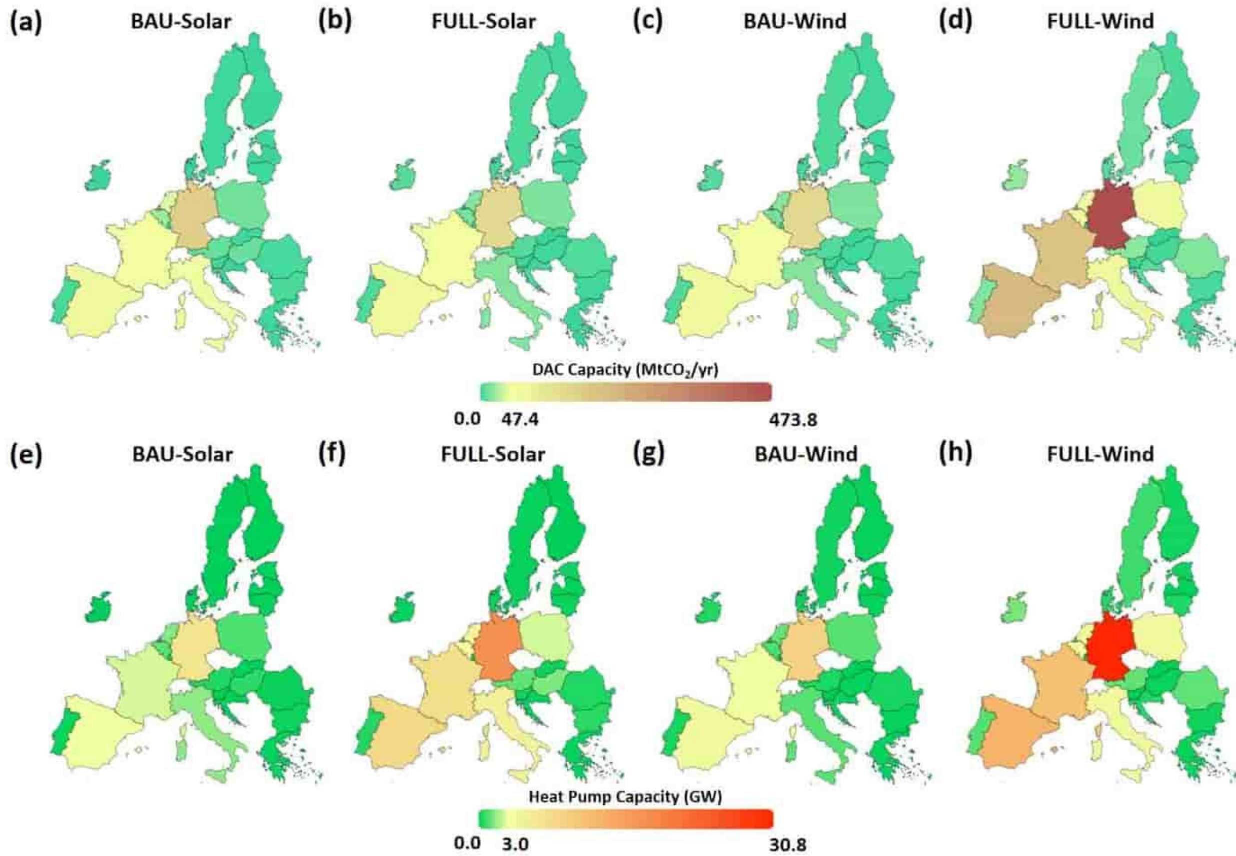


Supplementary Figure 56. Battery storage (GWh) and interface capacity (GW) across EU member countries by 2050 under renewable expansion scenarios. a., Battery storage capacity (GWh) under the BAU-solar scenario. **b.,** Battery storage capacity (GWh) under the FULL-solar scenario. **c.,** Battery storage capacity (GWh) under the BAU-wind scenario. **d.,** Battery storage capacity (GWh) under the FULL-wind scenario. **e.,** Battery interface capacity (GW) under the BAU-solar scenario. **f.,** Battery interface capacity (GW) under the FULL-solar scenario. **g.,** Battery interface capacity (GW) under the BAU-wind scenario. **h.,** Battery interface capacity (GW) under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.



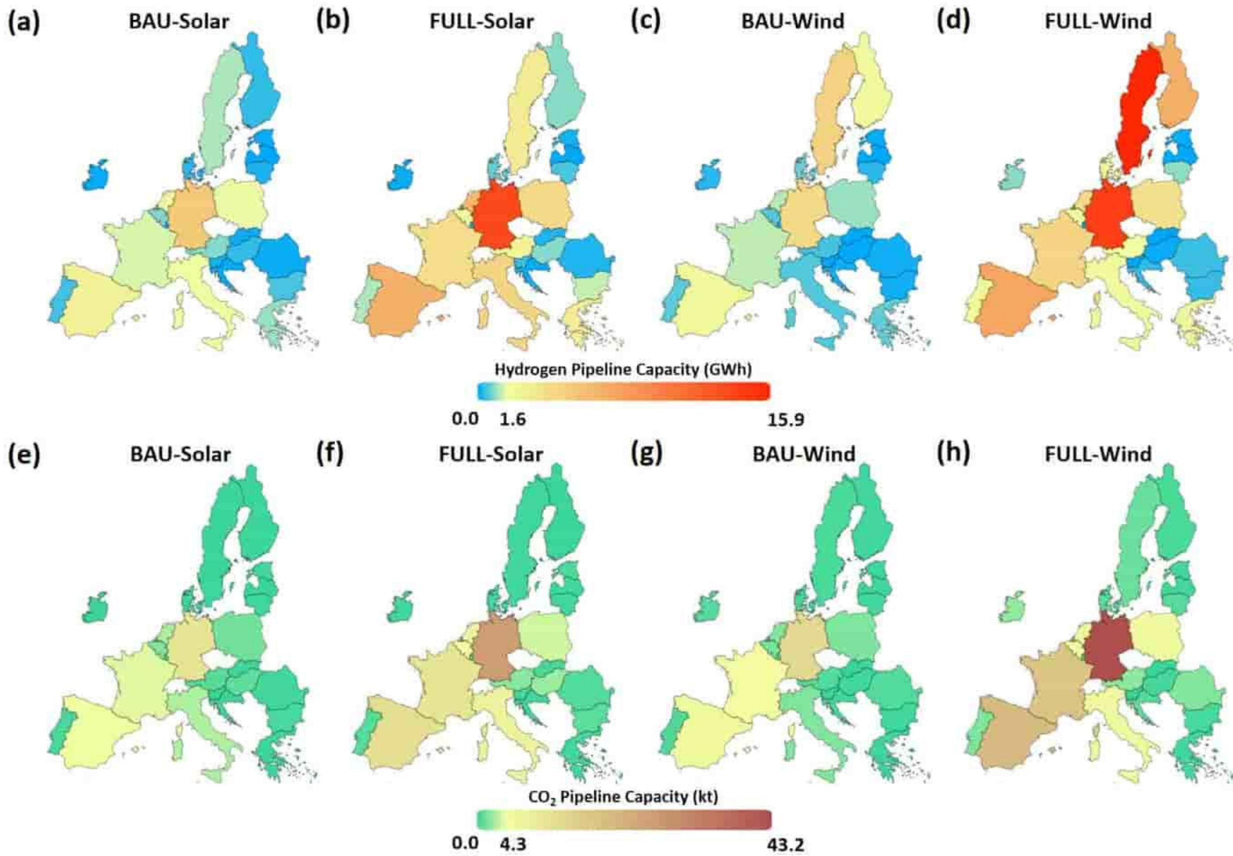
Supplementary Figure 57. Heat pump capacity (GW) to support the electrification strategy and electrolyzer capacity (GW) required for green hydrogen deployment across EU member countries by 2050 under renewable expansion scenarios. a., Heat pump capacity (GW) under the BAU-solar scenario. **b.,** Heat pump capacity (GW) under the FULL-solar scenario. **c.,** Heat pump capacity (GW) under the BAU-wind scenario. **d.,** Heat pump capacity (GW) under the FULL-wind scenario. **e.,** Electrolyzer capacity (GW) under the BAU-solar scenario. **f.,** Electrolyzer capacity (GW) under the FULL-solar scenario. **g.,** Electrolyzer capacity (GW) under the BAU-wind scenario. **h.,** Electrolyzer capacity (GW) under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

Supplementary Fig. 58 addresses the role of Direct Air Capture (DAC) in achieving carbon offsetting potential across the EU. Germany exhibits the highest DAC capacity requirements, with up to 473.8 MtCO_2 yr^{-1} in carbon capture under the FULL-wind scenario. France and Spain also demonstrate substantial DAC capacity needs, with up to 186.9 MtCO_2 yr^{-1} and 212.2 MtCO_2 yr^{-1}, respectively. Under the FULL-solar scenario, Italy also sees a considerable increase in DAC capacity needs (122.4 MtCO_2 yr^{-1}), reflecting the potential for coupling renewable power generation with carbon capture. Moreover, heat pump capacity is essential to support DAC operations, as these systems require substantial heat energy to drive the carbon capture process. Under the FULL-wind scenario, Germany's heat pump requirements reach 30.8 GW, while France and Spain also indicate significant heat pump needs of 11.2 GW and 12.8 GW, respectively, emphasizing the importance of heat supply in the DAC process. The inclusion of heat pumps in this analysis addresses the heat energy requirements, ensuring that the renewable energy expansion strategies for carbon offsetting potential are aligned with the operational requirements of DAC.



Supplementary Figure 58. DAC deployment capacity ($MtCO_2$ yr^{-1}) and heat pump capacity (GW) required to support the carbon offsetting strategy across EU member countries by 2050 under renewable expansion scenarios. a., DAC carbon capture capacity ($MtCO_2$ yr^{-1}) under the BAU-solar scenario. **b.,** DAC carbon capture capacity ($MtCO_2$ yr^{-1}) under the FULL-solar scenario. **c.,** DAC carbon capture capacity ($MtCO_2$ yr^{-1}) under the BAU-wind scenario. **d.,** DAC carbon capture capacity ($MtCO_2$ yr^{-1}) under the FULL-wind scenario. **e.,** Heat pump capacity (GW) under the BAU-solar scenario. **f.,** Heat pump capacity (GW) under the FULL-solar scenario. **g.,** Heat pump capacity (GW) under the BAU-wind scenario. **h.,** Heat pump capacity (GW) under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

The pipeline network capacities, depicted in **Supplementary Fig. 59**, represent the amount of hydrogen or CO_2 that can be transported through the pipeline at any given time under different scenarios across EU countries. In the BAU-solar scenario, Germany exhibits the highest hydrogen pipeline capacity needs, reaching 5.2 GWh, reflecting its extensive industrial base and significant reliance on hydrogen for decarbonization. Similarly, countries like Italy and Poland also demonstrate substantial requirements of 1.7 GWh and 1.5 GWh, respectively, under the same scenario. However, under the FULL-solar scenario, the hydrogen pipeline capacity in Germany rises significantly to 13.7 GWh, with Poland and Italy showing similar growth patterns. The FULL-wind scenario also underscores the dominant role of countries such as Sweden reaching up to 15.9 GWh. For CO_2 transport, Germany and Spain exhibit the highest CO_2 pipeline capacity requirements, with up to 9.7 kt and 4.3 kt, respectively, under the BAU-solar scenario. In contrast, Italy's CO_2 pipeline capacity escalates to 7.3 kt under the FULL-solar scenario, indicating the increased need for CO_2 transport infrastructure as renewable power utilized for carbon offsetting expands. Similarly, Germany, France, and Spain continue to dominate CO_2 pipeline capacity in the wind power implementation scenarios, requiring up to 43.2 kt in the FULL-wind scenario. Furthermore, the results for CO_2 pipeline capacity in countries including Austria, Portugal, Estonia, Luxembourg, Malta, Ireland, Sweden, and Finland, indicate the need for cross-border transport to either the Netherlands or Denmark, based on cost-effectiveness, as detailed in **Supplementary Table 6**. These findings emphasize spatial diversity in the need for both local and cross-border pipeline networks to adequately transport hydrogen and CO_2 under different scenarios.



Supplementary Figure 59. Hydrogen pipeline capacity (GWh) and CO_2 pipeline capacity (kt) across EU member countries by 2050 under renewable expansion scenarios. a., Hydrogen pipeline capacity (GWh) under the BAU-solar scenario. **b.,** Hydrogen pipeline capacity (GWh) under the FULL-solar scenario. **c.,** Hydrogen pipeline capacity (GWh) under the BAU-wind scenario. **d.,** Hydrogen pipeline capacity (GWh) under the FULL-wind scenario. **e.,** CO_2 pipeline capacity (kt) under the BAU-solar scenario. **f.,** CO_2 pipeline capacity (kt) under the FULL-solar scenario. **g.,** CO_2 pipeline capacity (kt) under the BAU-wind scenario. **h.,** CO_2 pipeline capacity (kt) under the FULL-wind scenario. The maps were created using the Flourish Studio visualization tool.

Supplementary Methods

Scenario design

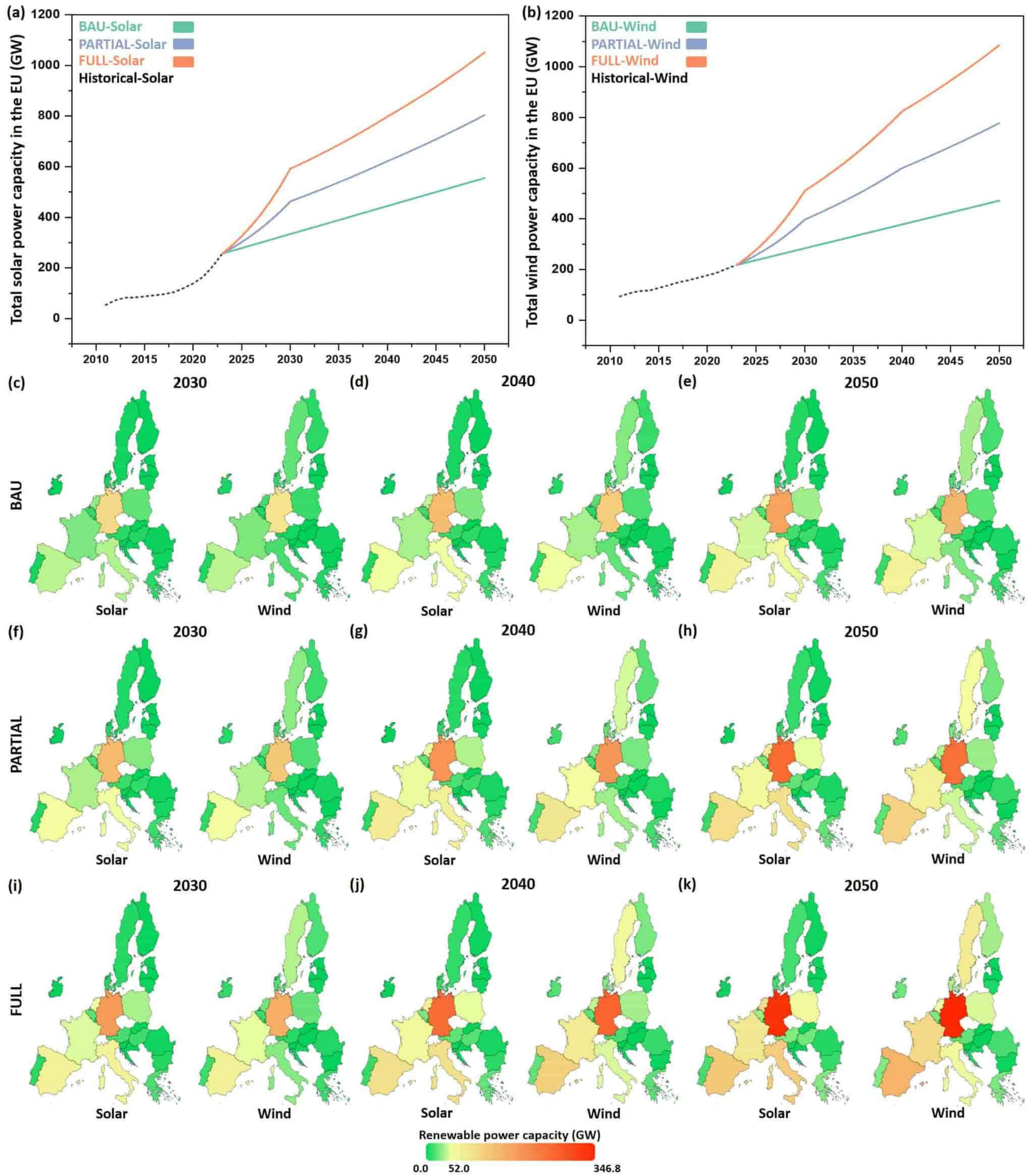
This section outlines the strategic scenarios to assess the impact of policy-driven interventions in renewable capacity expansion and sector-specific strategies for reducing natural gas reliance, thereby enhancing energy security and supporting decarbonization efforts. The design of these scenarios reflects evolving EU policy ambitions and investment strategies in response to recent geopolitical tensions, particularly the progressive shift away from natural gas dependence. In order to reflect geopolitical uncertainties, such as potential disruptions or supply chain bottlenecks that may affect the extent and pace of renewable infrastructure deployment, differentiated ambition levels are embedded across the BAU, PARTIAL, and FULL scenarios. This set of scenarios represent a plausible spectrum of policy responses, ranging from minimal intervention to accelerated deployment. Specifically, the scenarios incorporate near- and long-term policy goals, including the REPowerEU targets for 2030[19, 20], the EU's 2040 emissions reduction milestones[21], and the 2050 net-zero objective[22]. Furthermore, to capture uncertainties in economic and technological developments, each scenario is evaluated under three distinct cost development trajectories for clean energy installations, reflecting a comprehensive spectrum of historical learning rates and anticipated future deployment conditions. **Supplementary Table 2** summarizes the strategic scenarios and cost trajectories considered in this analysis.

Supplementary Table 2. Description of the strategic scenarios and cost trajectories used to evaluate renewable capacity expansion and its role in reducing sector-specific natural gas reliance across the EU.

Scenario	Description
FULL	Reflects an ambitious policy response to geopolitical disruptions, with the EU meeting the REPowerEU 2030 targets of 592 GW in solar power capacity and 510 GW in wind power capacity[19, 20]. Beyond 2030, capacity continues to expand in line with the EU's 2040 goal of a 90% emissions reduction relative to 1990 and its 2050 net-zero objective[21], emphasizing extensive deployment of renewables to structurally reduce natural gas consumption across sectors.
BAU	Represents a business-as-usual trajectory, in which solar and wind capacity expansion continues at historical growth rates derived from capacity expansion data[23], capturing a lower-bound pathway with limited policy intervention resulting in slower progress on renewable deployment and prolonged natural gas dependence.
PARTIAL	Depicts an intermediate response, where geopolitical disruptions moderately accelerate renewable deployment. Capacity expansion follows the average between the FULL and BAU scenarios, enabling comparative

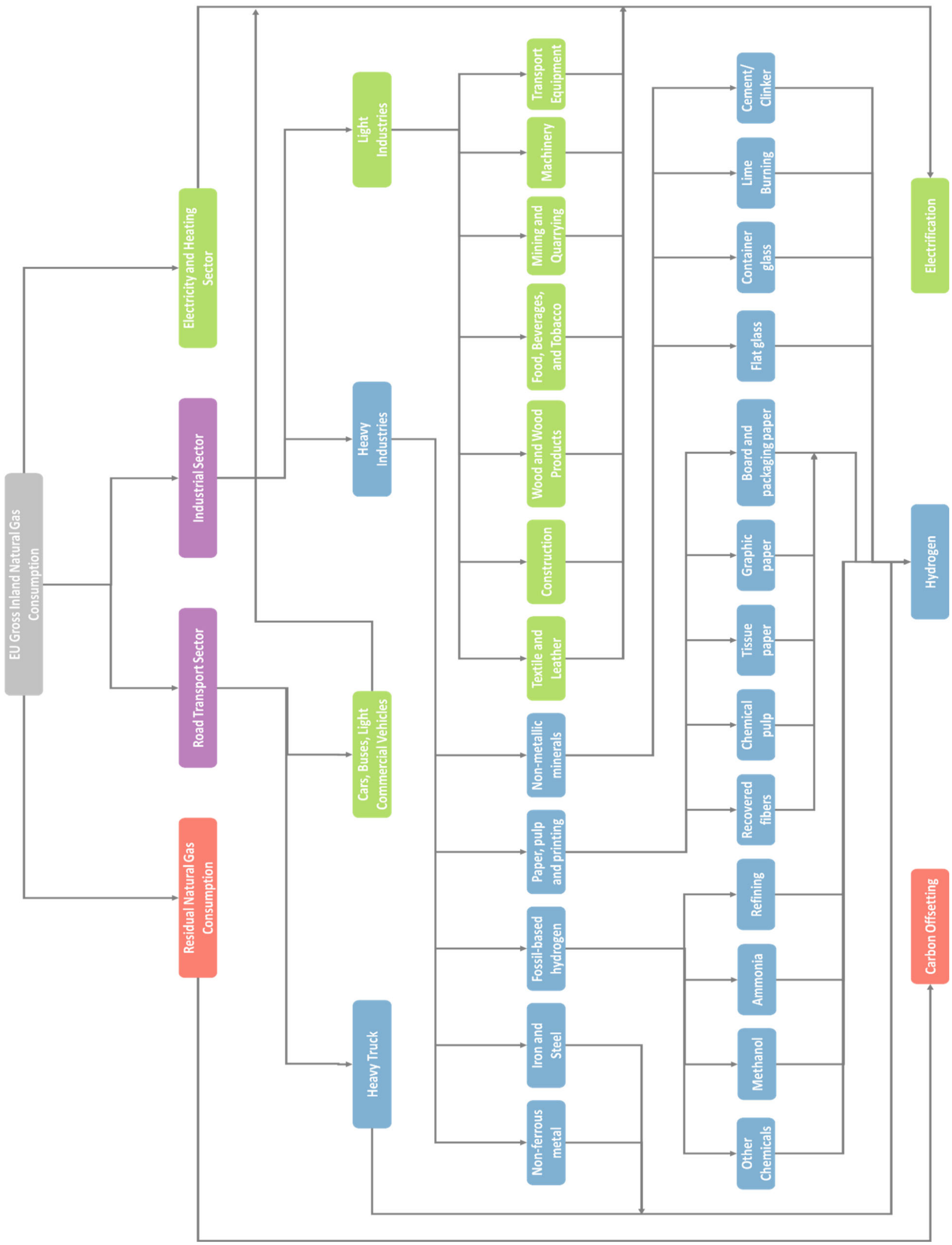
	insights into the trade-offs among policy ambition, energy security, economic feasibility, and emissions mitigation.
Slow Cost Trajectory	Assesses cost implications of renewable energy deployment under a slow improvement scenario, highlighting economic challenges and conservative historical learning rates[24].
Nominal Cost Trajectory	Captures a nominal rate of cost improvements, providing a balanced perspective on technological advancements based on moderate historical learning rates[24].
Fast Cost Trajectory	Reflects rapid improvements in cost-effectiveness for renewable power installations, emphasizing aggressive historical learning rates[24].

Supplementary Figs. 60a and b present the projections for solar and wind power capacity across the EU in different scenarios by 2050. These projections reflect a range of responses to geopolitical tensions, illustrating proactive measures for achieving energy security and long-term climate sustainability. The breakdown of solar and wind capacity projections factoring in the current proportion of renewable capacities across EU countries is illustrated in **Supplementary Figs. 60**c to e to provide a comprehensive view of the energy transition under each scenario. This country-specific analysis helps identify the varying contributions of EU member states to the overall renewable capacity growth.



Supplementary Figure 60. Renewable capacity growth in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability. a., Solar power capacity projections in the EU under different scenarios (GW). **b.,** Wind power capacity projections in the EU under different scenarios (GW). **c.,** Solar and wind power capacity in different EU countries under the BAU implementation scenario in 2030. **d.,** Solar and wind power capacity in different EU countries under the BAU implementation scenario in 2040. **e.,** Solar and wind power capacity in different EU countries under the BAU implementation scenario in 2050. **f.,** Solar and wind power capacity in different EU countries under the PARTIAL implementation scenario in 2030. **g.,** Solar and wind power capacity in different EU countries under the PARTIAL implementation scenario in 2040. **h.,** Solar and wind power capacity in different EU countries under the PARTIAL implementation scenario in 2050. **i.,** Solar and wind power capacity in different EU countries under the FULL implementation scenario in 2030. **j.,** Solar and wind power capacity in different EU countries under the FULL implementation scenario in 2040. **k.,** Solar and wind power capacity in different EU countries under the FULL implementation scenario in 2050. The maps were created using the Flourish Studio visualization tool.

The sector-specific breakdown of gross inland natural gas consumption provides the analytical foundation for aligning renewable capacity expansion with targeted decarbonization strategies across the EU. **Supplementary Fig. 61** illustrates how key sectors, including electricity and heating, industry, road transportation, and residual use, are mapped to strategic interventions such as electrification, green hydrogen deployment, and carbon offsetting. This categorization, based on country-specific gross inland consumption data (including both imports and domestic production), enables the differentiated utilization of renewable energy where natural gas demand can be directly reduced and the application of offsetting measures. By bridging scenario design with sectoral demand structures, this framework supports targeted assessment of energy security and decarbonization planning amidst geopolitical disruptions.



Supplementary Figure 61. Schematic representation of sector-specific natural gas consumption across the EU, serving as the analytical basis for linking renewable capacity

deployment with tailored decarbonization strategies. The sectors are color-coded according to their corresponding intervention pathways: green for electrification, blue for hydrogen production, orange for carbon offsetting, purple for sectors applicable to both electrification and hydrogen, and grey indicating total gross inland natural gas consumption. This mapping supports the scenario-based evaluation of sectoral strategies for enhancing energy security and climate mitigation.

The reference energy system modeled in this work reflects a multi-sectoral configuration that strategically aligns expanding renewable energy capacity with targeted interventions to reduce natural gas dependence. Within the electricity and heating sector, solar and wind power installations are leveraged to enable direct electrification. To capture spatial and temporal variability in renewable generation across the EU, the framework adopts an hourly resolution timescale using solar irradiance and wind power data normalized to a [0,1] scale for country-specific output patterns[25]. Integrated battery storage capacities are included in line with the IEA's specification, pairing renewable installations with four-hour storage scaled to 20% of output capacity[26]. Additionally, the frequency distribution of net load ramp rates, normalized to peak load, as utilized in previous studies[27, 28, 29], are used to assess the grid integration challenges associated with renewable variability at different time horizons (2030, 2040, and 2050) in the investigated scenarios. In this regard, the future electricity demands for EU countries were obtained from previous literature[30], and combined with the hourly load profiles from the European Network of Transmission System Operators for Electricity[31], to illustrate demand patterns across the EU.

In the industrial sector, the reference energy system distinguishes between light industries, targeted for electrification, and heavy industries, better suited for green hydrogen deployment due to their hard-to-abate emissions. This categorization, based on IEA classifications[32, 33], supports sector-specific modeling of renewable capacity utilization aligned with technological feasibility and energy service requirements. Dedicated projects are considered for green hydrogen production, with electrolyzer infrastructure between 5-10 MW, consistent with project-level benchmarks reported by the European Hydrogen Observatory[34]. To demonstrate the feasibility of hydrogen use in these sectors, **Supplementary Table 3** presents a comparison of specific energy consumption (SEC) for conventional natural gas-based processes and the green hydrogen alternatives incorporated in this analysis across various industrial applications[35]. Technology

Readiness Levels (TRL) for hydrogen-based technologies are also included to indicate their technological viability as a decarbonization option in the modeled industrial sectors.

Supplementary Table 3. Comparison of SEC for natural gas-based technologies and green hydrogen-based alternatives in heavy industrial sectors, along with the TRL for the hydrogen-based technologies.

Industrial Sector	SEC for H_2 vs Natural gas (MWh/t)	References	TRL for Hydrogen Technology	References
Iron and Steel	1.89/3.2	36/37, 38	8	36
Non-ferrous metals	1.9/2.1	35/37	4-5	35
Cement/Clinker	0.97/0.97	35/37	4-5	35
Lime burning	1.03/1.03	35/37	3-5	35
Container glass	1.28/1.61	35/37	4-5	35
Flat glass	2.17/3.03	35/37	4-5	35
Board and packaging paper	1.36/1.36	35/35	8-9	35
Graphic paper	2.0/2.0	35/35	8-9	35
Tissue paper	1.92/1.92	35/35	8-9	35
Recovered fibers	0.15/0.139	35/35	8-9	35
Chemical pulp	2.86/3.42	35/35	8-9	35
Refining	*	-	7-9	35
Ammonia	*	-	9	35/37
Methanol	*	-	9	35/37
Other Chemicals	*	-	9	35/37

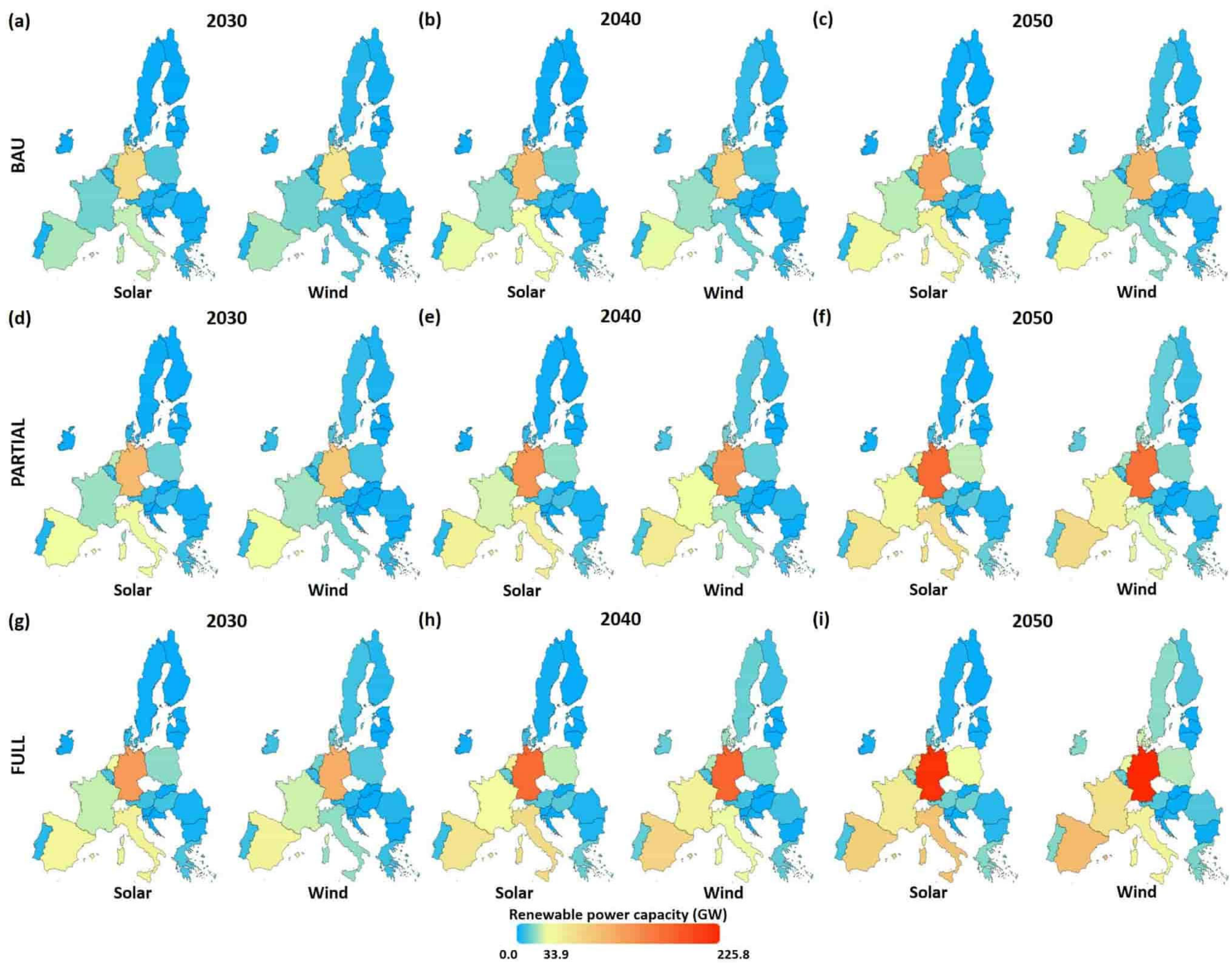
*The comparison between SEC for natural gas and hydrogen-based technologies is not illustrated for refining, ammonia, methanol, and other chemical sectors, as natural gas in these sectors is primarily used to meet hydrogen production demands.

The transportation sector encompasses several modes, including aviation, marine, rail, and road transportation. However, aviation primarily relies on jet fuel[39, 40, 41], and marine transportation predominantly utilizes heavy fuel oil and marine diesel oil[42, 43], making natural gas reliance negligible in these modes. Similarly, rail transportation is mainly powered by diesel, with minimal natural gas use[44]. Therefore, these sectors are not directly relevant to the study's focus on reducing natural gas dependence. According to estimates by the European Commission, the transportation sector needs a 32% share of renewable energy to achieve the REPowerEU goals[45]. As per the IEA, while biofuels currently make up the largest portion of the renewable energy share in transport, the rapid expansion of electric vehicle (EV) sales and renewable energy capacity is expected to play an increasingly dominant role, particularly in road transportation sector[20]. Consequently, given the focus of this study on mitigating natural gas dependence amidst recent geopolitical disruptions, the scope within the transportation sectors is narrowed to road transport, where natural gas plays a more dominant role. In this regard, the analysis differentiates between electrification and hydrogen use, with passenger cars, light commercial vehicles, buses, and coaches slated for electrification with the growing adoption of EVs and renewable electricity integration, whereas heavy trucks are designated for hydrogen[12]. This segment-level distinction within the road transportation sector enables a targeted assessment of electrification and hydrogen pathways and their contribution to natural gas reduction across scenarios for renewable capacity buildout.

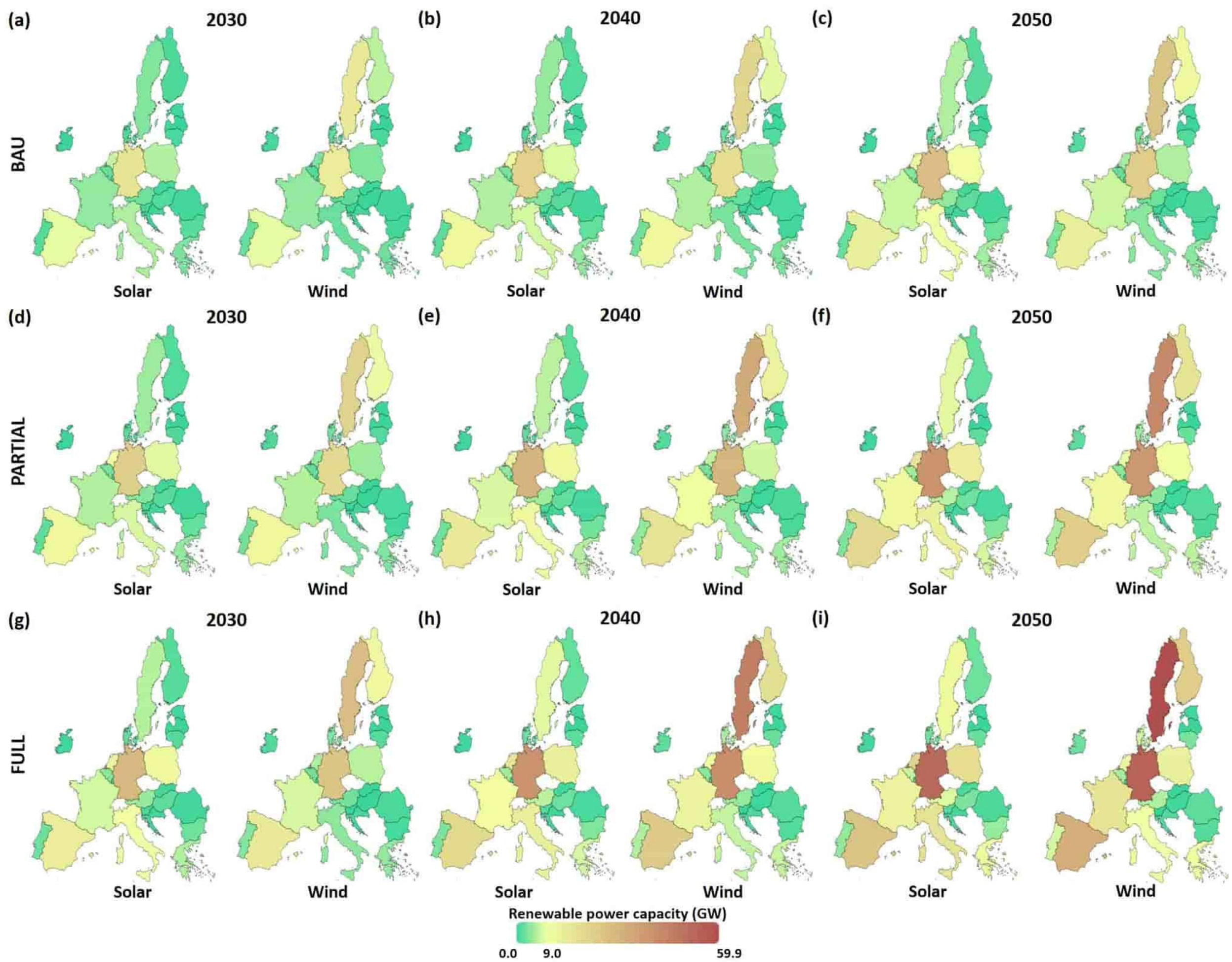
The categorization in **Supplementary Fig. 61** reflects the strategic deployment of renewable capacity expansion to align energy security with climate change mitigation, using sector-specific natural gas consumption as the central metric. In this regard, the use of electrification pathways in light industries is informed by IEA assessments, which identify low-temperature heat processes as having the highest electrification potential in the industrial sector[46] and list light industrial applications as representative of such thermal demand profiles[32]. While this classification scheme supports the scenario-based analysis of renewable-driven decarbonization strategies, it does not encompass the full diversity of emerging technological pathways or broader structural shifts in the industrial landscape. Specifically, advancements in high-temperature processes in heavy industries, such as electrowinning in the iron and steel sector[47], plasma technologies in cement production[48], electric furnaces for all qualities of glass[49], etc., may expand the future scope of electrification as technological readiness improves. These developments may lead to reconfiguration of production chains, market-driven shifts in output, or greater operational flexibility, thereby reshaping the natural gas and hydrogen demand profiles over time. Accordingly, this schematic is not intended as an exhaustive mapping of all future industrial transformations, but rather as a targeted representation to support the scenario-based evaluation of renewable-driven strategies aimed at mitigating the impact of sector-specific natural gas consumption.

Based on the sector-specific natural gas reliance across EU member states, this work considers the strategic deployment of solar and wind power expansion for electrification, hydrogen production, and carbon offsetting. As a result, the electricity and heat supplied through electrification, the hydrogen produced, and the carbon captured through DAC vary according to the sectoral natural gas demand in different countries. In this regard, **Supplementary Figs. 62**a to d illustrate these variations, with detailed bifurcations, providing a foundation for renewable power deployment strategies that effectively reduce natural gas dependence across the EU. Specifically, **Supplementary Fig. 62**a presents the breakdown of natural gas consumption across sectors such as electricity and heating, light industries, heavy industries, road transportation, and residual consumption. This sectoral analysis supports a targeted strategy for renewable capacity deployment, addressing country-specific patterns in natural gas use to align with energy security and decarbonization goals. **Supplementary Fig. 62**b shows the breakdown within the light industrial sectors, including transportation equipment, machinery, mining and quarrying, food, beverages and tobacco, wood and wood products, construction, textile and leather. This distribution informs the key areas within light industries that are suitable for electrification. **Supplementary Fig. 62**c illustrates the heavy industrial sector, which is better suited for hydrogen-based decarbonization strategies due to the higher energy demands and hard-to-abate emissions. Five key subsectors are covered, constituting iron and steel, non-ferrous metals, non-metallic minerals, paper, pulp and printing, and natural gas-based hydrogen consumption sectors. Within non-metallic minerals, four subcategories are considered: cement/clinker, lime burning, container glass, and flat glass. For paper, pulp, and printing, five subcategories are highlighted: board and packaging paper, graphic paper, tissue paper, chemical pulp, and recovered fibers. Lastly, the natural gas-based hydrogen consumption sectors include four subcategories: refining, ammonia, methanol, and other chemicals. By detailing the natural gas consumption patterns in these subsectors, this work considers the utilization of green hydrogen-based technologies where technically feasible. Lastly, **Supplementary Fig. 62**d illustrates the ratio between renewable capacity utilization toward electrification, hydrogen production, and carbon offsetting across the scenarios based on sector-specific natural gas dependence, as presented earlier. **Supplementary Figs. 63-65** show the varying levels of renewable power capacity utilized for electrification, hydrogen production, and carbon offsetting in the investigated scenarios over different time horizons (2030, 2040, and 2050) across EU member states, reflecting the progressive shift in natural gas reliance reduction and long-term decarbonization goals.

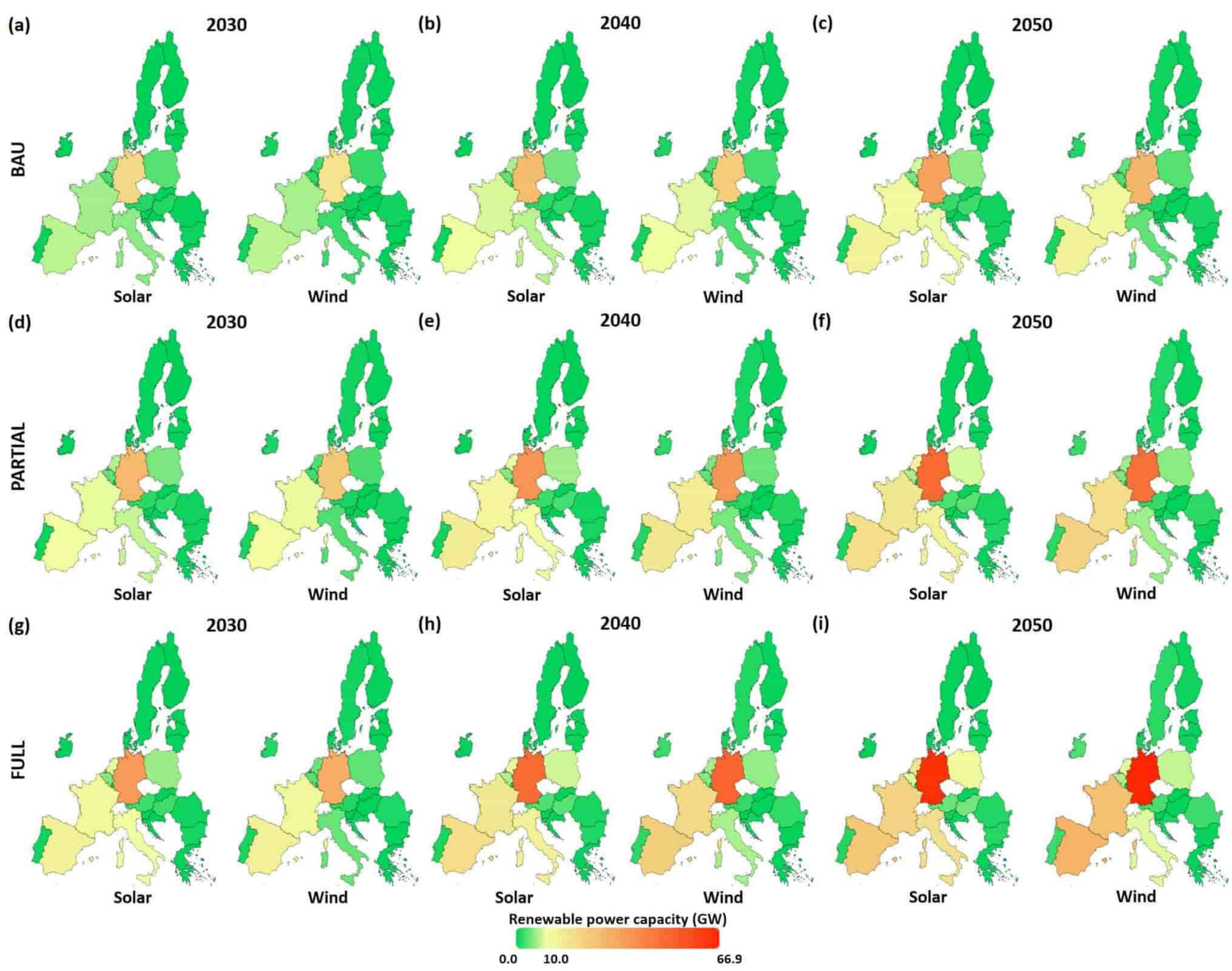
Supplementary Figure 62. Breakdown of natural gas reliance across different sectors and corresponding renewable capacity deployment strategies across EU member states in the investigated scenarios. a., Distribution of natural gas consumption across key sectors, including electricity and heating, light industries, heavy industries, road transportation, and residual natural gas consumption. **b.,** Distribution of natural gas reliance within the light industrial sector, highlighting the subcategories of transportation equipment, machinery, mining and quarrying, food, beverages, and tobacco, wood and wood products, construction, textiles and leather, primarily targeted for electrification. **c.,** Distribution of natural gas reliance within heavy industrial sectors, including iron and steel, non-ferrous metals, non-metallic minerals (with sub-categories of cement/clinker, lime burning, flat glass, container glass), paper, pulp and printing (with sub-categories of board and packaging paper, graphic paper, tissue paper, chemical pulp, and recovered fibers) and natural gas-based hydrogen consumption sectors (with sub-categories of refining, ammonia, methanol, and other chemicals) indicating sectors suited for hydrogen-based decarbonization strategies. **d.,** Distribution of renewable capacity utilization toward electrification, hydrogen production, and carbon offsetting, based on sector-specific natural gas reliance, illustrating the varying levels of solar and wind power deployment across the scenarios. Acronyms for the EU member states follow the glossary by the European Commission: Germany (DE); Italy (IT); France (FR); Netherlands (NL); Spain (ES); Poland (PL); Belgium (BE); Greece (EL); Austria (AT); Hungary (HU); Czechia (CZ); Portugal (PT); Sweden (SE); Denmark (DK); Romania (RO); Bulgaria (BG); Slovakia (SK); Estonia (EE); Finland (FI); Slovenia (SI); Luxembourg (LU); Lithuania (LT); Malta (MT); Ireland (IE); Croatia (HR); Latvia (LV).



Supplementary Figure 63. Renewable capacity expansion contributing to electrification potential in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability. a., Solar and wind power capacity utilized for electrification potential in different EU countries under the BAU implementation scenario in 2030. **b.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the BAU implementation scenario in 2040. **c.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the BAU implementation scenario in 2050. **d.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the PARTIAL implementation scenario in 2030. **e.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the PARTIAL implementation scenario in 2040. **f.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the PARTIAL implementation scenario in 2050. **g.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the FULL implementation scenario in 2030. **h.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the FULL implementation scenario in 2040. **i.,** Solar and wind power capacity utilized for electrification potential in different EU countries under the FULL implementation scenario in 2050. The maps were created using the Flourish Studio visualization tool.



Supplementary Figure 64. Renewable capacity expansion contributing to green hydrogen deployment in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability. a., Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the BAU implementation scenario in 2030. **b.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the BAU implementation scenario in 2040. **c.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the BAU implementation scenario in 2050. **d.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the PARTIAL implementation scenario in 2030. **e.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the PARTIAL implementation scenario in 2040. **f.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the PARTIAL implementation scenario in 2050. **g.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the FULL implementation scenario in 2030. **h.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the FULL implementation scenario in 2040. **i.,** Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the FULL implementation scenario in 2050. The maps were created using the Flourish Studio visualization tool.



Supplementary Figure 65. Renewable capacity expansion contributing to carbon offsetting potential through DAC systems in the EU, amidst geopolitical disruptions to enhance

climate sustainability. a., Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the BAU implementation scenario in 2030. **b.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the BAU implementation scenario in 2040. **c.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the BAU implementation scenario in 2050. **d.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the PARTIAL implementation scenario in 2030. **e.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the PARTIAL implementation scenario in 2040. **f.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the PARTIAL implementation scenario in 2050. **g.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the FULL implementation scenario in 2030. **h.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the FULL implementation scenario in 2040. **i.,** Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under the FULL implementation scenario in 2050. The maps were created using the Flourish Studio visualization tool.

To address the infrastructure requirements for hydrogen transport across the investigated scenarios, this work incorporates repurposed natural gas pipelines into the proposed modeling framework. The transition from natural gas to specific hydrogen needs is facilitated by repurposed pipeline expansion, aligning with the reduction of natural gas reliance across various EU countries as identified in the scenario design. In this regard, **Supplementary Table 4** summarizes the estimated pipeline lengths for repurposed hydrogen transport infrastructure in EU countries based on data from the Europe Gas Tracker[50] and the European Hydrogen Backbone[51]. In addition, the future trajectory for increasing cost-competitiveness of these repurposed hydrogen networks is considered based on cost projections from previous literature[12].

Supplementary Table 4. Estimated pipeline lengths (km) for repurposed hydrogen transport infrastructure across the EU.

Country	Pipeline Length (km)
Germany	3906
Italy	148

France	865
Netherlands	109
Spain	79
Poland	20
Belgium	22
Greece	12
Austria	87
Hungary	675
Czechia	152
Portugal	797
Sweden	496
Denmark	222
Romania	599
Bulgaria	116
Slovakia	46
Estonia	6
Finland	835
Slovenia	297
Luxembourg	6
Lithuania	138
Malta	0*
Ireland	12
Croatia	2500
Latvia	6

*In the case of Malta, the pipeline infrastructure length is considered zero due to no reliance on hydrogen across the investigated scenarios based on sector-specific natural gas consumption, as depicted in Fig. S57d.

In addition to the hydrogen transport network, the proposed framework integrates CO_2 transport and storage infrastructure to support the decarbonization efforts via carbon offsetting. The evaluation begins by assessing the local CO_2 storage capacities in EU countries[52], as outlined in **Supplementary Table 5**. This strategy ensures that domestic storage infrastructure primarily supports each country's carbon offsetting potential under the investigated scenarios. However, in cases where the local CO_2 storage capacity is insufficient or not available to meet the needs of the modeled scenarios, cross-border CO_2 transport is considered. For cross-border CO_2 transport, the framework follows an established approach from prior literature[53], which identifies Denmark and the Netherlands as pre-selected locations within the EU. To ensure cost-effectiveness, the selection between Denmark and the Netherlands is based on the shortest distance between geographical centers from the EU country. CO_2 transport and storage costs are derived from previous literature[54], which assumes a pipeline transportation length of 100 miles for cost estimation purposes. This strategy aligns with the IEA's emphasis on the flexibility of DAC infrastructure[55], which can be located near suitable storage sites for carbon removal. Additionally, the pipeline infrastructure length serves as a standard reference point to represent the proximity of storage sites, enabling a comparative analysis of the economic implications for carbon offsetting across different EU countries. In the case of cross-border CO_2 transport, the pipeline length is adjusted according to the specific transportation distances required between countries.

Supplementary Table 5. Local CO_2 storage capacities for EU member states and cross-border transport destinations where required.

Country	CO_2 Storage Capacity (Mt)	Cross-Border Transport Destination (if required)
Germany	17080	-
Italy	6550	-
France	8692	-
Netherlands	2340	-
Spain	14179	-
Poland	2940	-
Belgium	199**	Netherlands
Greece	254	-
Austria	*	Netherlands
Hungary	616	-
Czechia	853	-
Portugal	*	Netherlands
Sweden	*	-
Denmark	2756	-
Romania	9000	-
Bulgaria	2120	-
Slovakia	1716	-
Estonia	*	Denmark
Finland	*	-
Slovenia	94	-
Luxembourg	*	Netherlands
Lithuania	57	-
Malta	*	Netherlands
Ireland	*	Netherlands
Croatia	2899	-
Latvia	404	-

*Countries considered for cross-border CO_2 transport to either Netherlands or Denmark due to no clear indication of the extent of local CO_2 storage capacity.

**Belgium was considered for cross-border CO_2 transport and storage when insufficient local storage capacity was observed across the investigated scenarios.

Optimization modeling framework

In this section, we present the optimization modeling framework for assessing the economic feasibility of the proposed scenarios. This framework maximizes the net present value, targeting the optimal utilization of renewable power capacities across different scenarios. The optimization framework is crucial for aligning the economic viability of investigated scenarios with the EU's strategic goal of enhancing energy security and climate mitigation, emphasizing the efficient use of renewable energy expansion. The constraints in the model are defined across several sets, each representing a distinct aspect of the analysis. Set *S*, with the lower-case symbol $s \in [1, 3]$, accounts for the different strategies, including electrification, green hydrogen production, and carbon offsetting. Set *J*, with the lower-case symbol $j \in [1, 3]$, encapsulates trajectories at varying paces (Slow, Nominal, Fast) in the increasing cost-competitiveness of renewable installations, highlighting the dynamic nature of technological advancement. Set *T*, with the lower-case symbol $t \in [1, 8760]$, corresponds to an hourly resolution timescale for fluctuations in wind and solar power generation. Set *N*, with the lower-case symbol $n \in [1, 27]$, spans the progression from 2024 to 2050, reflecting the long-term objective of energy security and climate benefits. Lastly, set *I*, with the lower-case symbol $i \in [1, 26]$, accounts for the geographical variability in EU countries, capturing regional differences in energy needs and resources. Cyprus is not considered here as part of the analysis due to no gross inland consumption of natural gas. The general systems optimization framework used in the study for different strategies and respective constraints is presented below.

max $NPV_{s,j,n,i}$

s.t. Load balance constraints in **Supplementary Equations (1)-(12)**

Operational constraints in **Supplementary Equations (13)-(83)**

Techno-economic evaluation constraints in **Supplementary Equations (84)-(130)**

where $NPV_{s,j,n,i}$ refers to the net present value for the different scenarios incorporating the strategies of electrification, green hydrogen production, and carbon offsetting.

Load balance constraints

In the load balance constraints, we account for the expansion in renewable power capacities based on the regional data for wind power generation potential and solar irradiation intensity[25]. The power generated by wind turbines depends on the rated wind power capacity (Pr) and normalized wind power generation potential across the EU countries ($v_{s,j,n,i,t}$).

$$Pwp_{s,j,n,i,t} = Pr \cdot v_{s,j,n,i,t}, \qquad \forall s \in S,\ j \in J,\ n \in N,\ i \in I,\ t \in T \tag{1}$$

where $Pwp_{s,j,n,i,t}$ is the wind power output. On the other hand, for a solar photovoltaic (PV) system, the total power available at a given time is a function of incident radiation, the efficiency of the solar panel, and the surface area of the collector panels. It can be represented as a linear function as shown below:

$$Psp_{s,j,n,i,t} = \mu^{PV} \cdot r_{s,j,n,i,t} \cdot S^{PV}, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I,\ t \in T \tag{2}$$

where $Psp_{s,j,n,i,t}$ is the output PV power, μ^{PV} is the solar panel efficiency, $r_{s,j,n,i,t}$ is the incident solar irradiation, and S^{PV} is the panel surface area. Utilizing the calculated wind or solar power values, we get $Pa_{s,j,n,i,t}$, which is the total available power that must be distributed among the utilized and surplus power components at different time intervals, as demonstrated in Supplementary Equation (3).

$$Pa_{s,j,n,i,t} = Pu_{s,j,n,i,t} + Psl_{s,j,n,i,t}, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I,\ t \in T \tag{3}$$

where $Pu_{s,j,n,i,t}$ and $Psl_{s,j,n,i,t}$ represent the utilized and surplus power at different time intervals. In the case of the electrification strategy, the utilized power component ($Pu_{1,j,n,i,t}$) is used to meet the electricity and heating demands in different EU countries, as depicted in Supplementary Equation (4). The utilized power component in the green hydrogen strategy ($Pu_{2,j,n,i,t}$) is used to operate the electrolyzer infrastructure whereas in the carbon offsetting strategy ($Pu_{3,j,n,i,t}$), it is used to meet the electricity and thermal energy demands of the DAC infrastructure. The heating requirements for the DAC infrastructure are met using the operation of heat pumps, as depicted in Supplementary Equation (5), following the approach highlighted in previous literature[56, 57, 58, 59].

$$Pu_{1,j,n,i,t} = Pelec_{j,n,i,t} + Phpe_{j,n,i,t}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{4}$$

$$Pu_{3,j,n,i,t} = Pec_{j,n,i,t} + Phpc_{j,n,i,t}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{5}$$

where $Pelec_{j,n,i,t}$ and $Phpe_{j,n,i,t}$ refer to the components used for electricity and heat generation in the electrification strategy; $Pec_{j,n,i,t}$ and $Phpc_{j,n,i,t}$ refer to the respective components in the carbon offsetting strategy. Supplementary Equations (6)-(7) estimate the total electricity and heat that can be supplied in the electrification strategy with the subsequent distribution shown in Supplementary

Equations (8)-(9). The total electricity generated is distributed between the road transportation sector ($Pelec^{rt}_{j,n,i}$), for the operation of passenger cars, light commercial vehicles, buses, and coaches, and the broader electricity sector ($Pelec^{E\&H}_{j,n,i}$). Meanwhile, the total heat generated is utilized between the heating sector ($Pheat^{E\&H}_{j,n,i}$) and various light industries ($Pheat^{li}_{j,n,i}$). Within the light industrial sector, the distribution is considered between transportation equipment ($Pheat^{te}_{j,n,i}$), machinery ($Pheat^{mc}_{j,n,i}$), mining and quarrying ($Pheat^{mq}_{j,n,i}$), food, beverages, and tobacco ($Pheat^{fbt}_{j,n,i}$), wood and wood products ($Pheat^{wp}_{j,n,i}$), construction ($Pheat^{ct}_{j,n,i}$), and textile and leather ($Pheat^{tl}_{j,n,i}$), as shown in Supplementary Equation (10). Correspondingly, Supplementary Equation (11) shows the split between the total electricity and heat generated in the electrification strategy, based on the parameter ef_i for different EU countries as depicted in Supplementary Table 5. These distributions, including the parameter ef_i, are determined based on the sector-specific natural gas reliance across the electricity and heating sectors, light industries, and the road transportation sector in different EU countries, as shown in Fig S57, while accounting for the relative efficiencies of natural gas-based systems in power generation, heating, and vehicles, compared to their electrified counterparts[60, 61]. Similarly, Supplementary Equation (12) indicates the distribution of electricity ($Pec_{j,n,i,t}$) and heating requirements ($Phtc_{j,n,i,t}$) for the DAC infrastructure in the carbon offsetting strategy based on the estimations by the IEA[62].

$$Pelec^{total}_{j,n,i} = \sum_{t\in T} Pelec_{j,n,i,t}, \qquad \forall j\in J,\ n\in N,\ i\in I \tag{6}$$

$$Pheat^{total}_{j,n,i} = \sum_{t\in T} Phte_{j,n,i,t}, \qquad \forall j\in J,\ n\in N,\ i\in I \tag{7}$$

$$Pelec^{total}_{j,n,i} = Pelec^{E\&H}_{j,n,i} + Pelec^{rt}_{j,n,i}, \qquad \forall j\in J,\ n\in N,\ i\in I \tag{8}$$

$$Pheat^{total}_{j,n,i} = Pheat^{E\&H}_{j,n,i} + Pheat^{li}_{j,n,i}, \qquad \forall j\in J,\ n\in N,\ i\in I \tag{9}$$

$$\begin{aligned} Pheat^{li}_{j,n,i} = {} & Pheat^{te}_{j,n,i} + Pheat^{mc}_{j,n,i} + Pheat^{mq}_{j,n,i} + Pheat^{fbt}_{j,n,i}, \qquad \forall j\in J,\ n\in N,\ i\in I \\ & + Pheat^{wp}_{j,n,i} + Pheat^{ct}_{j,n,i} + Pheat^{tl}_{j,n,i} \end{aligned} \tag{10}$$

$$Pheat^{total}_{j,n,i} = ef_i \cdot Pelec^{total}_{j,n,i}, \qquad \forall j\in J,\ n\in N,\ i\in I \tag{11}$$

$$Phtc_{j,n,i,t} = dfr \cdot Pec_{j,n,i,t}, \qquad \forall j\in J,\ n\in N,\ i\in I,\ t\in T \tag{12}$$

Operational constraints

The systems optimization framework in this study is subject to operational constraints that govern equipment performance, the total reduction in natural gas consumption in different strategies, and the corresponding avoided emissions. For instance, based on the power that has been utilized in the heat pumps in the electrification and carbon offsetting strategies, the total heat energy supplied ($Phte_{j,n,i,t}$, $Phtc_{j,n,i,t}$) can be estimated using the coefficient of performance (COP) for heat pumps, as described in Supplementary Equations (13)-(14). While evaluating the electrification potential, we consider the assessment of battery storage capacities ($bcp_{j,n,i}$) and interface capacities ($icp_{j,n,i}$) based on the definition of integrated storage capacities by IEA, which pairs the renewable installation with four-hour battery storage, scaled to 20% of the output capacity[26]. Supplementary Equations (15)-(16) indicate the calculation of these storage capacities, where $P^{out}_{j,n,i}$ represents the output capacity corresponding to the maximum values of solar irradiation ($r^{out}_{j,n,i}$) or wind power generation potential ($v^{out}_{j,n,i}$) across EU countries. Similarly, in the case of green hydrogen and carbon offsetting strategies, these constraints include determining hydrogen production from the electrolyzers ($hyd_{j,n,i,t}$) and CO_2 capture quantities ($cc_{j,n,i,t}$) from DAC units, calculated based on equipment efficiencies, as shown in Supplementary Equations (17)-(18), where η^{ELE} and LHV denote the electrolyzer's efficiency and the lower heating value for hydrogen, df refers to the specific electricity requirement for the DAC units. Supplementary Equation (19)-(20) are used to calculate the pipeline capacities based on the maximum amounts of hydrogen produced and CO_2 captured in any time interval.

$$Phte_{j,n,i,t} = Phpe_{j,n,i,t} \cdot COP, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{13}$$

$$Phtc_{j,n,i,t} = Phpc_{j,n,i,t} \cdot COP, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{14}$$

$$bcp_{j,n,i} = 0.2 \cdot P^{max}_{j,n,i} \cdot 4, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{15}$$

$$icp_{j,n,i} = P^{max}_{j,n,i} \cdot 0.2, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{16}$$

$$hyd_{j,n,i,t} = \frac{Pu_{2,j,n,i,t} \cdot \eta^{ELE}}{LHV}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{17}$$

$$cc_{j,n,i,t} = Pec_{j,n,i,t} \cdot df, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{18}$$

$$pip^{hyd}_{j,n,i} \geq hyd_{j,n,i,t} \cdot LHV, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{19}$$

$$pip^{cc}_{j,n,i} \geq cc_{j,n,i,t}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{20}$$

Additionally, these constraints consider the power utilization in different equipment based on the number of units utilized and the individual capacities. For instance, the total power consumed in heat pumps in the electrification and carbon offsetting strategy can be described using ph^{min} and ph^{max} , which refer to the minimum and maximum capacities for individual heat pumps, as shown in Supplementary Equations (21)-(22), and the respective number of units ($Nhpe_{j,n,i}$, $Nhpc_{j,n,i}$). Correspondingly, using the number of electrolyzers ($Ne_{j,n,i}$), the total power utilized in the green hydrogen strategy is illustrated in Supplementary Equation (23), where Pe^{max} and Pe^{min} denote the maximum and minimum power consumption in the electrolyzer. In the carbon offsetting strategy, the number of DAC units ($Nd_{j,n,i}$) and the maximum (cd^{max}) and minimum capacity (cd^{min}) for these units determine the carbon captured in each time interval.

$$Nhpe_{j,n,i} \cdot ph^{min} \leq Phpe_{j,n,i,t} \leq Nhpe_{j,n,i} \cdot ph^{max}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{21}$$

$$Nhpc_{j,n,i} \cdot ph^{min} \leq Phpc_{j,n,i,t} \leq Nhpc_{j,n,i} \cdot ph^{max}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{22}$$

$$Ne_{j,n,i} \cdot Pe^{min} \leq Pu_{2,j,n,i,t} \leq Ne_{j,n,i} \cdot Pe^{max}, \quad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{23}$$

$$Nd_{j,n,i} \cdot cd^{min} \leq cc_{j,n,i,t} \leq Nd_{j,n,i} \cdot cd^{max}, \qquad \forall j \in J,\ n \in N,\ i \in I,\ t \in T \tag{24}$$

Supplementary Equations (25) to (28) can be used to determine the total reduction in natural gas consumption ($Rd^{E\&H}_{j,n,i}$, $Rd^{rt}_{j,n,i}$) and the avoided carbon emissions ($Em^{E\&H}_{j,n,i}$, $Em^{rt}_{j,n,i}$) based on the electrification strategy in the electricity and heating and road transportation sector, where eng , hng , rng indicate the ratios for efficiency in power generation, heating, vehicles in electrification strategy to the natural gas based system; cng indicates the carbon intensity for natural gas utilization. Supplementary Equations (29) to (44) can be used to determine the total reduction in natural gas consumption ($Rd^{li}_{j,n,i}$, $Rd^{te}_{j,n,i}$, $Rd^{mc}_{j,n,i}$, $Rd^{mq}_{j,n,i}$, $Rd^{fbt}_{j,n,i}$, $Rd^{wp}_{j,n,i}$, $Rd^{ct}_{j,n,i}$, and $Rd^{tl}_{j,n,i}$) and the avoided carbon emissions ($Em^{li}_{j,n,i}$, $Em^{te}_{j,n,i}$, $Em^{mc}_{j,n,i}$, $Em^{mq}_{j,n,i}$, $Em^{fbt}_{j,n,i}$, $Em^{wp}_{j,n,i}$, $Em^{ct}_{j,n,i}$, and $Em^{tl}_{j,n,i}$) based on the electrification strategy in various light industries.

$$Rd^{E\&H}_{j,n,i} = Pheat^{E\&H}_{j,n,i} \cdot hng + Pelec^{E\&H}_{j,n,i} \cdot eng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{25}$$

$$Em_{j,n,i}^{E\&H} = Rd_{j,n,i}^{E\&H} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{26}$$

$$Rd_{j,n,i}^{rt} = Pelec_{j,n,i}^{rt} \cdot rng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{27}$$

$$Em_{j,n,i}^{rt} = Rd_{j,n,i}^{rt} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{28}$$

$$Rd_{j,n,i}^{li} = Pheat_{j,n,i}^{li} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{29}$$

$$Rd_{j,n,i}^{te} = Pheat_{j,n,i}^{te} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{30}$$

$$Em_{j,n,i}^{te} = Rd_{j,n,i}^{te} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{31}$$

$$Rd_{j,n,i}^{mc} = Pheat_{j,n,i}^{mc} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{32}$$

$$Em_{j,n,i}^{mc} = Rd_{j,n,i}^{mc} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{33}$$

$$Rd_{j,n,i}^{mq} = Pheat_{j,n,i}^{mq} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{34}$$

$$Em_{j,n,i}^{mq} = Rd_{j,n,i}^{mq} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{35}$$

$$Rd_{j,n,i}^{fbt} = Pheat_{j,n,i}^{fbt} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{36}$$

$$Em_{j,n,i}^{fbt} = Rd_{j,n,i}^{fbt} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{37}$$

$$Rd_{j,n,i}^{wp} = Pheat_{j,n,i}^{wp} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{38}$$

$$Em_{j,n,i}^{wp} = Rd_{j,n,i}^{wp} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{39}$$

$$Rd_{j,n,i}^{ct} = Pheat_{j,n,i}^{ct} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{40}$$

$$Em_{j,n,i}^{ct} = Rd_{j,n,i}^{ct} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{41}$$

$$Rd_{j,n,i}^{tl} = Pheat_{j,n,i}^{tl} \cdot hng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{42}$$

$$Em_{j,n,i}^{tl} = Rd_{j,n,i}^{tl} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{43}$$

$$\begin{aligned} Em_{j,n,i}^{li} = {} & Em_{j,n,i}^{te} + Em_{j,n,i}^{mc} + Em_{j,n,i}^{mq} + Em_{j,n,i}^{fbt} + Em_{j,n,i}^{wp} + Em_{j,n,i}^{ct}, \qquad \forall j \in J,\ n \in N,\ i \in I \\ & + Em_{j,n,i}^{tl} \end{aligned} \tag{44}$$

In the case of the green hydrogen strategy, Supplementary Equations (45)-(46) calculate the total hydrogen produced ($hyd_{j,n,i}^{t}$), along with the distribution between the heavy industrial sectors ($hyd_{j,n,i}^{hi}$) and the operation of heavy trucks in the road transportation sector ($hyd_{j,n,i}^{ht}$). Supplementary Equation (47) shows the further distribution between categories within the heavy industrial sector, including iron and steel, non-ferrous metals, non-metallic minerals, paper, pulp, and printing, and refining and chemicals. Furthermore, Supplementary Equations (48)-(50) illustrate the further bifurcations in the non-metallic minerals (constituting cement/clinker, lime-burning, container glass, flat glass), paper, pulp, and printing (constituting board and packaging paper, graphic paper, tissue paper, chemical pulp, and recovered fibers), refining and chemicals (constituting refining, ammonia, methanol, and other chemicals). Similar to the electrification strategy, these distributions are determined based on the sector-specific reliance on natural gas, ensuring that renewable energy potential is strategically deployed to meet the hydrogen needs of each sector, as shown in Supplementary Fig. 57.

$$hyd^{t}_{j,n,i} = \sum_{t \in T} hyd_{j,n,i,t}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{45}$$

$$hyd^{t}_{j,n,i} = hyd^{hi}_{j,n,i} + hyd^{ht}_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{46}$$

$$hyd^{hi}_{j,n,i} = hyd^{is}_{j,n,i} + hyd^{nf}_{j,n,i} + hyd^{nm}_{j,n,i} + hyd^{ppp}_{j,n,i} + hyd^{rc}_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{47}$$

$$hyd^{nm}_{j,n,i} = hyd^{ck}_{j,n,i} + hyd^{lb}_{j,n,i} + hyd^{ctg}_{j,n,i} + hyd^{ftg}_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{48}$$

$$hyd^{ppp}_{j,n,i} = hyd^{bp}_{j,n,i} + hyd^{gp}_{j,n,i} + hyd^{tp}_{j,n,i} + hyd^{rf}_{j,n,i} + hyd^{cp}_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{49}$$

$$hyd^{rc}_{j,n,i} = hyd^{ref}_{j,n,i} + hyd^{amm}_{j,n,i} + hyd^{mth}_{j,n,i} + hyd^{oc}_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{50}$$

Based on the utilization of green hydrogen, Supplementary Equations (51)-(52) are used to estimate the reduction in natural gas reliance in the road transportation sector for heavy trucks and the avoided emissions, where $htng$ indicates the ratios for efficiency in hydrogen-based vehicles to the natural gas-based alternative. Similarly, Supplementary Equations (53)-(82) can be used to determine the total reduction in natural gas consumption ($Rd^{is}_{j,n,i}$, $Rd^{nf}_{j,n,i}$, $Rd^{ck}_{j,n,i}$, $Rd^{lb}_{j,n,i}$, $Rd^{ctg}_{j,n,i}$, $Rd^{ftg}_{j,n,i}$, $Rd^{bp}_{j,n,i}$, $Rd^{gp}_{j,n,i}$, $Rd^{tp}_{j,n,i}$, $Rd^{rf}_{j,n,i}$, $Rd^{cp}_{j,n,i}$, $Rd^{ref}_{j,n,i}$, $Rd^{amm}_{j,n,i}$, $Rd^{mth}_{j,n,i}$, and $Rd^{oc}_{j,n,i}$) and the avoided carbon emissions ($Em^{is}_{j,n,i}$, $Em^{nf}_{j,n,i}$, $Em^{ck}_{j,n,i}$, $Em^{lb}_{j,n,i}$, $Em^{ctg}_{j,n,i}$, $Em^{ftg}_{j,n,i}$, $Em^{bp}_{j,n,i}$, $Em^{gp}_{j,n,i}$, $Em^{tp}_{j,n,i}$, $Em^{rf}_{j,n,i}$, $Em^{cp}_{j,n,i}$, $Em^{ref}_{j,n,i}$, $Em^{amm}_{j,n,i}$, $Em^{mth}_{j,n,i}$, and $Em^{oc}_{j,n,i}$) based on the hydrogen strategy in various heavy industries, with $isng$, $nfng$, $ckng$, $lbng$, $ctgng$, $ftgng$, $bpng$, $gpng$, $tpng$, $rfng$, and $cpng$ indicating the ratio of efficiency for hydrogen-based technology to natural gas based alternative in iron and steel, non-ferrous metals, cement/clinker, lime-burning, container glass, flat glass, board and packaging paper, graphic paper, tissue paper, chemical pulp, and recovered fibers, respectively, as depicted in Supplementary Table 12. In the case of heavy industrial sectors, where the role of green hydrogen is used to reduce dependence on natural gas-based hydrogen, including refining, ammonia, methanol, and other chemicals, $hydg_i$ represents the natural gas requirement for each kg of hydrogen consumed in different EU countries, as detailed in Supplementary Table 6. Moreover, the total potential for carbon capture ($Em_{j,n,i}^{cap}$) in the carbon offsetting strategy can be calculated using Supplementary Equation (83).

$$Rd_{j,n,i}^{ht} = hyd_{j,n,i}^{ht} \cdot LHV \cdot htng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{51}$$

$$Em_{j,n,i}^{ht} = Rd_{j,n,i}^{ht} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{52}$$

$$Rd_{j,n,i}^{is} = hyd_{j,n,i}^{is} \cdot LHV \cdot isng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{53}$$

$$Em_{j,n,i}^{is} = Rd_{j,n,i}^{is} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{54}$$

$$Rd_{j,n,i}^{nf} = hyd_{j,n,i}^{nf} \cdot LHV \cdot nfng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{55}$$

$$Em_{j,n,i}^{nf} = Rd_{j,n,i}^{nf} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{56}$$

$$Rd_{j,n,i}^{ck} = hyd_{j,n,i}^{ck} \cdot LHV \cdot ckng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{57}$$

$$Em_{j,n,i}^{ck} = Rd_{j,n,i}^{ck} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{58}$$

$$Rd_{j,n,i}^{lb} = hyd_{j,n,i}^{lb} \cdot LHV \cdot lbng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{59}$$

$$Em_{j,n,i}^{lb} = Rd_{j,n,i}^{lb} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{60}$$

$$Rd_{j,n,i}^{ctg} = hyd_{j,n,i}^{ctg} \cdot LHV \cdot ctgng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{61}$$

$$Em_{j,n,i}^{ctg} = Rd_{j,n,i}^{ctg} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{62}$$

$$Rd_{j,n,i}^{ftg} = hyd_{j,n,i}^{ftg} \cdot LHV \cdot ftgng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{63}$$

$$Em_{j,n,i}^{ftg} = Rd_{j,n,i}^{ftg} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{64}$$

$$Rd_{j,n,i}^{bp} = hyd_{j,n,i}^{bp} \cdot LHV \cdot bpng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{65}$$

$$Em_{j,n,i}^{bp} = Rd_{j,n,i}^{bp} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{66}$$

$$Rd_{j,n,i}^{gp} = hyd_{j,n,i}^{gp} \cdot LHV \cdot gpng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{67}$$

$$Em_{j,n,i}^{gp} = Rd_{j,n,i}^{gp} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{68}$$

$$Rd_{j,n,i}^{tp} = hyd_{j,n,i}^{tp} \cdot LHV \cdot tpng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{69}$$

$$Em_{j,n,i}^{tp} = Rd_{j,n,i}^{tp} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{70}$$

$$Rd_{j,n,i}^{rf} = hyd_{j,n,i}^{rf} \cdot LHV \cdot rfng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{71}$$

$$Em^{rf}_{j,n,i} = Rd^{rf}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{72}$$

$$Rd^{cp}_{j,n,i} = hyd^{cp}_{j,n,i} \cdot LHV \cdot cpng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{73}$$

$$Em^{cp}_{j,n,i} = Rd^{cp}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{74}$$

$$Rd^{ref}_{j,n,i} = hyd^{ref}_{j,n,i} \cdot hydg_i, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{75}$$

$$Em^{ref}_{j,n,i} = Rd^{ref}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{76}$$

$$Rd^{amm}_{j,n,i} = hyd^{amm}_{j,n,i} \cdot hydg_i, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{77}$$

$$Em^{amm}_{j,n,i} = Rd^{amm}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{78}$$

$$Rd^{mth}_{j,n,i} = hyd^{mth}_{j,n,i} \cdot hydg_i, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{79}$$

$$Em^{mth}_{j,n,i} = Rd^{mth}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{80}$$

$$Rd^{oc}_{j,n,i} = hyd^{oc}_{j,n,i} \cdot hydg_i, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{81}$$

$$Em^{oc}_{j,n,i} = Rd^{oc}_{j,n,i} \cdot cng, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{82}$$

$$Em^{cap}_{j,n,i} = \sum_{t \in T} cc_{j,n,i,t}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{83}$$

Techno-economic evaluation constraints

While considering the economic evaluation in the study, the net present value can be calculated using Supplementary Equation (84), where $ACF_{s,j,n,i}$ and $TC_{s,j,n,i}$ refer to the annual cash flow and total capital investment in different strategies. The annual cash flow is determined by considering the yearly revenue generated in different strategies and the operating costs incurred during the same period. The salvage value is incorporated in the final year to account for the residual value of the process components utilized in the investigated scenarios.

$$NPV_{s,j,n,i} = \sum_{M=1}^{NY} \frac{ACF_{s,j,n,i}}{(1+dr)^M} - TC_{s,j,n,i}, \qquad \forall s \in S,\ j \in J,\ n \in N,\ i \in I \tag{84}$$

Supplementary Equation (85) depicts the total income for the electrification strategy ($Re_{1,j,n,i}$) calculated using the electricity (ec_i) and natural gas prices (nc_i) for the EU countries, detailed in Supplementary Table 7. Similarly, Supplementary Equations (86)-(87) can be used to calculate the income for the green hydrogen and carbon capture strategies, where C^{sp} and H_2^{SP} refer to the price in the carbon market and the green hydrogen selling price.

$$Re_{1,j,n,i} = Pelec^{total}_{j,n,i} \cdot ec_i + Pheat^{total}_{j,n,i} \cdot nc_i, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{85}$$

$$Re_{2,j,n,i} = \sum_{t \in T} hyd_{j,n,i,t} \cdot H_2^{SP}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{86}$$

$$Re_{3,j,n,i} = \sum_{t \in T} cc_{j,n,i,t} \cdot C^{sp}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{87}$$

The total initial investment across different strategies is calculated by evaluating the renewable capacity expansion cost and specific process components, as shown in Supplementary Equations (88)-(90). The initial capital expenditure for the renewable infrastructure incorporates the projections for the unit capital cost (\$/kW) for solar and wind power installations illustrated in Supplementary Table 8. In the electrification strategy, the initial capital expenditure combines the investment in renewable infrastructure with the capital expenditure on battery storage ($Cb_{j,n,i}$) and interface ($Cnt_{j,n,i}$) and heat pump units ($Chpe_{j,n,i}$). The cost of heat pump units is determined using Supplementary Equations (92)-(93), where $AChp_n$ and bhp represent the capital cost for each heat pump unit and the learning rate exponent, respectively, qhp_n indicates the expected increase in the number of installed units[63]. Supplementary Equations (95)-(96) are used to calculate the total investment for the battery storage and interface capacities, where ACb_n (\$/kWh) and ACi_n (\$/kW) represent the trajectories for the unit capital cost based on previous literature[64], as illustrated in Supplementary Table 10. For the green hydrogen and carbon capture strategies, the initial investment similarly includes costs for renewable infrastructure. Specifically, the green hydrogen strategy also involves capital expenditure for electrolyzer units, calculated using Supplementary Equation (97), where ACe_n refers to the cost trajectory based on previous literature[65]. Supplementary Equation (98) is used to calculate the cost of hydrogen pipeline infrastructure based on the pipeline capacity, length of repurposed hydrogen pipeline network in different EU countries (rl_i) depicted in Supplementary Table 3, and the projections for cost-competitiveness of repurposed hydrogen networks[12]. In the carbon capture strategy, the capital expenditure associated with DAC units is calculated using Supplementary Equations (99)-(100), where ACd_n and bd indicate the capital cost for the DAC units and the learning rate exponent, respectively, with qd_n referring to the projected growth in DAC capacity[66]. rep^{hpe} and rep^{hpc} refer to the replacement cycles for the heat pump units based on operating life in the electrification and carbon offsetting strategies, respectively. rep^{bcp} and rep^{icp} refer to the replacement cycles for the battery storage and interface based on operating life, respectively.

$$TC_{1,j,n,i} = Cr_{1,j,n,i} + Cb_{j,n,i} + Cnt_{j,n,i} + Chpe_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{88}$$

$$TC_{2,j,n,i} = Cr_{2,j,n,i} + Ce_{j,n,i} + Ctr_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{89}$$

$$TC_{3,j,n,i} = Cr_{3,j,n,i} + Cd_{j,n,i} + Chpc_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{90}$$

$$Cr_{s,j,n,i} = Nr_{s,j,n,i} \cdot ACr_{n}, \qquad \forall s \in S,\ j \in J,\ n \in N,\ i \in I \tag{91}$$

$$Chpe_{j,n,i} = Nhpe_{j,n,i} \cdot AChp_{n} \cdot rep^{hpe}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{92}$$

$$AChp_{n} = AChpi \cdot qhp_{n}^{-bhp}, \qquad \forall n \in N \tag{93}$$

$$Chpc_{j,n,i} = Nhpc_{j,n,i} \cdot AChp_{n} \cdot rep^{hpc}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{94}$$

$$Cb_{j,n,i} = bcp_{j,n,i} \cdot ACb_{n} \cdot rep^{bcp}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{95}$$

$$Cnt_{j,n,i} = icp_{j,n,i} \cdot ACi_{n} \cdot rep^{icp}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{96}$$

$$Ce_{j,n,i} = Ne_{j,n,i} \cdot ACe_{n}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{97}$$

$$Ctr_{j,n,i} = pip_{j,n,i}^{hyd} \cdot ACtr_{n} \cdot rl_{i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{98}$$

$$Cd_{j,n,i} = Nd_{j,n,i} \cdot ACd_{n}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{99}$$

$$ACd_{n} = ACdi \cdot qd_{n}^{-bd}, \qquad \forall n \in N \tag{100}$$

$$TCe_{j,n,i} = Cr_{1,j,n,i} + Cb_{j,n,i} + Ct_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{101}$$

Correspondingly, based on the total project lifespan, the salvage values for the process components across different scenarios can be calculated using the double depreciation method depicted in Supplementary Equations (102)-(109), while the total salvage value is estimated by Supplementary Equations (110)-(112).

$$SALr_{s,j,n,i} = sr \cdot Cr_{s,j,n,i}, \qquad \forall s \in S,\ j \in J,\ n \in N,\ i \in I \tag{102}$$

$$SALhpe_{j,n,i} = shp \cdot Chpe_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{103}$$

$$SALhpc_{j,n,i} = shp \cdot Chpc_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{104}$$

$$SALb_{j,n,i} = sb \cdot Cb_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{105}$$

$$SALnt_{j,n,i} = st \cdot Cnt_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{106}$$

$$SALe_{j,n,i} = se \cdot Ce_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{107}$$

$$SALtr_{j,n,i} = str \cdot Ctr_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{108}$$

$$SALd_{j,n,i} = sd \cdot Cd_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{109}$$

$$SAL_{1,j,n,i} = SALr_{1,j,n,i} + SALb_{j,n,i} + SALnt_{j,n,i} + SALhpe_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{110}$$

$$SAL_{2,j,n,i} = SALr_{2,j,n,i} + SALe_{j,n,i} + SALtr_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{111}$$

$$SAL_{3,j,n,i} = SALr_{3,j,n,i} + SALd_{j,n,i} + SALhpe_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{112}$$

Moreover, the operating costs for each strategy account for projections in unit operating expenditure (\$/kW-yr) for the solar and wind energy installations illustrated in Supplementary Table 9. Supplementary Equations (117)-(118) indicate the calculation for the operating cost for battery storage and interface capacities based on the projections for unit operating expenditure based on previous literature[64], as shown in Supplementary Table 10. For process components like electrolyzers, heat pumps, DAC units, and pipeline infrastructure, operating costs are calculated as a percentage of their capital cost, as depicted in Supplementary Equations (119)-(123). Additionally, in the carbon capture strategy, Supplementary Equations (124)-(125) calculate the operating cost associated with the storage and transportation of captured CO_2.

$$Op_{1,j,n,i} = Opr_{1,j,n,i} + Opb_{j,n,i} + Opnt_{j,n,i} + Ophpe_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{113}$$

$$Op_{2,j,n,i} = Opr_{2,j,n,i} + Ope_{j,n,i} + Optr_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{114}$$

$$\begin{aligned} Op_{3,j,n,i} = {} & Opr_{3,j,n,i} + Opd_{j,n,i} + Opctr_{j,n,i} + Opcst_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \\ & + Ophpc_{j,n,i} \end{aligned} \tag{115}$$

$$Opr_{s,j,n,i} = Nr_{s,j,n,i} \cdot opfr_n, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I \tag{116}$$

$$Opb_{j,n,i} = bcp_{j,n,i} \cdot opfb_n, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I \tag{117}$$

$$Opnt_{j,n,i} = icp_{j,n,i} \cdot opfi_n, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I \tag{118}$$

$$Ophpe_{j,n,i} = Chpe_{j,n,i} \cdot cfhp, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{119}$$

$$Ophpc_{j,n,i} = Chpc_{j,n,i} \cdot cfhp, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{120}$$

$$Ope_{j,n,i} = Ce_{j,n,i} \cdot cfe, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{121}$$

$$Optr_{j,n,i} = Ctr_{j,n,i} \cdot cftr, \qquad \forall s \in S, j \in J,\ n \in N,\ i \in I \tag{122}$$

$$Opd_{j,n,i} = Cd_{j,n,i} \cdot cfd, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{123}$$

$$Opctr_{j,n,i} = \sum_{t \in T} cc_{j,n,i,t} \cdot ctr, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{124}$$

$$Opcst_{j,n,i} = \sum_{t \in T} cc_{j,n,i,t} \cdot cst, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{125}$$

$$Ope_{j,n,i} = Opr_{1,j,n,i} + Opb_{j,n,i} + Opnt_{j,n,i}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{126}$$

The levelized costs associated with different strategies are calculated based on the utilization levels of renewable capacity expansion, which can be used to attain electrification potential, green hydrogen production, and the implementation of carbon offsetting measures, as depicted in Supplementary Equations (127)-(130).

$$LCOE_{j,n,i} = \frac{TCe_{j,n,i} \cdot CRF + Ope_{j,n,i}}{\sum_{t \in T} Pu_{1,j,n,i,t}}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{127}$$

$$LCOHe_{j,n,i} = \frac{Chpe_{j,n,i} \cdot CRF + LCOE_{j,n,i} \cdot \sum_{t \in T} Phpe_{j,n,i,t} + Ophpe_{j,n,i}}{\sum_{t \in T} Phte_{j,n,i,t}}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{128}$$

$$LCOH_{j,n,i} = \frac{TC_{2,j,n,i} \cdot CRF + Op_{2,j,n,i}}{\sum_{t \in T} hyd_{j,n,i,t}}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{129}$$

$$LCOC_{j,n,i} = \frac{TC_{3,j,n,i} \cdot CRF + Op_{3,j,n,i}}{\sum_{t \in T} cc_{j,n,i,t}}, \qquad \forall j \in J,\ n \in N,\ i \in I \tag{130}$$

Notations

Sets/Indices

I	Set representing the different EU countries, indexed by i
J	Set representing the varying paces in the increasing cost-competitiveness of renewable power installations, indexed by j
N	Set representing the years in progression for different strategies, indexed by n
S	Set representing the investigated strategies, including electrification, green hydrogen production, and carbon offsetting, indexed by s
T	Set representing the hourly resolution time scale, indexed by t

Parameters

$ACdi$	Total initial capital expenditure for the DAC units (\$/tCO_2)
ACb_n	Total capital expenditure on battery storage in the year n (\$/kWh)
ACd_n	Total capital expenditure for DAC units in the year n (\$/tCO_2)
ACe_n	Total capital expenditure for electrolyzer in the year n (\$/MW)
$AChpi$	Total initial capital expenditure for the heat pumps (\$/MW)
$AChp_n$	Total capital expenditure on heat pump in the year n (\$/MW)
ACi_n	Total capital expenditure on battery interface in the year n (\$/kW)

ACr_n	Total capital expenditure on renewable capacity expansion in the year *n* ($/kW)
$ACtr_n$	Total capital expenditure on repurposed hydrogen pipeline network in the year *n* ($/kW/km)
bd	Learning rate exponent for the DAC
bhp	Learning rate exponent for the heat pumps
bpng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in board and packaging paper industry
cd^{max}	Maximum carbon captured in the DAC units ($kgCO_2$)
cd^{min}	Minimum carbon captured in the DAC units ($kgCO_2$)
cfd	Percentage of capital expenditure used to estimate the operating cost for the DAC (%)
cfe	Percentage of capital expenditure used to estimate the operating cost for the electrolyzer (%)
cfhp	Percentage of capital expenditure used to estimate the operating cost for the heat pumps (%)
cftr	Percentage of capital expenditure used to estimate the operating cost for the hydrogen pipeline infrastructure (%)
ckng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in cement/clinker industry
cng	Carbon intensity of natural gas utilization ($kgCO_2$/kWh)
COP	Coefficient of performance for heat pumps
cpng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in chemical pulp industry
CRF	Capital Recovery Factor
C^{SP}	Price in the carbon market ($/$kgCO_2$)
cst	Storage cost for the captured CO_2 ($/$kgCO_2$)
ctgng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in container glass industry
ctr	Transportation cost for the captured CO_2 ($/$kgCO_2$)
df	Specific electricity requirement in the DAC ($kgCO_2$/kWh)
dfr	Ratio for the electricity and thermal energy requirements for the DAC infrastructure
dr	Discount rate (%)
ec_i	Electricity price in the country represented by index *i* ($/kWh)
ef_i	Ratio for the transformation output between heat and electricity generated as part of the electrification strategy in the country represented by index *i*
eng	Ratio for efficiency in power generation in electrification strategy to natural gas-based system
ftgng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in flat glass industry
gpng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in graphic paper industry
H_2^{SP}	Hydrogen selling price ($/kg-$H_2$)

hng	Ratio for efficiency in heating in electrification strategy to natural gas-based system
htng	Ratio for efficiency in vehicle operation in green hydrogen strategy to natural gas-based system
$hydg_i$	Natural gas requirement for each kg of hydrogen consumed in the country represented by index *i*
isng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in iron and steel industry
lbng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in lime-burning industry
LHV	Lower heating value of hydrogen (kWh/kg-H_2)
nc_i	Natural gas price in the country represented by index *i* ($/kWh)
nfng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in non-ferrous metal industry
NY	Total project life for renewable capacity expansion in different scenarios (yr)
$opfb_n$	Operating cost for the battery storage infrastructure in the electrification strategy in the year *n* ($/kWh-yr)
$opfi_n$	Operating cost for the battery interface infrastructure in the electrification strategy in the year *n* ($/kWh-yr)
$opfr_n$	Operating cost for the renewable capacity expansion in the year *n* ($/kW-yr)
Pe^{max}	Maximum power consumption in the electrolyzer (kWh)
Pe^{min}	Minimum power consumption in the electrolyzer (kWh)
ph^{max}	Maximum power consumption in the heat pump (kWh)
ph^{min}	Minimum power consumption in the heat pump (kWh)
qd_n	Ratio for the installed DAC capacity in the year *n* to the current year
qhp_n	Ratio of the number of installed heat pump units in the year *n* to the current year
rep^{bcp}	Replacement parameter for the battery storage in the electrification strategy
rep^{hpc}	Replacement parameter for the heat pump unit in the carbon offsetting strategy
rep^{hpe}	Replacement parameter for the heat pump unit in the electrification strategy
rep^{icp}	Replacement parameter for the battery interface in the electrification strategy
rfng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in recovered fiber industry
rl_i	Pipeline infrastructure length of hydrogen transport in the country represented by index *i* (km)
rng	Ratio for efficiency in vehicle operation in electrification strategy to natural gas-based system
sb	Salvage value factor for the battery storage
sd	Salvage value factor for the DAC
se	Salvage value factor for the electrolyzer

shp	Salvage value factor for the heat pump
snt	Salvage value factor for the battery interface
sr	Salvage value factor for the renewable capacity expansion
str	Salvage value factor for the hydrogen pipeline infrastructure
tpng	Ratio for efficiency in hydrogen-based technology to natural gas based alternative in tissue paper industry
μ^{PV}	Solar panel efficiency (%)
η^{ELE}	Efficiency for the electrolyzer (%)

Discrete variables

$Nd_{j,n,i}$	Number of DAC units used in the carbon offsetting scenario with cost-effectiveness trajectory *j* in the year *n* for country *i*
$Ne_{j,n,i}$	Number of electrolyzers used in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i*
$Nhpc_{j,n,i}$	Number of heat pumps used in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i*
$Nhpe_{j,n,i}$	Number of heat pumps used in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i*

Continuous variables

$ACF_{s,j,n,i}$	Annual cash flow in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$bcp_{j,n,i}$	Battery storage capacities in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Cb_{j,n,i}$	Total capital expenditure on battery storage in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$cc_{j,n,i,t}$	CO_2 captured in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kg)
$Cd_{j,n,i}$	Total capital expenditure on DAC units in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Ce_{j,n,i}$	Total capital expenditure on electrolyzers in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Chpc_{j,n,i}$	Total capital expenditure on heat pumps in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Chpe_{j,n,i}$	Total capital expenditure on heat pumps in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Cnt_{j,n,i}$	Total capital expenditure on battery interface in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)

$Cr_{1,j,n,i}$	Total capital expenditure on renewable capacity expansion in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Cr_{2,j,n,i}$	Total capital expenditure on renewable capacity expansion in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Cr_{3,j,n,i}$	Total capital expenditure on renewable capacity expansion in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Cr_{s,j,n,i}$	Total capital expenditure on renewable capacity expansion in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Ctr_{j,n,i}$	Total capital expenditure on hydrogen pipeline infrastructure in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Em^{amm}_{j,n,i}$	Total avoided carbon emissions due to ammonia production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{bp}_{j,n,i}$	Total avoided carbon emissions in board and packaging paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{bp}_{j,n,i}$	Total avoided carbon emissions in graphic paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{cap}_{j,n,i}$	Total CO_2 captured in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$Em^{ck}_{j,n,i}$	Total avoided carbon emissions in cement/clinker industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{cp}_{j,n,i}$	Total avoided carbon emissions in chemical pulp industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{ctg}_{j,n,i}$	Total avoided carbon emissions in container glass industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{ct}_{j,n,i}$	Total avoided carbon emissions in construction industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{E\&H}_{j,n,i}$	Total avoided carbon emissions in the electricity and heating sector based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{fbt}_{j,n,i}$	Total avoided carbon emissions in food, beverages, and tobacco industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{ftg}_{j,n,i}$ Total avoided carbon emissions in flat glass industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{ht}_{j,n,i}$ Total avoided carbon emissions in the road transportation sector, for the operation of heavy trucks, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{is}_{j,n,i}$ Total avoided carbon emissions in iron and steel industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{lb}_{j,n,i}$ Total avoided carbon emissions in lime-burning industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{li}_{j,n,i}$ Total avoided carbon emissions in the light industrial sector based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{mc}_{j,n,i}$ Total avoided carbon emissions in machinery industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{mq}_{j,n,i}$ Total avoided carbon emissions in mining and quarrying industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{mth}_{j,n,i}$ Total avoided carbon emissions due to methanol production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{nf}_{j,n,i}$ Total avoided carbon emissions in non-ferrous metal industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{oc}_{j,n,i}$ Total avoided carbon emissions due to other chemical production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{ref}_{j,n,i}$ Total avoided carbon emissions due to refining, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{rf}_{j,n,i}$ Total avoided carbon emissions in recovered fiber industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{rt}_{j,n,i}$ Total avoided carbon emissions in the road transportation sector, for the operation of passenger cars, light commercial vehicles, buses, and coaches, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{te}_{j,n,i}$ Total avoided carbon emissions in transportation equipment industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)

$Em^{tl}_{j,n,i}$	Total avoided carbon emissions in textile and leather industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{tp}_{j,n,i}$	Total avoided carbon emissions in tissue paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$Em^{wp}_{j,n,i}$	Total avoided carbon emissions in wood and wood product industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($kgCO_2$)
$hyd^{amm}_{j,n,i}$	Total hydrogen supplied to ammonia production, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{bp}_{j,n,i}$	Total hydrogen supplied to the board and packaging paper industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ck}_{j,n,i}$	Total hydrogen supplied to the cement/clinker industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{cp}_{j,n,i}$	Total hydrogen supplied to the chemical pulp industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ctg}_{j,n,i}$	Total hydrogen supplied to the container glass industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ftg}_{j,n,i}$	Total hydrogen supplied to the flat glass industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{gp}_{j,n,i}$	Total hydrogen supplied to the graphic paper industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{hi}_{j,n,i}$	Total hydrogen supplied to the heavy industrial sector in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ht}_{j,n,i}$	Total hydrogen supplied to the operation of heavy trucks in the road transportation sector in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{is}_{j,n,i}$	Total hydrogen supplied to the iron and steel industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd_{j,n,i,t}$	Hydrogen produced in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kg)

$hyd^{lb}_{j,n,i}$	Total hydrogen supplied to the lime-burning industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{mth}_{j,n,i}$	Total hydrogen supplied to methanol production, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{nf}_{j,n,i}$	Total hydrogen supplied to the non-ferrous metal industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{nm}_{j,n,i}$	Total hydrogen supplied to the non-metallic mineral industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{oc}_{j,n,i}$	Total hydrogen supplied to other chemical production, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ppp}_{j,n,i}$	Total hydrogen supplied to the paper, pulp, and printing industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{rc}_{j,n,i}$	Total hydrogen supplied to the refining and chemical industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{ref}_{j,n,i}$	Total hydrogen supplied to refining, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{rf}_{j,n,i}$	Total hydrogen supplied to the recovered fiber industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{t}_{j,n,i}$	Total hydrogen produced in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$hyd^{tp}_{j,n,i}$	Total hydrogen supplied to the tissue paper industries, within the heavy industrial sector, based on the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$icp_{j,n,i}$	Battery interface capacities in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kW)
$LCOC_{j,n,i}$	Levelized cost of carbon capture in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($/kg)
$LCOE_{j,n,i}$	Levelized cost of electricity in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($/kWh)
$LCOHe_{j,n,i}$	Levelized cost of heat in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($/kWh)
$LCOH_{j,n,i}$	Levelized cost of hydrogen in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($/kg)

$NPV_{s,j,n,i}$	Net present value in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Nr_{s,j,n,i}$	Total renewable capacity expansion in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* (kW)
$Op_{1,j,n,i}$	Total operating expenses in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Op_{2,j,n,i}$	Total operating expenses in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Op_{3,j,n,i}$	Total operating expenses in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opb_{j,n,i}$	Total operating expenses for battery storage in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opcst_{j,n,i}$	Total operating expenses for storage of the captured CO_2 in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opctr_{j,n,i}$	Total operating expenses for transportation of the captured CO_2 in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opd_{j,n,i}$	Total operating expenses for DAC in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Ope_{j,n,i}$	Total operating expenses for electrolyzers in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Ophpc_{j,n,i}$	Total operating expenses for heat pumps in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Ophpe_{j,n,i}$	Total operating expenses for heat pumps in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opnt_{j,n,i}$	Total operating expenses for battery interface in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opr_{1,j,n,i}$	Total operating expenses for renewable capacity expansion in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opr_{2,j,n,i}$	Total operating expenses for renewable capacity expansion in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opr_{3,j,n,i}$	Total operating expenses for renewable capacity expansion in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Opr_{s,j,n,i}$	Total operating expenses for renewable capacity expansion in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)

$Optr_{j,n,i}$	Total operating expenses for hydrogen pipeline infrastructure in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$Pa_{s,j,n,i,t}$	Available power in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pec_{j,n,i,t}$	Electricity component in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pelec^{E\&H}_{j,n,i}$	Total electricity supplied to the broader electricity sector as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pelec_{j,n,i,t}$	Electricity generated in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pelec^{rt}_{j,n,i}$	Total electricity supplied to the road transportation sector for the operation of passenger cars, light commercial vehicles, buses, and coaches in the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pelec^{total}_{j,n,i}$	Total electricity produced in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{ct}_{j,n,i}$	Total heat supplied to the construction industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{E\&H}_{j,n,i}$	Total heat supplied to the broader heating sector as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{fbt}_{j,n,i}$	Total heat supplied to the food, beverages, and tobacco industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{li}_{j,n,i}$	Total heat supplied to the light industrial sector as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{mc}_{j,n,i}$	Total heat supplied to the machinery industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{mq}_{j,n,i}$	Total heat supplied to the mining and quarrying industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{te}_{j,n,i}$	Total heat supplied to the transportation equipment industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{tl}_{j,n,i}$	Total heat supplied to the textile and leather industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Pheat^{total}_{j,n,i}$	Total heat produced in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Pheat^{wp}_{j,n,i}$	Total heat supplied to the wood and wood product industries, within the light industrial sector, as part of the electrification strategy under cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Phpc_{j,n,i,t}$	Power component in the carbon offsetting strategy used for heat pumps with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Phpe_{j,n,i,t}$	Power component in the electrification strategy used for heat pumps with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Phtc_{j,n,i,t}$	Heat generated in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Phte_{j,n,i,t}$	Heat generated in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$pip^{cc}_{j,n,i}$	Pipeline capacity in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kg)
$pip^{hyd}_{j,n,i}$	Pipeline capacity in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$P^{out}_{j,n,i}$	Output capacity from the solar or wind power installation in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
Pr	Rated output power of wind turbine
$Psl_{s,j,n,i,t}$	Surplus power generated in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Psp_{s,j,n,i,t}$	Solar power generated in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pu_{1,j,n,i,t}$	Utilized power component in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pu_{2,j,n,i,t}$	Utilized power component in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pu_{3,j,n,i,t}$	Utilized power component in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pu_{s,j,n,i,t}$	Utilized power component in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)
$Pwp_{s,j,n,i,t}$	Wind power generated in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t* (kWh)

$Rd^{amm}_{j,n,i}$ Reduction in natural gas consumption due to ammonia production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{bp}_{j,n,i}$ Reduction in natural gas consumption in board and packaging paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{ck}_{j,n,i}$ Reduction in natural gas consumption in cement/clinker industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{cp}_{j,n,i}$ Reduction in natural gas consumption in chemical pulp industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{ctg}_{j,n,i}$ Reduction in natural gas consumption in container glass industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{ct}_{j,n,i}$ Reduction in natural gas consumption in construction industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{E\&H}_{j,n,i}$ Reduction in natural gas consumption in the electricity and heating sector based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{fbt}_{j,n,i}$ Reduction in natural gas consumption in food, beverages, and tobacco industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{ftg}_{j,n,i}$ Reduction in natural gas consumption in container glass industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{gp}_{j,n,i}$ Reduction in natural gas consumption in graphic paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{ht}_{j,n,i}$ Reduction in natural gas consumption in the road transportation sector, for the operation of heavy trucks, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{is}_{j,n,i}$ Reduction in natural gas consumption in iron and steel industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{lb}_{j,n,i}$ Reduction in natural gas consumption in lime-burning industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{li}_{j,n,i}$ Reduction in natural gas consumption in the light industrial sector based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)

$Rd^{mc}_{j,n,i}$	Reduction in natural gas consumption in machinery industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{mq}_{j,n,i}$	Reduction in natural gas consumption in mining and quarrying industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{mth}_{j,n,i}$	Reduction in natural gas consumption due to methanol production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{nf}_{j,n,i}$	Reduction in natural gas consumption in non-ferrous metal industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{oc}_{j,n,i}$	Reduction in natural gas consumption due to other chemical production, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{ref}_{j,n,i}$	Reduction in natural gas consumption due to refining, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{rf}_{j,n,i}$	Reduction in natural gas consumption in recovered fiber industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{rt}_{j,n,i}$	Reduction in natural gas consumption in the road transportation sector, for the operation of passenger cars, light commercial vehicles, buses, and coaches, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{te}_{j,n,i}$	Reduction in natural gas consumption in transportation equipment industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{tl}_{j,n,i}$	Reduction in natural gas consumption in textile and leather industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{tp}_{j,n,i}$	Reduction in natural gas consumption in tissue paper industries, within the heavy industrial sector, based on green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Rd^{wp}_{j,n,i}$	Reduction in natural gas consumption in wood and wood product industries, within the light industrial sector, based on electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* (kWh)
$Re_{1,j,n,i}$	Total revenue in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)

$Re_{2,j,n,i}$ Total revenue in the green hydrogen strategy with cost-effectiveness trajectory j in the year n for country i ($)

$Re_{3,j,n,i}$ Total revenue in the carbon offsetting strategy with cost-effectiveness trajectory j in the year n for country i ($)

$r^{out}_{j,n,i}$ Solar radiation intensity corresponding to the output capacity in the electrification strategy with cost-effectiveness trajectory j in the year n for country i (W/m^2)

$r_{s,j,n,i,t}$ Solar radiation intensity in the strategy s with cost-effectiveness trajectory j in the year n for country i with different time intervals represented by index t (W/m^2)

$SAL_{1,j,n,i}$ Total salvage value in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SAL_{2,j,n,i}$ Total salvage value in the green hydrogen strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SAL_{3,j,n,i}$ Total salvage value in the carbon offsetting strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALb_{j,n,i}$ Total salvage value for battery storage in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALd_{j,n,i}$ Total salvage value for DAC in the carbon offsetting strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALe_{j,n,i}$ Total salvage value for electrolyzers in the green hydrogen strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALhpc_{j,n,i}$ Total salvage value for heat pumps in the carbon offsetting strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALhpe_{j,n,i}$ Total salvage value for heat pumps in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALnt_{j,n,i}$ Total salvage value for battery interface in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALr_{1,j,n,i}$ Total salvage value for renewable capacity expansion in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALr_{2,j,n,i}$ Total salvage value for renewable capacity expansion in the green hydrogen strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALr_{3,j,n,i}$ Total salvage value for renewable capacity expansion in the carbon offsetting strategy with cost-effectiveness trajectory j in the year n for country i ($)

$SALr_{s,j,n,i}$ Total salvage value for renewable capacity expansion in the strategy s with cost-effectiveness trajectory j in the year n for country i ($)

$SALtr_{j,n,i}$ Total salvage value for hydrogen pipeline infrastructure in the green hydrogen strategy with cost-effectiveness trajectory j in the year n for country i ($)

S^{PV} Solar panel surface area (m^2)

$TC_{1,j,n,i}$ Total capital expenditure in the electrification strategy with cost-effectiveness trajectory j in the year n for country i ($)

$TC_{2,j,n,i}$	Total capital expenditure in the green hydrogen strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$TC_{3,j,n,i}$	Total capital expenditure in the carbon offsetting strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$TCe_{j,n,i}$	Total capital expenditure on electricity generation and storage equipment in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$TC_{s,j,n,i}$	Total capital expenditure in the strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* ($)
$v^{out}_{j,n,i}$	Wind power generation potential corresponding to the output capacity in the electrification strategy with cost-effectiveness trajectory *j* in the year *n* for country *i*
$v_{s,j,n,i,t}$	Wind power generation potential [0,1] in a strategy *s* with cost-effectiveness trajectory *j* in the year *n* for country *i* with different time intervals represented by index *t*

Input parameters

Supplementary Table 6. Ratio for the transformation output (represented by ef_i) between heat and electricity generated as part of the electrification strategy based on the sector-specific natural gas reliance across the electricity and heating sectors, light industries, and the road transportation sector in different EU countries, as shown in Fig S57, while accounting for the relative efficiencies of natural gas-based systems in power generation, heating, and vehicles, compared to their electrified counterparts[60, 61].

Index (*i*)	Country	ef_i
1	Germany	0.85
2	Italy	0.37
3	France	0.89
4	Netherlands	0.64
5	Spain	0.24
6	Poland	1.58
7	Belgium	0.66
8	Greece	0.06
9	Austria	1.01
10	Hungary	0.98
11	Czechia	1.58
12	Portugal	0.29
13	Sweden	3.07
14	Denmark	3.49
15	Romania	0.93
16	Bulgaria	0.67
17	Slovakia	1.14
18	Estonia	1.33
19	Finland	0.84
20	Slovenia	1.52
21	Luxembourg	1.54

22	Lithuania	4.49
23	Malta	0.00
24	Ireland	0.22
25	Croatia	0.62
26	Latvia	1.90

Supplementary Table 7. Natural gas requirement (kWh) for each kg of hydrogen consumed (represented by $hydg_i$) in the refining, ammonia, methanol, and other chemicals sectors in different EU countries[67, 68].

Index (i)	Country	$hydg_i$
1	Germany	38.89
2	Italy	42.32
3	France	38.95
4	Netherlands	41.56
5	Spain	41.69
6	Poland	43.47
7	Belgium	38.07
8	Greece	44.48
9	Austria	41.18
10	Hungary	40.49
11	Czechia	39.46
12	Portugal	41.00
13	Sweden	35.56
14	Denmark	44.50
15	Romania	42.82
16	Bulgaria	42.73
17	Slovakia	43.34
18	Estonia	0.00
19	Finland	39.94
20	Slovenia	37.38
21	Luxembourg	40.97
22	Lithuania	44.50
23	Malta	40.97
24	Ireland	43.35
25	Croatia	44.50
26	Latvia	40.97

Supplementary Table 8. Electricity and natural gas prices ($/kWh) (represented by ec_i and nc_i, respectively) in different EU countries[69, 70].

Index (i)	Country	ec_i	nc_i
1	Germany	0.45	0.13
2	Italy	0.42	0.11
3	France	0.25	0.11
4	Netherlands	0.42	0.22
5	Spain	0.27	0.12

6	Poland	0.19	0.08
7	Belgium	0.48	0.13
8	Greece	0.26	0.13
9	Austria	0.29	0.17
10	Hungary	0.13	0.04
11	Czechia	0.35	0.13
12	Portugal	0.23	0.15
13	Sweden	0.29	0.24
14	Denmark	0.42	0.18
15	Romania	0.21	0.06
16	Bulgaria	0.13	0.10
17	Slovakia	0.21	0.06
18	Estonia	0.24	0.12
19	Finland	0.28	0.13
20	Slovenia	0.21	0.11
21	Luxembourg	0.22	0.10
22	Lithuania	0.31	0.20
23	Malta	0.14	0.13
24	Ireland	0.30	0.16
25	Croatia	0.16	0.05
26	Latvia	0.34	0.12

Supplementary Table 9. Projections for the unit capital expenditure ($/kW) of solar and wind energy installations used to assess the economic feasibility of different trajectories (Slow, Nominal, Fast) incorporating electrification potential, green hydrogen production, and carbon offsetting[24].

	Solar Capacity Expansion			Wind Capacity Expansion		
Year	Slow	Nominal	Fast	Slow	Nominal	Fast
2024	1,852.8	1,852.8	1,852.8	1,333.3	1,333.3	1,333.3
2025	1,826.1	1,731.3	1,665.0	1,323.4	1,268.3	1,244.3
2026	1,799.4	1,672.9	1,584.5	1,313.5	1,244.7	1,214.6
2027	1,772.7	1,614.6	1,504.1	1,303.6	1,221.0	1,184.9
2028	1,745.9	1,556.2	1,423.7	1,293.7	1,197.3	1,155.2
2029	1,719.2	1,497.9	1,343.2	1,283.9	1,173.7	1,125.6
2030	1,692.5	1,439.6	1,262.8	1,274.0	1,150.0	1,095.9
2031	1,665.8	1,381.2	1,182.4	1,265.4	1,138.7	1,083.6
2032	1,639.0	1,322.9	1,101.9	1,256.8	1,127.4	1,071.2
2033	1,612.3	1,264.5	1,021.5	1,248.2	1,116.0	1,058.9
2034	1,585.6	1,206.2	941.0	1,239.6	1,104.7	1,046.6
2035	1,558.8	1,147.8	860.6	1,231.0	1,093.4	1,034.3
2036	1,531.4	1,128.7	851.0	1,222.4	1,082.1	1,022.0
2037	1,504.0	1,109.5	841.4	1,213.8	1,070.7	1,009.7
2038	1,476.6	1,090.4	831.8	1,205.2	1,059.4	997.4
2039	1,449.2	1,071.2	822.2	1,196.6	1,048.1	985.0
2040	1,421.8	1,052.1	812.6	1,188.1	1,036.8	972.7
2041	1,394.4	1,032.9	803.1	1,179.5	1,025.4	960.4

2042	1,367.0	1,013.8	793.5	1,170.9	1,014.1	948.1
2043	1,339.6	994.6	783.9	1,162.3	1,002.8	935.8
2044	1,312.2	975.5	774.3	1,153.7	991.5	923.5
2045	1,284.8	956.3	764.7	1,145.1	980.1	911.1
2046	1,257.4	937.2	755.1	1,136.5	968.8	898.8
2047	1,230.0	918.0	745.5	1,127.9	957.5	886.5
2048	1,202.6	898.9	735.9	1,119.3	946.2	874.2
2049	1,175.2	879.7	726.3	1,110.7	934.9	861.9
2050	1,147.8	860.6	716.7	1,102.2	923.5	849.6

Supplementary Table 10. Projections for the unit operating expenditure ($/kW-yr) of solar and wind energy installations used to assess the economic feasibility of different trajectories (Slow, Nominal, Fast) incorporating electrification potential, green hydrogen production, and carbon offsetting[24].

	Solar Capacity Expansion			Wind Capacity Expansion		
Year	Slow	Nominal	Fast	Slow	Nominal	Fast
2024	18.6	18.6	18.6	29.8	29.8	29.8
2025	18.4	17.6	17.0	29.6	28.8	27.4
2026	18.2	17.1	16.4	29.4	28.5	26.6
2027	17.9	16.6	15.7	29.2	28.1	25.9
2028	17.7	16.1	15.0	29.0	27.7	25.2
2029	17.5	15.6	14.3	28.8	27.4	24.4
2030	17.3	15.1	13.7	28.7	27.0	23.7
2031	17.0	14.7	13.0	28.5	26.8	23.3
2032	16.8	14.2	12.3	28.4	26.6	22.9
2033	16.6	13.7	11.6	28.3	26.4	22.5
2034	16.4	13.2	11.0	28.2	26.3	22.1
2035	16.1	12.7	10.3	28.1	26.1	21.6
2036	15.9	12.5	10.2	28.0	25.9	21.2
2037	15.7	12.4	10.1	27.9	25.7	20.8
2038	15.5	12.2	10.1	27.8	25.5	20.4
2039	15.2	12.1	10.0	27.7	25.3	20.0
2040	15.0	11.9	9.9	27.6	25.2	19.6
2041	14.8	11.7	9.8	27.5	25.0	19.2
2042	14.5	11.6	9.7	27.4	24.8	18.8
2043	14.3	11.4	9.7	27.3	24.6	18.3
2044	14.1	11.3	9.6	27.2	24.4	17.9
2045	13.8	11.1	9.5	27.1	24.2	17.5
2046	13.6	10.9	9.4	27.0	24.0	17.1
2047	13.4	10.8	9.3	26.9	23.9	16.7
2048	13.2	10.6	9.2	26.8	23.7	16.3
2049	12.9	10.5	9.2	26.7	23.5	15.9
2050	12.7	10.3	9.1	26.6	23.3	15.5

Supplementary Table 11. Projections for the unit capital and operating expenditure for battery storage (ACb_n and $opfb_n$) and interface infrastructure (ACi_n and $opfi_n$) in the electrification strategy.

Year	ACb_n (\$/kWh)	$opfb_n$ (\$/kWh.a)	ACi_n (\$/kW)	$opfi_n$ (\$/kW.a)
2024	258.1	3.6	129.1	1.8
2025	227.6	3.4	113.8	1.7
2026	200.7	3.2	100.4	1.6
2027	177.0	3.0	88.6	1.5
2028	156.1	2.8	78.1	1.4
2029	137.6	2.6	68.9	1.3
2030	121.4	2.4	60.7	1.2
2031	117.0	2.4	58.3	1.2
2032	112.7	2.4	56.1	1.2
2033	108.6	2.3	53.9	1.2
2034	104.7	2.3	51.8	1.1
2035	100.9	2.3	49.8	1.1
2036	97.2	2.2	47.8	1.1
2037	93.7	2.2	46.0	1.1
2038	90.3	2.2	44.2	1.1
2039	87.0	2.1	42.5	1.0
2040	83.8	2.1	40.8	1.0
2041	82.0	2.1	40.0	1.0
2042	80.2	2.1	39.2	1.0
2043	78.5	2.0	38.4	1.0
2044	76.8	2.0	37.7	1.0
2045	75.1	2.0	36.9	1.0
2046	73.5	2.0	36.2	1.0
2047	71.9	2.0	35.4	1.0
2048	70.4	1.9	34.7	0.9
2049	68.8	1.9	34.0	0.9
2050	67.3	1.9	33.1	0.9

Supplementary Table 12. Projections for the capital cost of heat pumps ($AChp_n$), DAC (ACd_n), and electrolyzer infrastructure (ACe_n) used in the optimization modeling framework to assess the economic feasibility of the different strategies. The unit MW refers to the power input in respective equipment.

Year	$AChp_n$ (\$/MW)	ACd_n (\$/tCO_2)	ACe_n (\$/MW)
2024	300000.0	141.0	1097000
2025	299093.2	131.9	1067600
2026	298189.1	123.4	1038989
2027	297287.7	115.5	1011144
2028	296389.1	108.0	984045.2
2029	295493.2	101.1	957672.7
2030	294600	94.6	932007.1

2031	294364	94.1	894354
2032	294128.2	93.6	858222.1
2033	293892.6	93.1	823550
2034	293657.2	92.6	790278.5
2035	293421.9	92.1	758351.3
2036	293186.9	91.6	727713.9
2037	292952	91.1	698314.2
2038	292717.3	90.6	670102.4
2039	292482.8	90.1	643030.2
2040	292248.5	89.6	617051.8
2041	292014.4	89.1	606703.8
2042	291780.5	88.7	596529.4
2043	291546.8	88.2	586525.6
2044	291313.2	87.7	576689.6
2045	291079.9	87.2	567018.5
2046	290846.7	86.8	557509.6
2047	290613.7	86.3	548160.2
2048	290380.9	85.9	538967.5
2049	290148.3	85.4	529929
2050	289915.9	84.9	521042.1

Supplementary Table 13. Parameters used in the optimization modeling frameworks to assess the economic feasibility of the different scenarios incorporating electrification potential along with green hydrogen production and carbon offsetting.

Parameters	Value	Unit
ACdi[71]	141	$/tCO_2$
AChpi[72]	300,000	$/MW
bd[73]	0.044	-
bhp[73]	0.0146	-
bpng[35]	1.0	-
cd^{max}[58]	11,400	$kgCO_2$
cd^{min}[58]	0.0	$kgCO_2$
cfd[74]	0.04	-
cfe[75]	0.03	-
cfhp[72]	0.05	-
ckng[35]	1.0	-
cng[76]	0.181	$kgCO_2$/kWh
COP[77]	3.0	-
cpng[35]	1.20	-
CRF[78]	0.11	-
C^{SP}[79]	107	$/tCO_2$
cst[54]	10.75	$/tCO_2$
ctgng[35]	1.26	-
ctr[54]	5.17	$/tCO_2$
df[80]	1.72	$kgCO_2$/kWh
dfr[80]	3.4	-

Parameters	Value	Unit
dr[78]	0.1	-
eng[60]	2.0	-
$ftgng$[35]	1.40	-
$gpng$[35]	1.0	-
H_2^{SP}[34]	7.59	\$/kg H_2
hng[61]	1.204	-
$htng$[60]	2.20	-
$isng$[35]	1.69	-
$lbng$[35]	1.0	-
LHV[81]	33.33	kWh/kg H_2
$nfng$[35]	1.10	-
NY[82]	25	
Pe^{max}[74]	1,000	kWh
Pe^{min}[74]	0.0	kWh
ph^{max}[74]	1,000	kWh
ph^{min}[74]	0.0	kWh
rep^{bcp}[64]	2.0	-
rep^{hpc}[72]	2.0	-
rep^{hpe}[72]	2.0	-
rep^{icp}[64]	2.0	-
$rfng$[35]	0.93	-
rng[60]	4.18	-
sb[83]	0.571	-
sd[83]	0.0	-
se[83]	0.27	-
shp[83]	0.571	-
snt[83]	0.571	-
sr[83]	0.0	-
str[83]	0.032	-
$tpng$[35]	1.0	-
μ^{PV}[84]	0.1662	-
η^{ELE}[74]	0.68	-

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