nature portfolio

Peer Review File

Aligning EU Energy Security and Climate Mitigation through Targeted Transition Strategies

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The research addresses the intertwined challenges of the climate crisis and energy security in the EU, exacerbated by geopolitical disturbances and the region's dependence on imported energy. It proposes a novel energy modeling framework to explore strategic scenarios for achieving energy resilience and climate sustainability through the expansion of renewable energy capacities, green hydrogen infrastructure, and carbon offset technologies. The findings emphasize the need for targeted policies, such as incentivizing renewable energy expansion and leveraging carbon credits, to bolster the EU's energy security while aligning with its ambitious decarbonization goals.

The study lacking the follwoing comments before publishing:
1-Provide a detailed explanation of the novel energy modeling framework, including its components, methodologies, and unique contributions compared to existing models.

2-Clearly specify the sources of data used for energy capacity, natural gas consumption, and economic implications to enhance credibility and reproducibility.

3-Expand on the assumptions and variables considered in the future scenarios, such as geopolitical factors, economic growth rates, and technology adoption timelines.

4-Strengthen the discussion on policy implications by suggesting specific mechanisms for incentivizing renewable energy and green hydrogen deployment.

5-Elaborate on the economic implications of transitioning to renewable energy and green hydrogen, addressing potential costs and benefits for stakeholders across the EU.

6-Provide a more detailed discussion on the design and implementation of carbon credit systems and their role in decarbonization strategies.

7-Address how the proposed strategies align with equity objectives, particularly in ensuring affordable energy access for all EU member states.

8-Compare the potential outcomes of the proposed strategies with alternative energy pathways to justify the recommended approach.

9-Discuss how uncertainties in geopolitical or technological developments are addressed within the modeling framework.

10- Include graphs or charts to illustrate the reduction in natural gas consumption, expansion of renewable capacities, and potential climate benefits under different scenarios.

Reviewer #2

(Remarks to the Author)

Key Results

The manuscript presents an impressive energy modeling study that integrates scenario building and optimization techniques to assess economic implications. The modeling work adds to the existing body of knowledge, distinguishing itself from prior studies through its unique specifications, scope, and results. The findings provide valuable insights into energy system transformations, with potential implications for policy and economic decision-making. The study demonstrates that an accelerated deployment of solar and wind capacity, electrification of consumption, investments in green hydrogen for heavy industry, and direct air capture are economically feasible in the EU.

Validity

While the modeling framework appears robust, I do not have the necessary expertise to assess the soundness of the model itself.

Significance

The research contributes meaningfully to energy transition modeling and economic assessments. However, its broader claims regarding geopolitical and climate mitigation contributions are rather superficial. While the results are relevant to ongoing discussions about EU energy security and emissions reduction strategies, the paper does not provide enough depth in geopolitical analysis or climate mitigation to substantiate this as a significant contribution. The novelty lies primarily in the modeling approach rather than in geopolitical or climate policy insights.
More modest goals would improve the paper. The paper shows interesting results from a novel modelling exercise – this is valuable enough – it does not need to make claims about geopolitics or climate mitigation. Simply mentioning once that the results of the paper will be relevant in the context of the EU trying to reduce reliance on gas imports while keeping its climate targets on track should suffice.

Data and Methodology

The methodological approach seems sound, and the data presentation is comprehensive in the ample supplementary material.

Analytical Approach

The analytical rigor of the modeling exercise appears strong, but the broader discussions on geopolitics and climate mitigation are not fully developed. The statistical and scenario-based analyses are well-structured, yet the claims about broader policy implications should be either developer or (preferably) pruned. If the authors wish to include policy discussions, they should provide a more in-depth analysis rather than high-level statements.

Suggested Improvements

Refocus the scope – The paper currently attempts to contribute to multiple distinct areas, including geopolitics and climate mitigation, but does not provide sufficient depth in these domains. A more modest and focused objective centered on the modeling exercise itself would strengthen the manuscript.
Concise framing of geopolitical discussion – The discussion on EU geopolitics is superficial. Key missing elements include internal gas production, the potential shifts in US LNG exports post-November 2024, and the complexities in defining 'allies.'
Reduce length and repetition – The manuscript is unnecessarily long and at times repetitive, particularly in discussions on geopolitics and climate mitigation. Streamlining the text would enhance readability and focus.
Clarify terminology – The term 'offsetting' is used in a way that differs from its conventional meaning in emissions trading. The authors should align this term with standard usage or provide a clear definition.
Update discussion points – Certain statements in the discussion section undermine the strength of the modeling work, either due to outdated claims or overly optimistic assertions:
Outdated: The role of targeted subsidies and feed-in tariffs has been well-established for over a decade; revising this statement to reflect current policy dynamics would be beneficial.
Wishful thinking: The assertion that fostering symbiotic relationships with supplier countries will enable green energy transitions is an idealized perspective that has proven difficult to achieve in practice.
Inaccurate: The manuscript refers to 'international agreements such as COP28,' but the COP is a decision-making body, not an international agreement. This should be corrected.

Clarity and Context
The paper's clarity can be improved by streamlining discussions and avoiding redundant explanations. The results should be contextualized appropriately, avoiding overstated or oversimplified claims about geopolitical or climate policy contributions. A brief mention of how the findings relate to EU energy security and climate targets should suffice, without making it a central claim.

References

The manuscript appropriately cites prior modeling exercises

Reviewer's Expertise

I do not have the necessary expertise to evaluate the technical soundness of the energy model itself. My assessment focuses on the clarity, relevance, and contextual framing of the paper's claims.

In conclusion, the manuscript presents valuable modeling work that contributes meaningfully to energy economics. However, its broader claims on geopolitics and climate mitigation should either be substantiated or simplified, and the discussion should be more concise and precise. Refining the focus to highlight the novelty of the modeling approach while streamlining extraneous discussions would significantly improve the manuscript.

Reviewer #3

(Remarks to the Author)
The paper presents a comprehensive study with valuable insights into energy planning within the European Union. However, after review, I consider the paper requires revisions before it can be accepted for publication. My feedback is as follows:

1. Terminology Consistency: The terms energy autonomy, energy resilience, and energy security are used interchangeably throughout the paper. While they share common elements, they have distinct meanings in the given context. I recommend selecting a single definition and ensuring consistency in its usage throughout the paper. This is particularly important for the title, where energy autonomy is used, despite energy security being the more frequently discussed term.

2. Title Re-evaluation: I consider energy security is more widely used than energy autonomy. Additionally, the term decarbonization potential appears to refer to cumulative emissions, but this could be misleading. The figure of 20.1 $GtCO_2$ is presented, yet it is unclear whether this refers to CO_2 emissions only or CO_2 equivalent. Moreover, this number is not referenced later in the manuscript.

3. Literature Review and Research Gap: The introduction does not sufficiently demonstrate a literature review identifying the research gap. It should explicitly state how this methodology is novel compared to previous studies using similar scenario analysis and optimization frameworks, such as TIMES, MESSAGE, OSeMOSYS, PyPSA, or Calliope.

4. Scenario Definition: The paper conceptualizes three scenarios (BAU, PARTIAL, and FULL), but later presents six scenarios in the graphs (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, FULL-wind). Please clarify this distinction in the introduction to enhance understanding.

5. Presentation of Results: The results for the PARTIAL scenario are barely discussed. While it represents an intermediate state between BAU and FULL, it still requires analysis to justify its inclusion. Otherwise, its purpose in the study remains unclear.

6. Clarification of a Key Variable: The variable Reduction in natural gas reliance (%) in the EU needs further explanation. For example, does this metric refer to the reduction in final energy consumption of imported natural gas as a proportion of total energy consumption?

7. Energy Security Considerations: The paper suggests that increased renewable energy deployment enhances energy security. However, no data is provided on the operational flexibility of the power system. Higher shares of renewables introduce challenges in ensuring adequacy and reliability. What specific definition of energy security is being used in this context?

8. Reference Energy System: Please provide details on the reference energy system implemented in the model. It would be helpful to understand how different sectors are modeled. For example: Is green hydrogen production based on dedicated projects, grid connection, or both? How is the road transport sector modeled? Are natural gas, gasoline, diesel, electricity, and hydrogen competing within each segment (passenger cars, two-wheelers, buses, trucks, etc.)?

9. Regional Trade Considerations: Since this is a multi-node model, a discussion on intra-regional trade potential within the EU would be valuable. The paper briefly mentions international trade outside the EU but does not explore integration opportunities within the union.

10. Supplementary Material Navigation: The supplementary material would benefit from a table of contents, table of figures, and table of tables, as it contains extensive information that is difficult to navigate.

11. Data and Code Availability: The manuscript lacks a clear statement on data availability and code availability. Including this information is essential for ensuring transparency and reproducibility, which would strengthen the study's credibility and prevent criticism related to limited accessibility.

Reviewer #4

(Remarks to the Author)
Review
Transforming the EU Energy Landscape to Align Climate Mitigation with Energy Autonomy Can Achieve Decarbonization

Potential of 20.1 $GtCO_2$ through 2050

The manuscript deals with an interesting topic. It is well written and the methods chosen are common for solving such problems. However, the manuscript does not clearly explain the novelty of the analysis performed. Several publications (scientific and technical reports) have already analysed possible paths of the energy transition and also pointed out security issues and dependencies (on energy and technology imports). From this perspective, it cannot be recognised that the present study has a high degree of novelty in the scientific literature (although I personally agree with most of the results). Therefore, in my view, the study is not ready for publication in Nature Communications.
Some more detailed comments on individual points of the manuscript:

Regarding Introduction
In general, the introduction is well written. The literature review needs to be improved, especially focussing on studies on energy security and energy dependency and the energy transition model in Europe in general. The introduction lacks the emphasis on novelty and the clear formulation of the research question and the aim of the proposed work.

Regarding Fig. 2:
The term "current" is somehow misleading. What is exactly analysed? Is it the current LCOE or the LCOE in 2050 under current policy? If it is the current LCOE, why values in a) and b) are different? Does this LCOE include all generation technologies or only solar PV and wind, respectively? Please explain this and improve the description of the figure.
Please explain your higher LCOE compared to other studies. For instance, you show current LCOE for solar PV in Germany of 0.17 /kWh and for 2050 a value of 0.07 $/kWh. This values are way higher than of other studies like in
• https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html,
• https://www.statista.com/statistics/1110938/eu-countries-solar-power-price/,
• https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3659, or
• https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023

Regarding Fig. S56:
The analysed pathways are highly simplified. Indeed, in the industries summarised under "heavy industries" various technological pathways for direct electrification exist or are under development (and thus maybe available until 2050) (see e.g. doi.org/10.1016/j.energy.2016.07.110).In the categorisation, also a more distinguished categorisation could be helpful. For instance: steel processing industry may have currently a high natural gas consumption due to furnaces, but these could be electrified via resistance heating (fully or partly). Same should be discussed also for other sectors. Besides technological pathways, also efficiency gains, changing production chains and markets as well as flexibility options in production should be mentioned and discussed as these drivers will change the energy demand for natural gas and hydrogen, respectively.

Regarding "Energy Security"
It is well noticed that the manuscript aims to focus on this important issue. However, it is not seen that any common or novel measurement for "dependency" and "security" rather than demand and costs are considered. Here, the manuscript needs to be improved to cover a broader understanding of these terms.

Regarding Discussion
The discussion is generally well written. In-line with the comments on other parts: Novelty of the findings is not well explained. In some cases, comparison with existing literature is done but this should be improved and extended. Some statements are general and findings in the result sections should be involved more. Also, limitations of the examined study need to be pointed out and discussed here.

Regarding Methods
All methods are briefly described in the main text. Additional information is given in supplementary material. The chosen approach is well suitable for the problem addressed and commonly used in scientific and technical reports on energy transition. It could be beneficial to add additional figures in the main text on important issues like the overall modelling framework and the analysed scenarios. Also here: The choice of e.g. the optimisation framework should be explained in more detail. It should be explained why this approach instead of widely used modelling frameworks (e.g. PyPSA Europe) is taken. Also, novel aspects of the chosen approach should be highlighted.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The revised version addressed my comments adequately.

The paper now focuses more on its valuable contribution - a new model trying to explore and evaluate the feasibility of pathways to reducing natural gas imports through accelerated deployment of renewables and electrification (and the implications on DAC). The framing is also more believable. We assume that reduction in natural gas imports represents a policy objective of the EU (because of the recent shocks resulting from geopolitical evolutions) and we assume reductions in CO2 emissions are also desirable. As such, the relevance of the question and of the implications are guaranteed, so we proceed to demonstrating possible pathways using the data and the model.

I still have a few observations to make.

At page 4: 'Previous studies also examine the European energy transition using modeling frameworks (...) without directly addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions'

This does not sound like a credible justification of the novelty. If this were true, you could simply use their results and argue they are relevant for the 'strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions'. In my view, the novelty of your work consists of the new model, new data that yield new results. The results are relevant because reducing imports and consumption of natural gas in the EU are an explicit policy goal due to the recent geopolitical experience and the imperative of mitigating climate change. This is already strong enough.

At page 5: 'seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation'
Again, that does not sound like what this paper is doing. Indeed, the results of your study can be relevant for this matter, but the matter itself is much more complex than that. It is absolutely fine for the paper not to go into all the complexities of the energy security - climate change nexus, so it does not have to make bold claims about it. For example, the issue of dependency on critical minerals, dominance of China in batteries and PV modules, and many other issues need to be addressed for an adequate treatment of energy security - climate mitigation.

At page 26:
- The discussion of carbon credits is a bit superficial. It is not clear what type of credits they are, who would be the buyers, it makes it seem like this has no cost implications for anyone, which is obviously impossible. This should either be elaborated or eliminated.
- The implied message that fossil fuel consumption is the primary root cause of expensive energy and that reducing fossil fuel consumption ensures affordable energy access is weak. This depends on many other factors including the actual price of fossil fuel (which may become lower as demand is reduced), the cost of capital (highly relevant for renewables), the market for clean technologies, the cost of transmission and distribution, etc. The hyper-simplified message is more fitting for a political statement than a research article. I suggest qualifying it or eliminating it.

The required changes are just nuances, but relevant nuances for the overall quality and robustness of this valuable piece.

Reviewer #4

(Remarks to the Author)
Dear Authors,
thank you for your revised manuscript and the detailed responses. In my opinion, the revised literature review is well done. It sets the frame for the submitted manuscript. However, it also shows that many exisiting reports deal with similar topics and thus the novelty is not very high but still ok.
With regard to the economic parameters - such as used for calculating LCOE - the response and the revised SI file clarify some assumptions. However, there are several further uncertainties that are not reflected and the presentation of results could have been done with regard to uncertainties, i.e. representing ranges instead of absolut values.

Version 2:

Reviewer comments:

Reviewer #4

(Remarks to the Author)
The revised manuscript looks good to me and seems ready for publication. I have no further comments.

Aligning EU Energy Security and Climate Mitigation through Targeted Transition Strategies

Apoorv Lal, Massimo Tavoni, Nathan Preuss, Fengqi You

Response to reviewers and actions taken

Reviewer 1

The research addresses the intertwined challenges of the climate crisis and energy security in the EU, exacerbated by geopolitical disturbances and the region's dependence on imported energy. It proposes a novel energy modeling framework to explore strategic scenarios for achieving energy resilience and climate sustainability through the expansion of renewable energy capacities, green hydrogen infrastructure, and carbon offset technologies. The findings emphasize the need for targeted policies, such as incentivizing renewable energy expansion and leveraging carbon credits, to bolster the EU's energy security while aligning with its ambitious decarbonization goals.

Reviewer's Comment (1)

The study lacking the follwoing comments before publishing:

1-Provide a detailed explanation of the novel energy modeling framework, including its components, methodologies, and unique contributions compared to existing models.

Answer: Thanks for the comment. We agree with the reviewer's feedback to highlight the unique contributions and provide a detailed explanation of the novel energy modeling framework. In the revised Introduction section, we establish the knowledge gap addressed in this work compared to existing assessments and outline the novel contributions through a set of bullet points. To further contextualize these contributions, Table S1 presents a comparative summary of key focus areas, insights from prior literature, and the corresponding contributions of this study. Additionally, the revised Systems Analysis Framework section in the main file describes the framework's components and methodologies.

Action

- *On pages 3 and 4 of the revised main file:*

"Empirical assessments demonstrate that renewable energy deployment can act as a substitute for energy imports, with various EU countries exhibiting improved efficiency and productivity through technological innovation and convergence toward renewable energy and

energy security goals[16]. Tracking the evolution of energy security indicators reveals that diversification of primary energy sources, along with the share and diversity of energy imports, are key drivers of improvement, with regional cluster analysis highlighting transferable policy insights[17]. Complementary assessments further suggest that sufficiency measures can substantially reduce final energy demand and alleviate pressure on supply-side interventions by 2050[18]. These insights are reinforced by policy mechanisms such as REPowerEU 2030[19, 20], and the recently announced targets for 2040[21], which collectively signal a strategic pivot toward renewable energy across electricity, heating, and transportation to reduce natural gas dependence. Nonetheless, recent setbacks in global emissions reduction efforts[22, 23] and reduced accessibility to affordable energy in the EU[24] reveal the susceptibilities in pre-conflict energy and climate strategies, indicating the need for scenario-based frameworks that align energy security improvements with climate mitigation, using reductions in natural gas consumption as a central metric across diverse renewable deployment pathways.

Previous studies also examine the European energy transition using modeling frameworks based on least-cost optimization to determine energy system configurations[25, 26, 27], or offer insights at the transmission network level[28]. These analyses outline the diversity of feasible system designs[29], foster communication across societal levels[30], generate high-level insights for multi-sector system integration[31], and investigate grid constraints[32]. Some assessments also focus on individual energy pathways[33, 34], or region-specific crisis responses[2], without directly addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions. Within this broader transition landscape, sectors that are difficult to electrify, such as heavy industries, require complementary technological pathways. Green hydrogen emerges as a promising vector for advancing energy transition and climate mitigation goals[35, 36], supported by the expansion of renewable capacity and offering a critical alternative to natural gas in heavy industries[37, 38, 39]. Recent literature highlights the importance of competitive and secure renewable hydrogen to minimize reliance on single suppliers[40]. Regional assessments further underscore the role of hydrogen infrastructure during the energy crisis[41], the feasibility of substituting carbon-intensive hydrogen production with renewable-based electrolysis[42], and the potential of hydrogen and power-to-liquid pathways to reduce energy-related import costs[43]. Additionally, studies emphasize the role of hydrogen in decarbonizing the European energy system, with projections of substantial hydrogen production by 2050[44, 45]. However, these opportunities require careful policy choices to *avoid perpetuating long-standing vulnerabilities*[46]*. These insights reinforce the need for sector-disaggregated analysis aimed at reducing natural gas consumption and emissions through targeted interventions, evaluated across diverse cost trajectories, to advance EU-wide energy security and decarbonization outcomes.*

While previous studies provide valuable perspectives, also summarized in Table S1 for comparative reference, this work seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation in the EU energy landscape, with the following novel contributions:

- *Develops a comprehensive scenario-based assessment centered on renewable expansion pathways and incorporating targeted strategies, including electrification, green hydrogen deployment, and carbon offsetting, to align the EU's dual goals of energy security and climate sustainability amidst geopolitical disruptions.*
- *Introduces a sector-disaggregated framework targeting reductions in natural gas consumption and emissions across electricity and heating, light and heavy industries, and transportation, capturing the differentiated impacts of transition strategies across spatial and temporal horizons in the EU.*
- *Establishes a robust analytical framework to evaluate the economic feasibility of targeted interventions, incorporating a comprehensive spectrum of technology cost trajectories informed by historical learning rates under varying renewable expansion scenarios.*

- *On pages 24 to 27 of the revised main file:*

"In this work, we utilize a novel energy systems modeling framework, depicted in ***Fig. 5****, to strategically enhance EU energy security while supporting climate mitigation efforts amid the evolving geopolitical landscape. While previously used frameworks such as TIMES*[25]*, MESSAGE*[26]*, OSeMOSYS*[118]*, Calliope*[119]*, and PyPSA-Eur*[120]*, provide valuable insights into least-cost energy system configurations, operational dispatch modeling, and transmission network representation, these approaches do not directly address the strategic urgency of energy security concerns tied to natural gas dependence amidst geopolitical disruptions. For instance, these frameworks estimate the energy system configurations that minimize cost based on energy service demands projected from macroeconomic indicators such as population or GDP*[28, 121]*. However, a targeted emphasis on sector-specific natural gas reduction, a critical dimension exposed by recent*

geopolitical disruptions and essential for aligning energy security and climate mitigation goals[122, 123], remains largely unexplored. Addressing this gap, the proposed framework integrates a detailed scenario design, driven by renewable capacity expansion, with an optimization modeling framework to enable a holistic evaluation of how policy-driven interventions and technological advancements can shape the EU's ability to decarbonize and secure its energy supply.

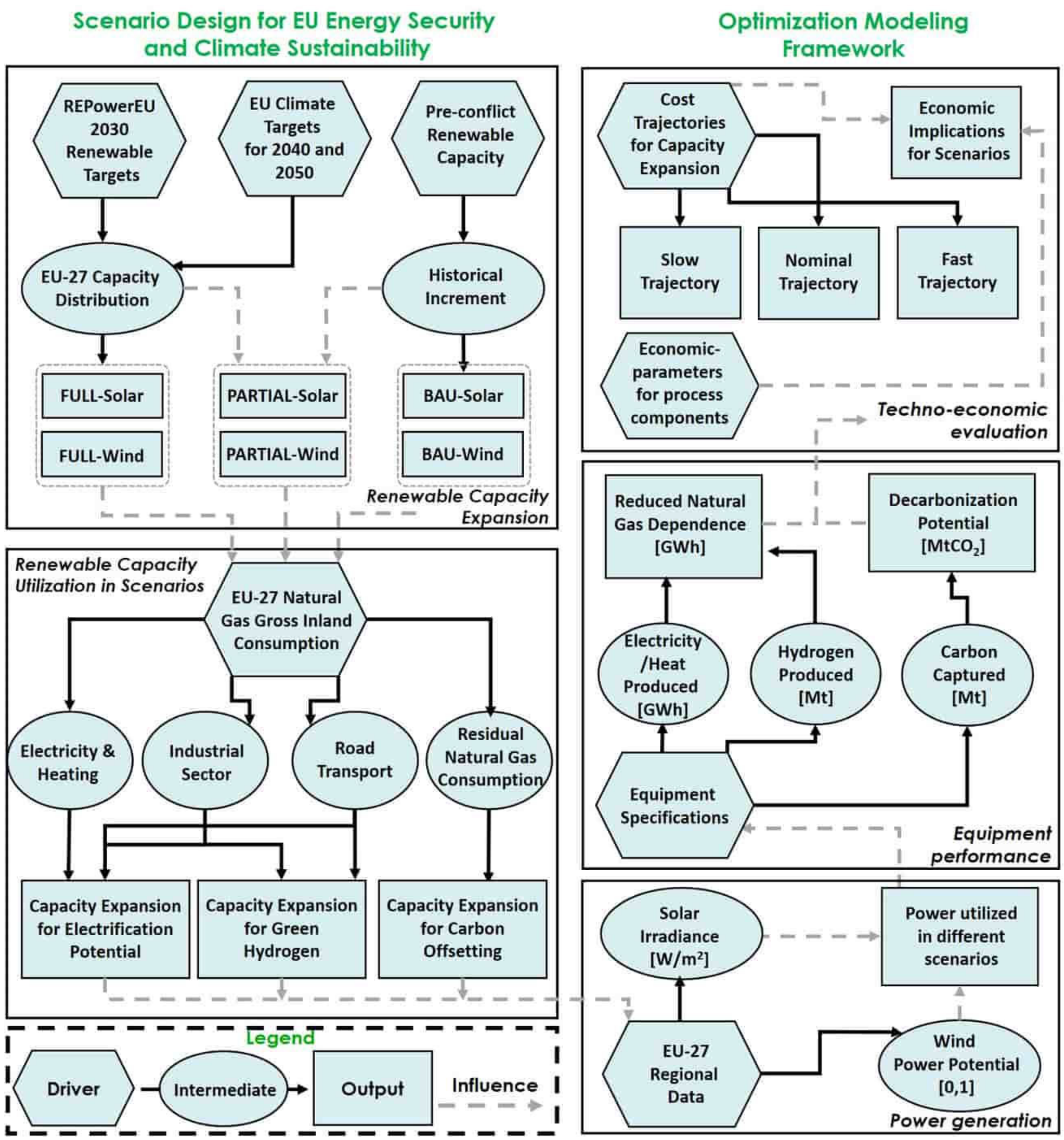

Fig. 5. *Schematic representation of the methodological framework used in the study. Note: hexagons indicate drivers and determinants, ovals with solid lines denote intermediate values,*

rectangles represent outputs, and dashed lines with arrows denote influences between two variables. EU: European Union, BAU: Business-as-usual.

*The scenario design in this work leverages the expansion of solar and wind power capacities, recognizing their increasing importance for strengthening energy security in response to geopolitical disruptions[20, 48], and for achieving climate targets[49]. These scenarios span a comprehensive spectrum of renewable energy growth trajectories, from business-as-usual increments based on historical trends to ambitious expansion aligned with policy momentum, enabling structured comparisons across varying levels of deployment. Within this framework, the systematic evaluation of strategic interventions, including electrification, green hydrogen production, and carbon offsetting, directly supports the EU's dual goals of reducing natural gas dependency and long-term climate mitigation. To reflect the diverse energy needs across the EU, the analysis incorporates the distribution of gross inland consumption of natural gas across key sectors, including electricity and heating, the industrial sector (light and heavy industries), road transportation, and residual uses. This sector-specific breakdown forms the foundation for targeted renewable capacity utilization in each scenario, ensuring that deployment strategies are guided by demand characteristics (**Figs. S61** and **S62**) rather than purely cost-optimization. By capturing these differentiated sectoral pathways, the scenario framework provides policy-relevant insights into how renewable-driven strategies can collectively advance energy security and emissions mitigation across the EU.*

Building upon this scenario design, this work employs an economic optimization paradigm, as used in previous studies[124, 125, 126, 127, 128], which maximizes the net present value (NPV) of targeted strategies, including electrification, green hydrogen deployment, and carbon offsetting, implemented in alignment with renewable capacity expansion. This approach enables a structured evaluation of how the economic feasibility of each scenario evolves alongside its decarbonization potential and contribution to energy security. In order to incorporate spatial characteristics, the framework integrates regional data for solar irradiance and wind power potential to assess renewable energy installations across different EU countries. Detailed equipment specifications, such as battery storage and interface capacities for electricity supply, heat pumps for thermal end uses, electrolyzers for green hydrogen production, and DAC systems for carbon removal, are embedded to estimate deployment needs across strategies. To account for future uncertainties in *technology costs, the framework includes projections for improvements in the cost-effectiveness of renewable installations under distinct trajectories*[59]*. In addition, it captures evolving cost-competitiveness for other infrastructure components based on the learning rate method*[129] *and established benchmarks from the previous literature*[112, 130]*. This approach enables a detailed evaluation of how technological advancements can influence the economic feasibility of each scenario.*

Therefore, by incorporating scenario-specific assumptions on renewable capacity expansion, regional data for sector-specific natural gas consumption, and future-oriented economic assessments, the proposed framework provides a comprehensive basis for evaluating EU energy security and climate mitigation strategies. This approach enables the temporal and spatial assessment of natural gas reduction potential, emissions mitigation, and the cost-effectiveness of electrification, hydrogen deployment, and carbon offsetting strategies across diverse sectors and regional contexts."

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- *On page 50 of the revised SI file:*

Table S1. *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.*

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Reviewer's Comment (2)

2-Clearly specify the sources of data used for energy capacity, natural gas consumption, and economic implications to enhance credibility and reproducibility.

Answer: Thanks for the comment. Following the reviewer's feedback, we have revised the Data Collection and Sources section in the main file to specify the datasets used. Additionally, supplementary tables have been included in the SI file to improve clarity and illustrate the underlying inputs.

Action

- *On page 23 of the revised main file:*

"In order to ensure the robustness of the energy systems modeling framework used in this work, comprehensive data sources were utilized throughout the analysis. The scenarios for renewable capacity expansion were designed to reflect both ambitious policy benchmarks and historical trends. Specifically, renewable capacity benchmarks for 2030, modeled under the REPowerEU initiative by the European Commission[19, 20], were used to establish the ambitious targets for solar and wind power deployment. Capacity projections for 2040 and 2050 were based on policy targets outlined in documentation from the European Commission[21], aligning with the EU's long-term climate goals. For historical trends, trajectories for solar and wind power capacities were derived from the database by IRENA[99]. To evaluate economic implications across scenarios, cost trajectories for solar and wind power installations were obtained from the Annual Technology Baseline by the National Renewable Energy Laboratory[59]. Moreover, sector-specific natural gas consumption and import dependency across EU countries were obtained from Eurostat[100] to support the assessment of electrification, hydrogen deployment, and carbon offsetting strategies. The electricity demands for EU countries at future time horizons were taken from previous literature[101], while the hourly load profiles were sourced from the European Network of Transmission System Operators for Electricity[102].

As part of the electrification strategy, the electricity and natural gas prices were obtained from Eurostat[103, 104]. Hydrogen consumption data and the corresponding natural gas requirements across various industrial sectors were gathered from the European Hydrogen Observatory[105, 106]. Data on the repurposed hydrogen pipeline infrastructure across EU countries was derived from the Europe Gas Tracker[107] and the European Hydrogen Backbone[108], enabling spatially resolved assessments of hydrogen transport requirements. In addition, local CO_2 storage capacities were *obtained from the EU GeoCapacity documentation by the European Commission*[109] *to support the carbon offsetting strategy. Lastly, detailed equipment specifications*[110, 111, 112, 113] *and cost components*[114, 115, 116, 117] *for electrolyzers, heat pumps, battery storage, and DAC infrastructure were included to comprehensively evaluate the economic implications of sector-specific interventions for energy security and climate mitigation across the EU."*

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- *On pages 127 to 132 of the revised SI file:*

Table S7. 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

Table S8. 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

Table S9. 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

Table S10. 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*

Table S11. 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

Table S12. 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

Table S13. 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	-
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	-

Parameters	Value	Unit
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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Reviewer's Comment (3)

3-Expand on the assumptions and variables considered in the future scenarios, such as geopolitical factors, economic growth rates, and technology adoption timelines.

Answer: Thanks for the comment. We agree with the reviewer's feedback to expand on the assumptions and variables considered in future scenarios. In the SI file, we have updated the scenario design section and included details on policy drivers, deployment timelines, economic growth considerations, and sectoral configurations reflected in the reference energy system.

Action

- *On pages 83 to 88 of the revised SI file:*

*"**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. Table S2 summarizes the strategic scenarios and cost trajectories considered in this analysis.

Table S2. 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].

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. ***Fig. S61*** *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.*

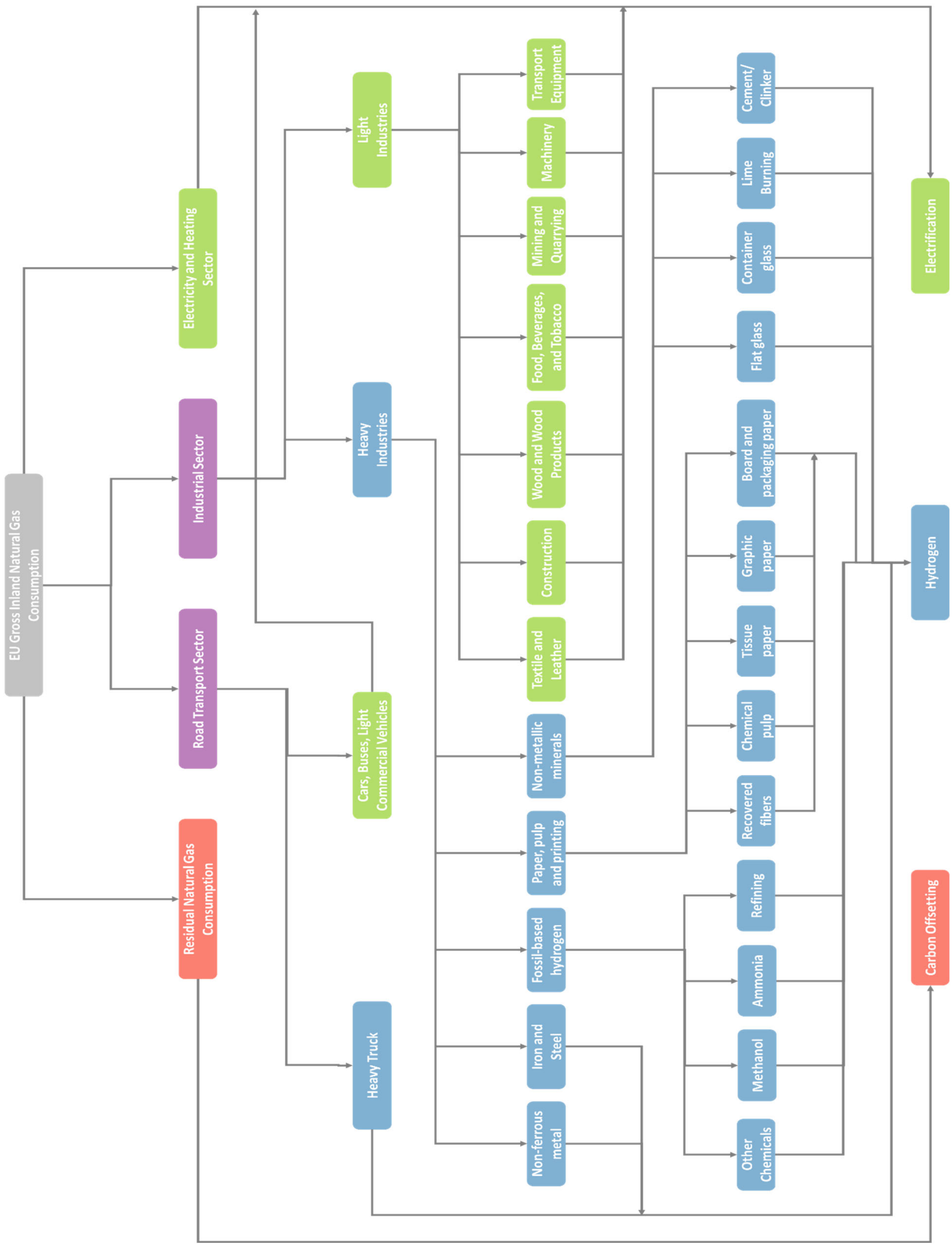

Fig. S61. *Schematic representation of sector-specific natural gas consumption across the EU, serving as the analytical basis for linking renewable capacity deployment with tailored* *decarbonization strategies. The sectors are color-coded according to their corresponding intervention pathways: green 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, Table S3 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.

Table S3. 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 the 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."*

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Reviewer's Comment (4) and (5)

4-Strengthen the discussion on policy implications by suggesting specific mechanisms for incentivizing renewable energy and green hydrogen deployment.

5-Elaborate on the economic implications of transitioning to renewable energy and green hydrogen, addressing potential costs and benefits for stakeholders across the EU.

Answer: Thanks for the comment. In the revised manuscript, we have strengthened the policy discussion by illustrating how sector-informed incentive design can guide natural gas displacement across EU member states through clean energy electrification and green hydrogen deployment. The revised discussion also highlights how differentiated policy instruments, aligned with evolving cost trajectories, can support affordable transition pathways and offer a strategic roadmap for stakeholders.

Action

- *On pages 17 to 18 of the revised main file:*

"In light of the recent geopolitical tensions and the pressing need for robust policy measures, this work offers a novel strategic perspective by targeting sector-specific reductions in natural gas consumption as a central metric to align energy security with climate goals. The proposed scenario framework demonstrates how strategic interventions, such as electrification and green hydrogen utilization, can be tailored to natural gas consumption profiles across EU member states, enabling a more targeted approach to prevent conflict-induced energy crises that lead to heightened consumer prices[60] and increased public expenditure to protect vulnerable populations from the resulting impact[61]. Achieving the REPowerEU 2030 policy targets[19, 20] is a critical step in this direction, supported by recent progress in expediting renewable energy permitting[62] and the establishment of industrial alliances[63]. In this context, the results from the FULL scenarios for solar and wind power expansion, aligned with these targets, indicate the potential to reduce gross inland natural gas consumption through electrification by up to 32.8% in 2030 and 50.9% by 2050. This reduction translates to sector-specific declines of 75.9%, 67.4%, and 68.6% in the electricity and heating, industrial, and road transportation sectors, respectively, by 2050. These insights suggest that renewable energy incentives should be designed as sector-informed mechanisms that account for differences in deployment needs, such as grid integration support[64] and dedicated schemes for clean industrial clusters[65], aligning with the EU strategy for energy system integration which emphasizes greater electrification of end-use sectors[66]. Similarly, green

hydrogen can play a critical role in reducing natural gas reliance in hard-to-abate sectors such as heavy industries. Results from the FULL capacity expansion scenarios indicate that green hydrogen deployment can avoid up to 10.3% of gross inland natural gas consumption and yield cumulative emissions reductions exceeding 947.5 $MtCO_2$ by 2050. By evaluating this potential at a spatial and sectoral level, this analysis underscores the strategic relevance of EU hydrogen initiatives[67] which support the development of electrolyzer capacity, and distribution infrastructure and facilitate industrial uptake of green hydrogen across member states[68]. Moreover, given the differentiated and essential role of green hydrogen revealed through scenario-based analysis, sector-specific Contracts for Difference[69, 70] can serve as targeted policy instruments to ensure deployment certainty and alignment with energy security and decarbonization objectives.

Over the years, technological advancements have improved the cost-effectiveness of renewable power generation[71, 72] and green hydrogen production[73, 74], which play a pivotal role in reducing fossil fuel use[75, 76]. The analysis demonstrates that under the FULL implementation scenario, targeted to reduce sectoral natural gas consumption across the EU, the annual total cost of electrification in 2050 can be reduced by up to 19.9% and 13.7% for solar and wind power installations, respectively, when comparing fast and slow cost-reduction trajectories. This finding underscores the importance of continued learning in lowering the total cost of transition. Furthermore, the LCOE shows a projected decline of up to 61.5% and 46.2%, and the LCOH by up to 60.2% and 41.3%, for solar and wind power respectively by 2050 across EU member states, with pronounced regional variation, highlighting that uniform incentive schemes may lead to misallocated support and reinforcing the need for regionally differentiated policy measures. Similarly, the annual total hydrogen production costs vary from $7.3 bn to $49.5 bn across the investigated scenarios in 2050, providing an indicative cost range that can inform strategic planning for industrial stakeholders in hard-to-abate sectors. As such, the economic implications of this transition offer scenario-based insights across stakeholder groups, enabling policymakers to align support instruments with sectoral and temporal differences in natural gas substitution potential across regions, while allowing industrial actors to evaluate the competitiveness of electrification and hydrogen deployment under varying cost trajectories. However, the realization of these cost benefits also hinges on policy measures that ensure infrastructure and supply chain readiness, such as mitigating potential bottlenecks in the availability of key solar and wind power *components. Thus, further government incentives focusing on research and development*[77] *and advanced manufacturing and installation processes that reduce "soft costs"*[78] *may be necessary to ensure adequate supply and accelerate cost reductions in wind and solar power expansion."*

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Reviewer's Comment (6) and (7)

6-Provide a more detailed discussion on the design and implementation of carbon credit systems and their role in decarbonization strategies.

7-Address how the proposed strategies align with equity objectives, particularly in ensuring affordable energy access for all EU member states.

Answer: Thanks for the comment. We agree with the reviewer's feedback to provide a more detailed discussion on the design and role of carbon credit systems, as well as the alignment of proposed strategies with equity objectives. In the revised manuscript, we have expanded the main text to illustrate how avoided emissions from scenario-driven, sector-specific strategies can serve as a basis for credit issuance, with implementation benchmarked against EU Emissions Trading System (ETS) reduction thresholds and supported by results in Fig. S22. We contextualize this design within the broader policy impetus that frames climate finance mechanisms as critical enablers of climate action (UNFCCC, 2023), particularly in supporting the affordability of clean energy transitions. Moreover, we address how the proposed strategies align with equity objectives through the progressive reduction of exposure to volatile fossil fuel markets, which have driven sharp increases in energy costs during recent geopolitical disruptions (Guan et al., 2023; Zhao et al., 2023). In doing so, the proposed strategies target a primary root cause, natural gas dependence, rather than relying on reactive compensatory mechanisms to ensure affordable energy access (IMF, 2022; World Economic Forum, 2022).

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Action

- *On page 19 of the revised main file:*

"While natural gas is often viewed as a transition fuel used to maintain energy systems as renewables are brought online[79], recent geopolitical disruptions highlight the need for the EU to align its energy security priorities with long-term climate objectives. Robust climate policies, such as carbon credit systems, can help reduce the EU's reliance on natural gas while advancing toward aggressive climate goals[80]. Specifically, avoided emissions driven by sector-specific targeted strategies can serve as the basis for credit issuance, with implementation benchmarked against reduction thresholds set under the EU Emissions Trading System (ETS). In this regard, the analysis presented in ***Fig. S22*** *illustrates how scenario-driven reductions in carbon emissions from electrification, hydrogen production, and carbon offsetting can be benchmarked against ETS-defined reduction targets, offering a foundation for the design and implementation of performance-based carbon credit systems. This impetus behind carbon credit mechanisms can be leveraged to help close climate finance gaps[81], a role emphasized by decision-making bodies such as COP28, which frame it as a critical enabler of climate action[82], particularly in supporting the affordability of clean energy transitions. Accordingly, in addition to bolstering decarbonization efforts, the proposed strategies align with equity objectives through the progressive reduction of exposure to volatile fossil fuel markets, which led to sharp increases in energy costs[83, 84], especially for households[1], during recent geopolitical disruptions. The implementation of emergency fiscal measures, such as energy price caps[85] and one-off subsidies[86], underscores these energy cost pressures, further highlighting how the proposed strategies target a primary root cause, reducing natural gas consumption, instead of relying on reactive compensatory mechanisms to ensure affordable energy access."*

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- *On page 39 of the revised SI file:*

"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. ***Fig. S22****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%. ***Fig. S22****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. These findings underscore the potential role of the ETS cap as both a compliance mechanism and benchmark for carbon credit issuance, where scenario-driven sectoral reductions may be credited within robust EU-aligned policy frameworks.*

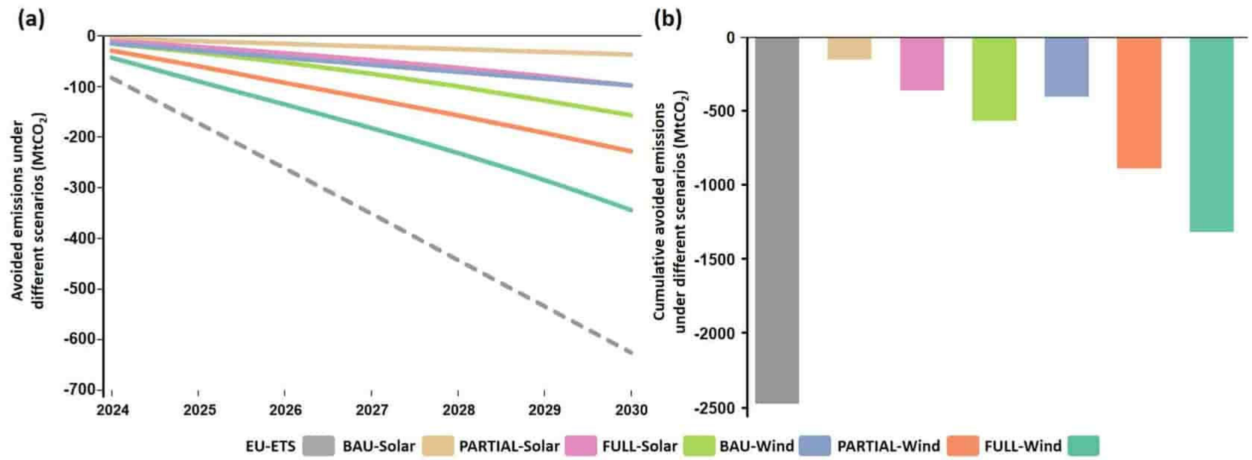

Fig. S22. a., *Annual emissions reductions ($MtCO_2$) under the EU-ETS cap trajectory and the BAU, PARTIAL, and FULL scenarios for solar and wind power expansion, incorporating electrification, hydrogen, and carbon offsetting strategies.* ***b.,*** *Cumulative avoided emissions ($MtCO_2$) under the BAU, PARTIAL, and FULL scenarios for wind and solar power expansion, benchmarked against the total emissions reduction required under the ETS over the same period."*

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Reviewer's Comment (8)

8-Compare the potential outcomes of the proposed strategies with alternative energy pathways to justify the recommended approach.

Answer: Thanks for the comment. We agree with the reviewer's suggestion to justify the recommended strategies by comparing them with alternative energy pathways. In the revised manuscript, we compare the scenario-based evaluation conducted in this work with different energy pathways explored in prior studies (Ruhnau et al., 2023; Shirizadeh et al., 2023; van der Zwaan et al., 2025; van Ouwerkerk et al., 2024), as well as selected elements of the EU action plan related to energy supply diversification (European Commission, 2025). This comparative discussion positions the proposed framework with existing approaches and highlights its ability to generate complementary and policy-relevant insights.

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Action

- *On page 21 of the revised main file:*

"While previous studies have also explored alternate energy pathways for Europe, providing valuable insights through a focused examination of renewable investments[33], hydrogen infrastructure[34], or region-specific crisis response to recent geopolitical tensions[2], this work presents a comprehensive evaluation of strategic scenarios incorporating electrification, green hydrogen, and carbon offsetting strategies. For instance, Ruhnau et al.[2] highlight the maximum reductions in natural gas consumption during the 2022 energy crisis, estimating savings of 10.6 TWh in industry and 5.9 TWh in the power sector in Germany. These reductions reflect an immediate crisis response during specific months in 2022; however, this study's analysis of the FULL scenarios for solar and wind capacity expansions with green hydrogen deployment indicates that up to 31.0 TWh and 101.0 TWh of industrial natural gas consumption in Germany can be reduced by 2050, respectively. Similarly, reductions in the electricity and heating sector can reach 220.8 TWh and 433.0 TWh under the same scenarios and time horizon, underscoring the value of sustained and tailored renewable deployment strategies that account for region-specific sectoral demand profiles. Shirizadeh et al.[94] estimate that clean hydrogen (produced from low-carbon electricity via electrolysis or natural gas with abated CO_2) can potentially meet nearly a quarter of Europe's final energy demand by 2050. van der Zwaan et al.[95] indicate that hydrogen can constitute approximately 6% of final energy consumption in Europe by mid-century under a deep decarbonization scenario. While these studies offer pertinent estimates of hydrogen's role in final energy demand, this analysis illustrates the contribution of green hydrogen, produced solely from renewable electricity, to reducing gross inland natural gas consumption across the EU. Under the BAU, PARTIAL, and FULL scenarios for solar and wind power expansion, green hydrogen alone accounts for a 1.7% to 10.3% reduction in natural gas use by 2050, providing sector-specific insights for energy security planning. van Ouwerkerk et al.[33] evaluate the economic and environmental benefits of residential renewable investments for single-family homes in Germany, identifying solar PV systems as a no-regret strategy during and beyond the energy crisis. Complementing this perspective and reinforcing the strategic role of solar power installations, the policy-driven scenarios evaluated in this analysis, when combined with targeted interventions, can reduce gross inland natural gas consumption in Germany and the EU by 21.6% to 42.9% and 17.2% to 37.0%, respectively, by 2050, translating into climate benefits of 0.6 $GtCO_2$ to 1.5 $GtCO_2$ and 2.0 $GtCO_2$ to 5.4 $GtCO_2$ in emissions reductions. Moreover, the EU action plan to address the energy crisis also outlines the role of diversifying natural gas sources[89]. This

pathway focuses on establishing agreements with alternative suppliers and infrastructure upgrades such as investment in terminals and gas interconnectors. These measures can alleviate energy security concerns, at least in the near term, by expanding supply routes; however, they do not inherently contribute to long-term climate mitigation. In contrast, the proposed strategies in this analysis center on reducing sector-specific natural gas consumption across the EU as a structural metric, thereby aligning energy security planning with the EU's climate objectives."

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Reviewer's Comment (9)

9-Discuss how uncertainties in geopolitical or technological developments are addressed within the modeling framework.

Answer: Thanks for the comment. Following the reviewer's suggestion, we have elaborated on how the proposed multi-scenario framework captures a wide range of future uncertainties, particularly those tied to geopolitical disruptions and evolving technological developments. Among these, the degree of policy ambition in response to geopolitical tensions emerges as the most influential factor shaping the modeled outcomes. This influence is reflected through differentiated renewable deployment scenarios, which affect the extent of sectoral natural gas displacement and the advancement of energy security and climate goals. Additionally, to capture uncertainties in economic and technological developments, distinct cost development trajectories are integrated into the analysis, influencing the relative economic feasibility of sector-specific strategies.

Action

- *On page 20 of the revised main file:*

"The evaluation of multiple scenarios in this analysis addresses uncertainties associated with geopolitical disruptions and technological developments in the context of aligning EU energy security with decarbonization goals. The scenario design includes technology-specific capacity expansion pathways, BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind, which reflect varying levels of strategic intervention, capturing different geopolitical responses and policy ambitions. Each scenario enables the exploration of energy security, climate mitigation benefits, and economic implications under alternative future conditions. Technological uncertainty is addressed by overlaying each policy-driven scenario with distinct cost trajectories, slow, nominal, and fast, reflecting potential variations in learning rates and deployment challenges for clean energy installations. This multi-scenario framework offers a comprehensive spectrum of potential outcomes that can inform adaptive strategies in response to changing geopolitical dynamics and technological developments. For instance, policymakers can derive actionable insights from the FULL scenarios, which underscores the importance of aggressive and early investments in renewable capacity deployment to achieve substantial reductions in natural gas consumption and build long-term security. The PARTIAL scenarios demonstrate a balanced approach, showing how even moderate renewable energy growth consistently strengthens energy

security, while the BAU scenarios highlight the vulnerabilities associated with delayed transitions. Additionally, the modeling framework emphasizes strategic diversification across electrification, hydrogen production, and carbon offsetting to improve robustness across sectors. For example, while electrification is targeted for light industries within the industrial sector and specific segments of road transportation (passenger cars, light commercial vehicles, buses, and coaches), green hydrogen is deployed as a versatile solution for hard-to-abate sectors, such as heavy industries and the operation of heavy trucks. By integrating policy-driven intervention scenarios, evolving cost dynamics, and sectoral differentiation, this analysis offers a strategic foundation for aligning energy security and climate goals under uncertain geopolitical and technological futures."

Reviewer's Comment (10)

10- Include graphs or charts to illustrate the reduction in natural gas consumption, expansion of renewable capacities, and potential climate benefits under different scenarios.

Answer: Thanks for the comment. We agree with the reviewer's feedback to illustrate key metrics such as the reduction in natural gas consumption, the expansion of renewable capacities, and potential climate benefits across different scenarios. In the revised manuscript, Figs. 1, 3, and 4 in the main file present a sector-specific analysis of natural gas reduction and cumulative avoided emissions, covering electricity and heating, light industries (including transportation equipment, machinery, textile and leather, etc.), heavy industries (including iron and steel, non-ferrous metals, non-metallic minerals, etc.), transportation, and carbon offsetting strategies. Additionally, Figs. S1-S21 and Figs. S63-S65 in the SI file depict a detailed spatial and sectoral breakdown of reduction in natural gas consumption, emissions reductions, and renewable capacity expansion across EU countries under different scenarios. Moreover, Figs. S56-S59 illustrate the infrastructure requirements for electrification, green hydrogen deployment, and carbon offsetting strategies in each scenario, highlighting the associated technological investments across member states.

Action

- *On page 7 of the revised main file:*

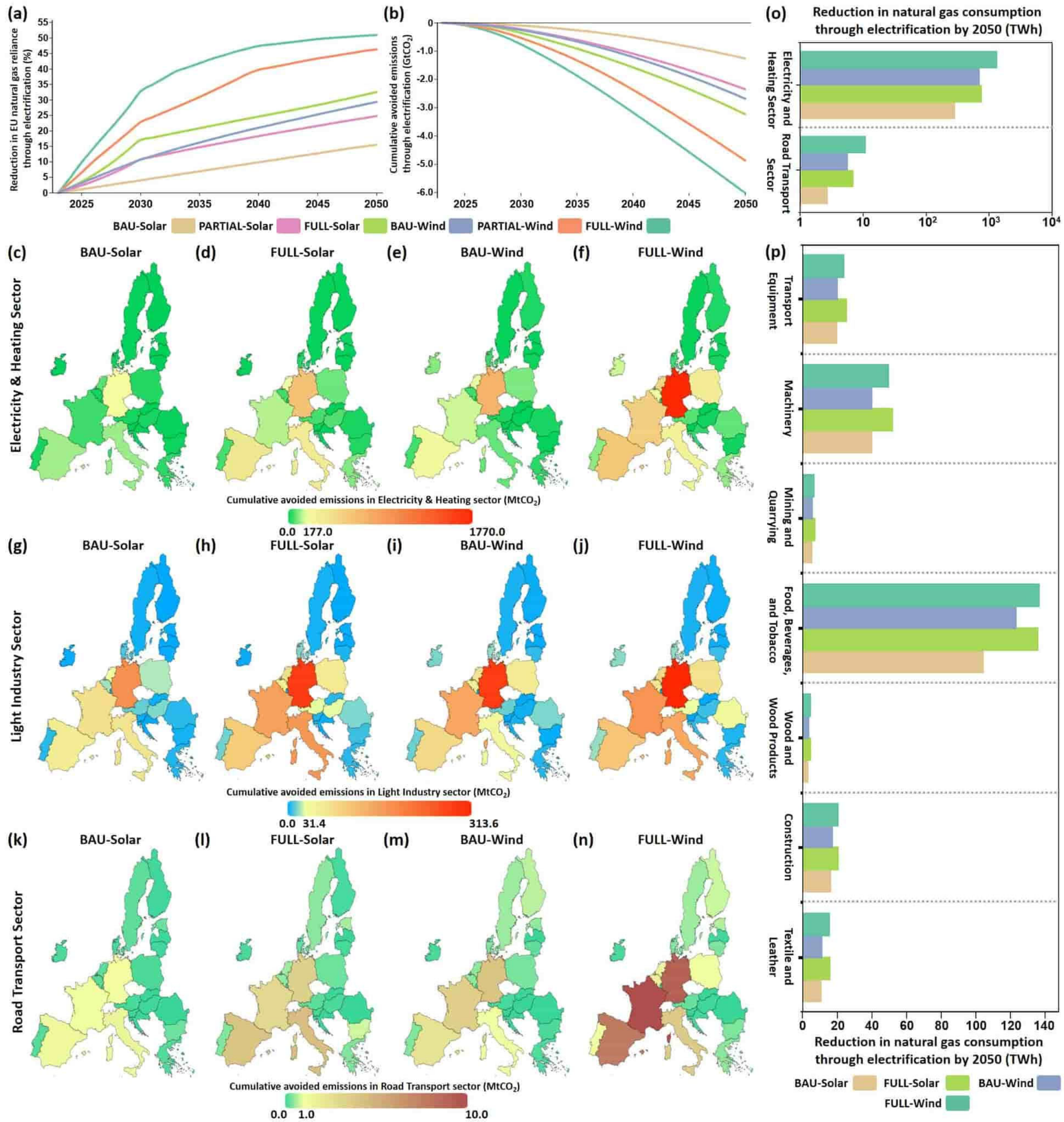

Fig. 1. a., *Reduction in natural gas reliance (%) in the EU through electrification based on gross inland consumption under different solar and wind power growth scenarios.* ***b.,*** *Cumulative avoided emissions (GtCO2) in the EU through the reduction in natural gas consumption based on electrification potential under different solar and wind power growth scenarios.* ***c-f.,*** *Cumulative avoided emissions (MtCO2) through the reduction in natural gas consumption based on electrification potential in the electricity and heating sector in different EU countries by 2050 under the BAU and FULL scenarios for solar and wind capacity expansion.* ***g-j.,***

Cumulative avoided emissions ($MtCO_2$) through the reduction in natural gas consumption based on electrification potential in the light industrial sector in different EU countries by 2050 under the BAU and FULL scenarios for solar and wind capacity expansion. ***k-n.,*** *Cumulative avoided emissions ($MtCO_2$) through the reduction in natural gas consumption based on electrification potential in the road transportation sector (for the operation of passenger cars, light commercial vehicles, buses, and coaches) in different EU countries through 2050 under the BAU and FULL scenarios for solar and wind capacity expansion.* ***o.,*** *Total reduction in EU natural gas reliance based on electrification potential in the electricity and heating sector and road transportation sector by 2050 under the BAU and FULL scenarios for solar and wind capacity expansion.* ***p.,*** *Total reduction in EU natural gas reliance based on electrification potential in the various light industries, including transportation equipment, machinery, mining and quarrying, food, beverages, and tobacco, wood and wood products, construction, and textile and leather by 2050 under the BAU and FULL scenarios for solar and wind capacity expansion.*

- *On page 12 of the revised main file:*

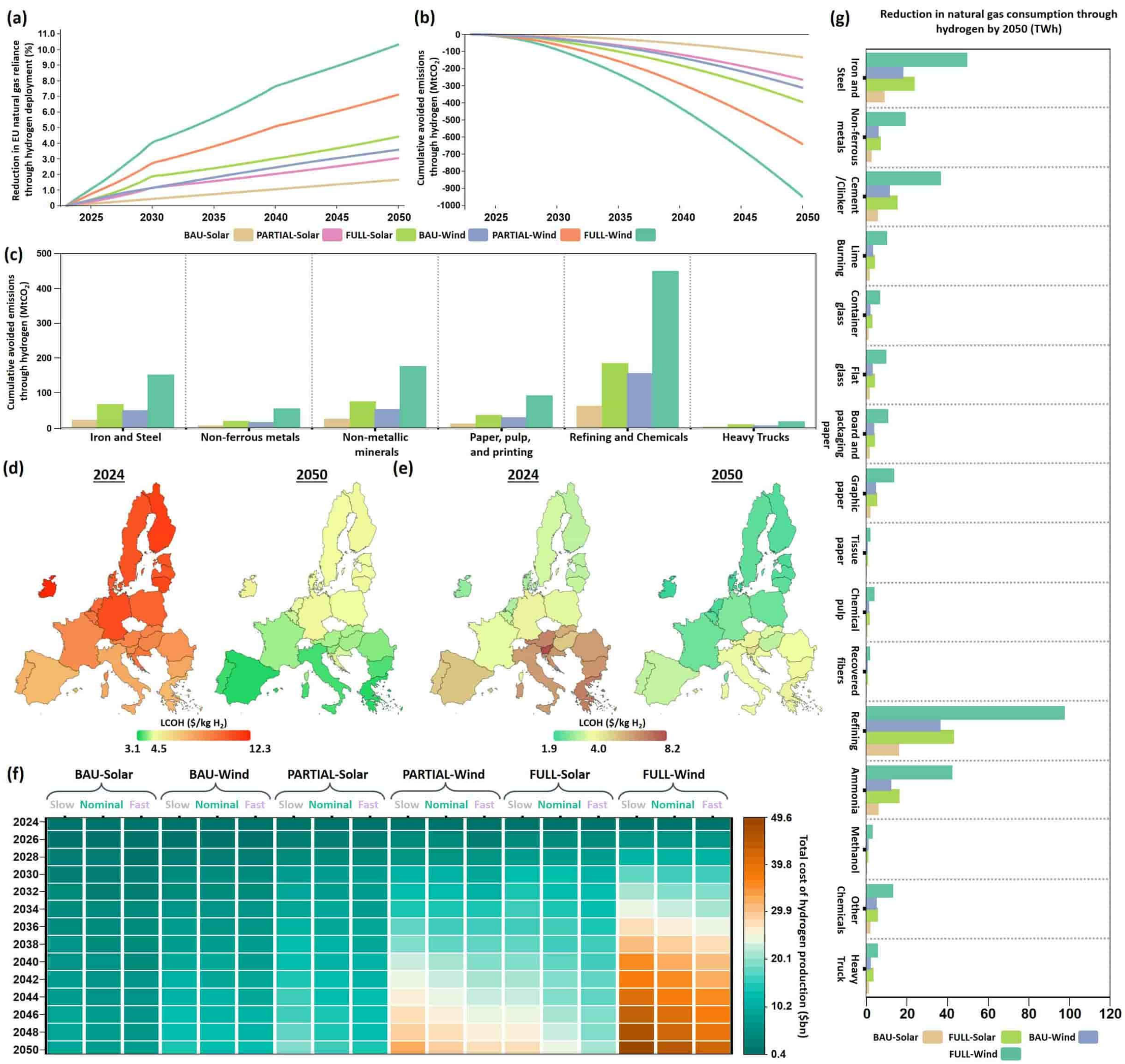

***Fig. 3. a.,** Reduction in natural gas reliance (%) in the EU through green hydrogen deployment based on gross inland consumption under different solar and wind power growth scenarios. **b.,** Cumulative avoided emissions ($MtCO_2$) in the EU through the reduction in natural gas consumption based on green hydrogen deployment under different solar and wind power growth scenarios. **c.,** Cumulative avoided emissions ($MtCO_2$) in the EU through the reduction in natural gas consumption based on the use of green hydrogen in heavy industrial sectors including iron and steel, non-ferrous metal, 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), and the operation of heavy trucks in the road transportation sector by 2050 under the BAU and FULL scenarios for solar and wind capacity expansion. ***d.,*** *Levelized cost of hydrogen (\$/kg H_2) through solar power expansion in 2024 and under a fast trajectory for increasing cost-competitiveness in 2050.* ***e.,*** *Levelized cost of hydrogen (\$/kg H_2) through wind power expansion in 2024 and under a fast trajectory for increasing cost-competitiveness in 2050.* ***f.,*** *Total annual cost of hydrogen production (\$bn) under different scenarios for renewable capacity expansion and varying trajectories for increasing cost-competitiveness till 2050.* ***g.,*** *Total reduction in EU natural gas reliance based on the use of green hydrogen in various heavy industries including iron and steel, non-ferrous metal, cement/clinker, lime-burning, container glass, flat glass, board and packaging paper, graphic paper, tissue paper, chemical pulp, and recovered fibers, refining, ammonia, methanol, other chemicals, and the operation of heavy trucks in the road transportation sector through 2050 under the BAU and FULL scenarios for solar and wind capacity expansion.*

- *On page 15 of the revised main file:*

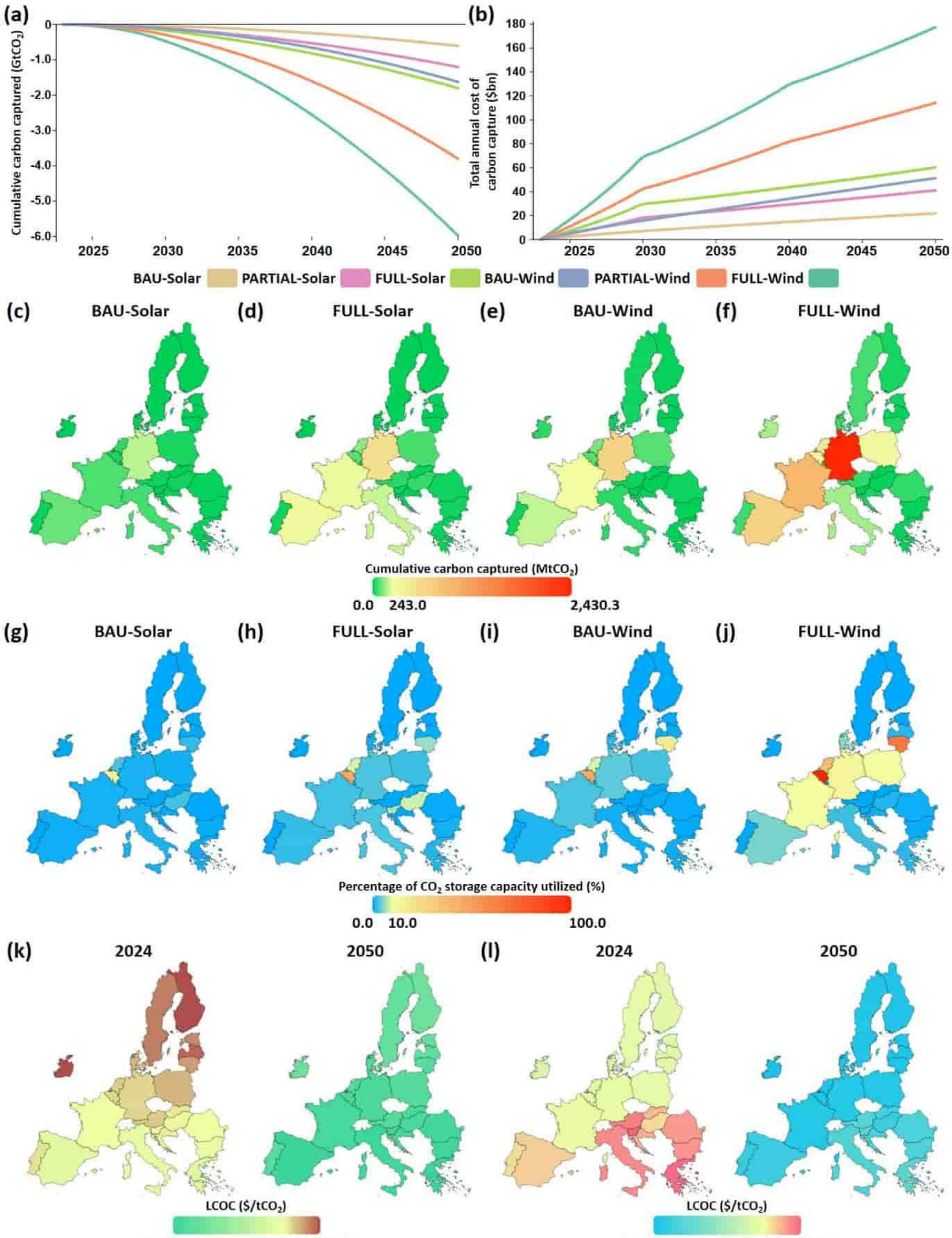

Fig 4. a., *Cumulative carbon captured (MtCO$_2$) through DAC systems in the EU under the different solar and wind power growth scenarios.* ***b.,*** *Total annual cost of carbon capture ($bn)*

through DAC systems under different scenarios for solar and wind power expansion and the fast trajectory for increasing cost-competitiveness till 2050. ***c-f.,*** *Cumulative carbon captured (MtCO_2) through DAC systems in different EU countries under the BAU and FULL scenarios for solar and wind capacity expansion.* ***g-j.,*** *Percentage of CO_2 storage capacity utilized (%) in different EU countries under the BAU and FULL scenarios for solar and wind capacity expansion.* ***k.,*** *Levelized cost of carbon capture (\$/tCO_2) through DAC systems based on solar power expansion in 2024 and under a fast trajectory for increasing cost-competitiveness in 2050.* ***l.,*** *Levelized cost of carbon capture (\$/tCO_2) through DAC systems based on wind power expansion in 2024 and under a fast trajectory for increasing cost-competitiveness in 2050.*

- *On pages 11 to 38 of the revised SI file:*

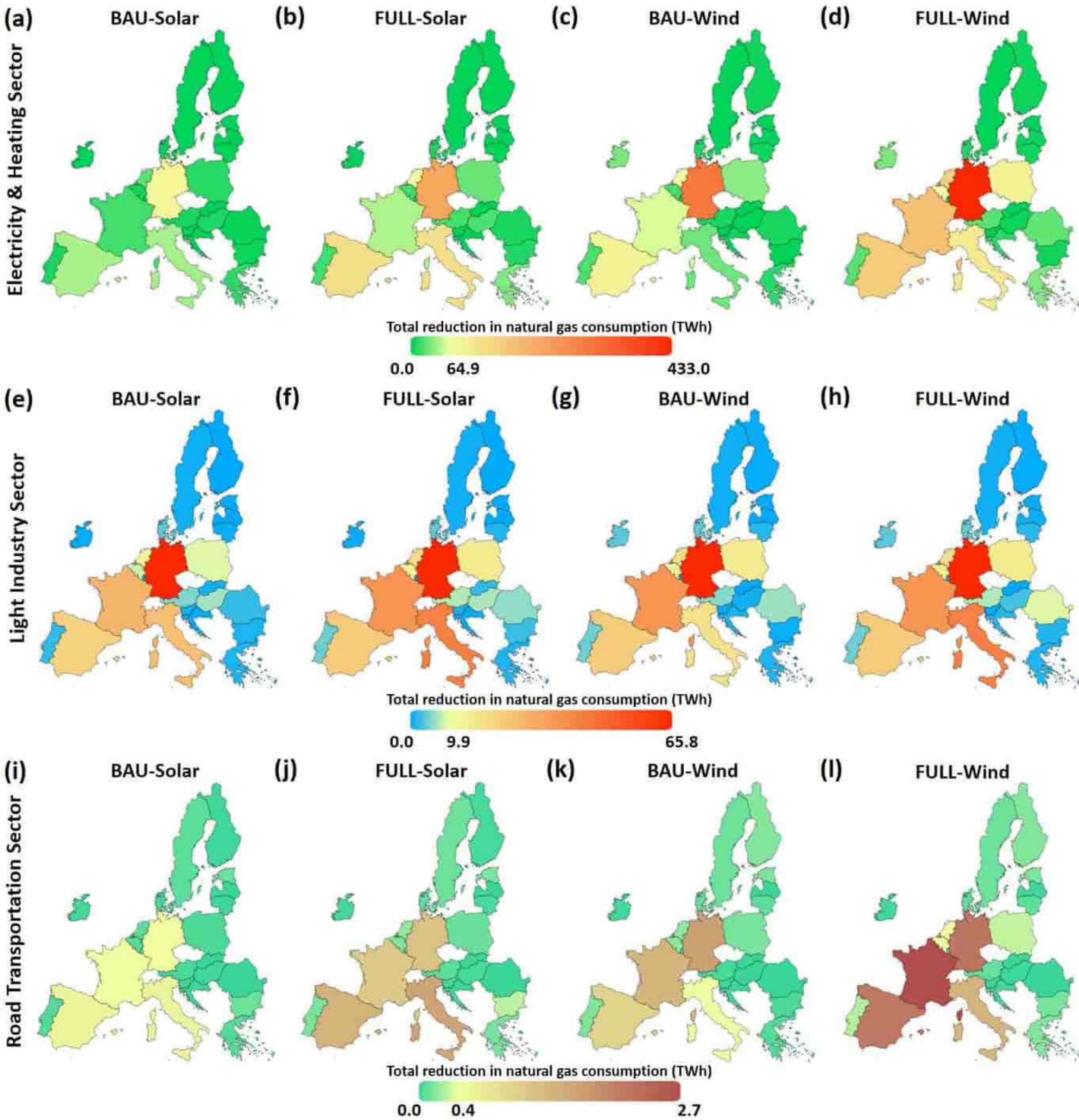

Fig. S1. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the electricity and heating sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the electricity and heating sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the electricity and heating sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the electricity and heating sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the light* *industrial sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the light industrial sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the light industrial sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the light industrial sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the road transportation sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the road transportation sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the road transportation sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the road transportation sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

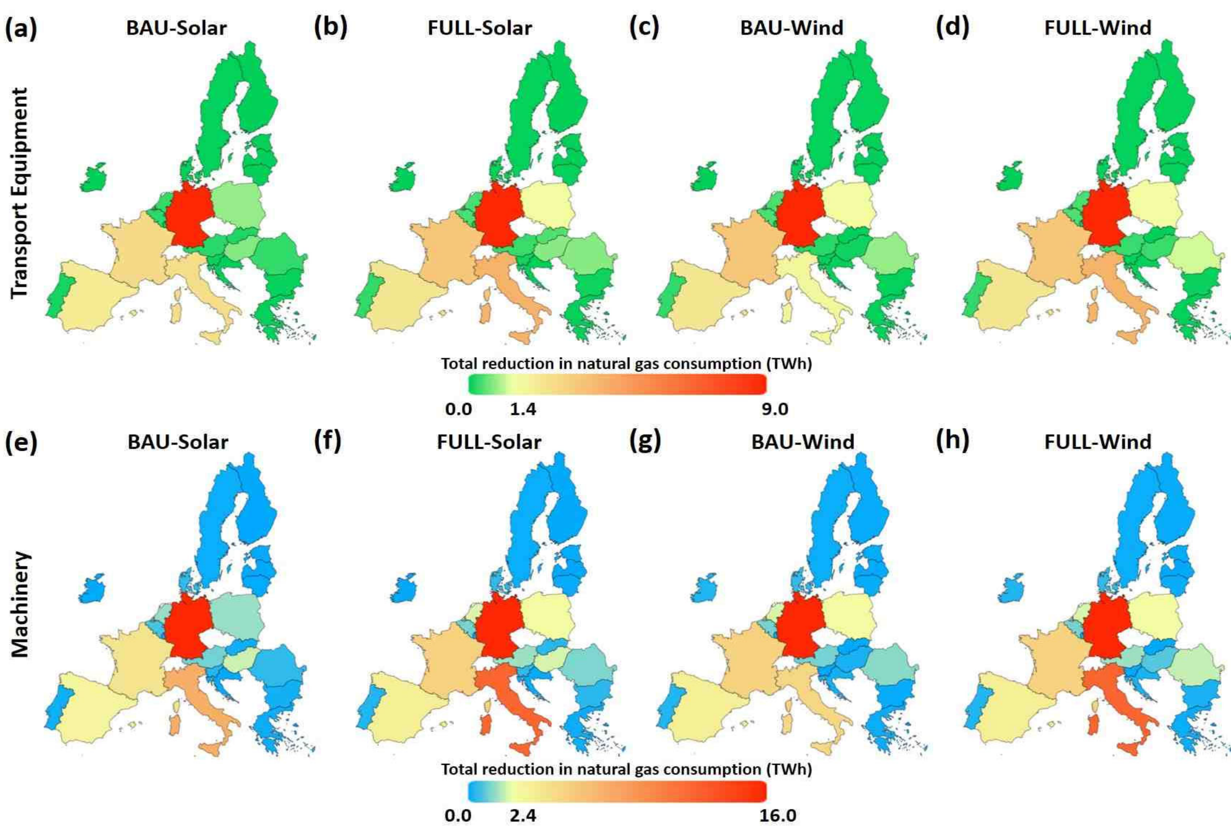

Fig. S2. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the transportation equipment sector based on the electrification potential under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the transportation equipment sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the transportation equipment sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the transportation equipment sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the machinery sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the machinery sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the machinery sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the machinery sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

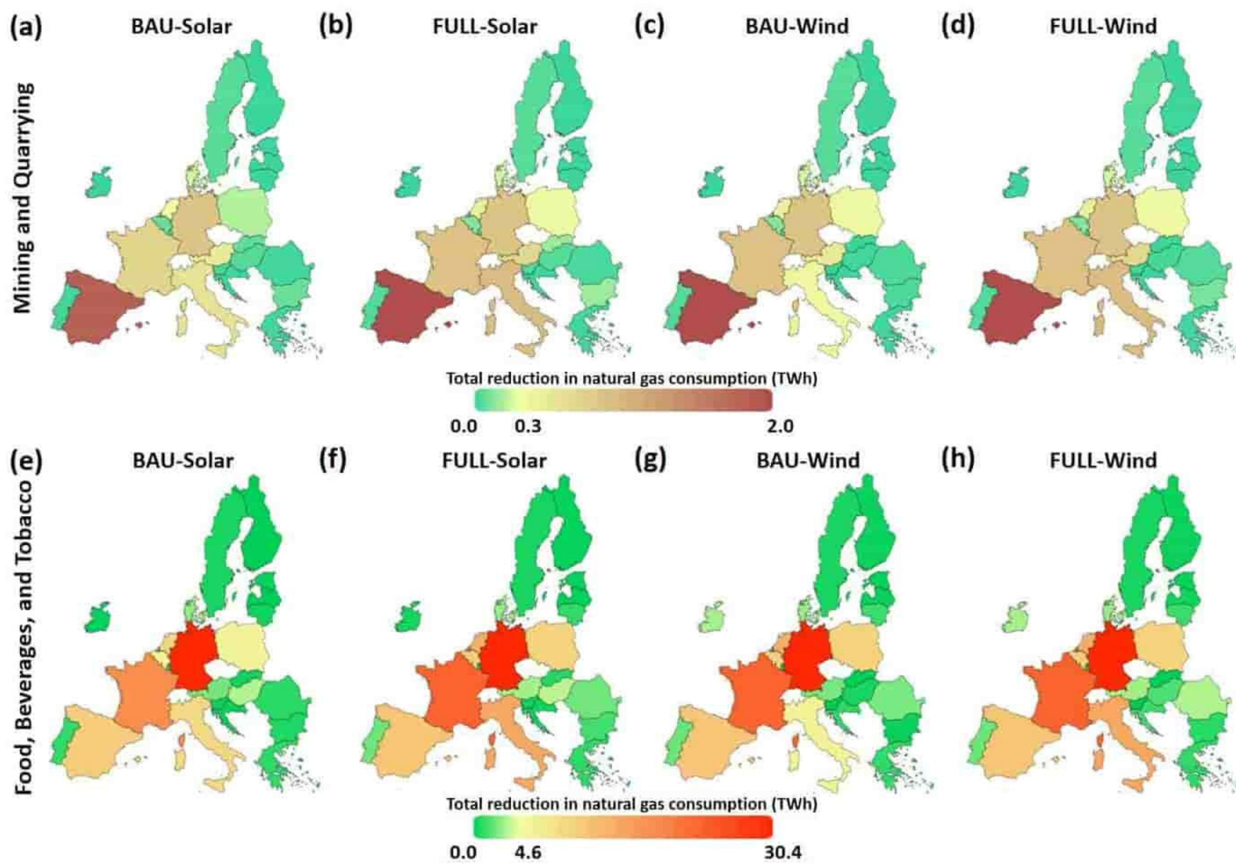

Fig. S3. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the mining and quarrying sector based on the electrification potential under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the mining and quarrying sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the mining and quarrying sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the mining and quarrying sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the food, beverages, and tobacco sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the food, beverages, and tobacco sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the food, beverages, and tobacco sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the food, beverages, and tobacco sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

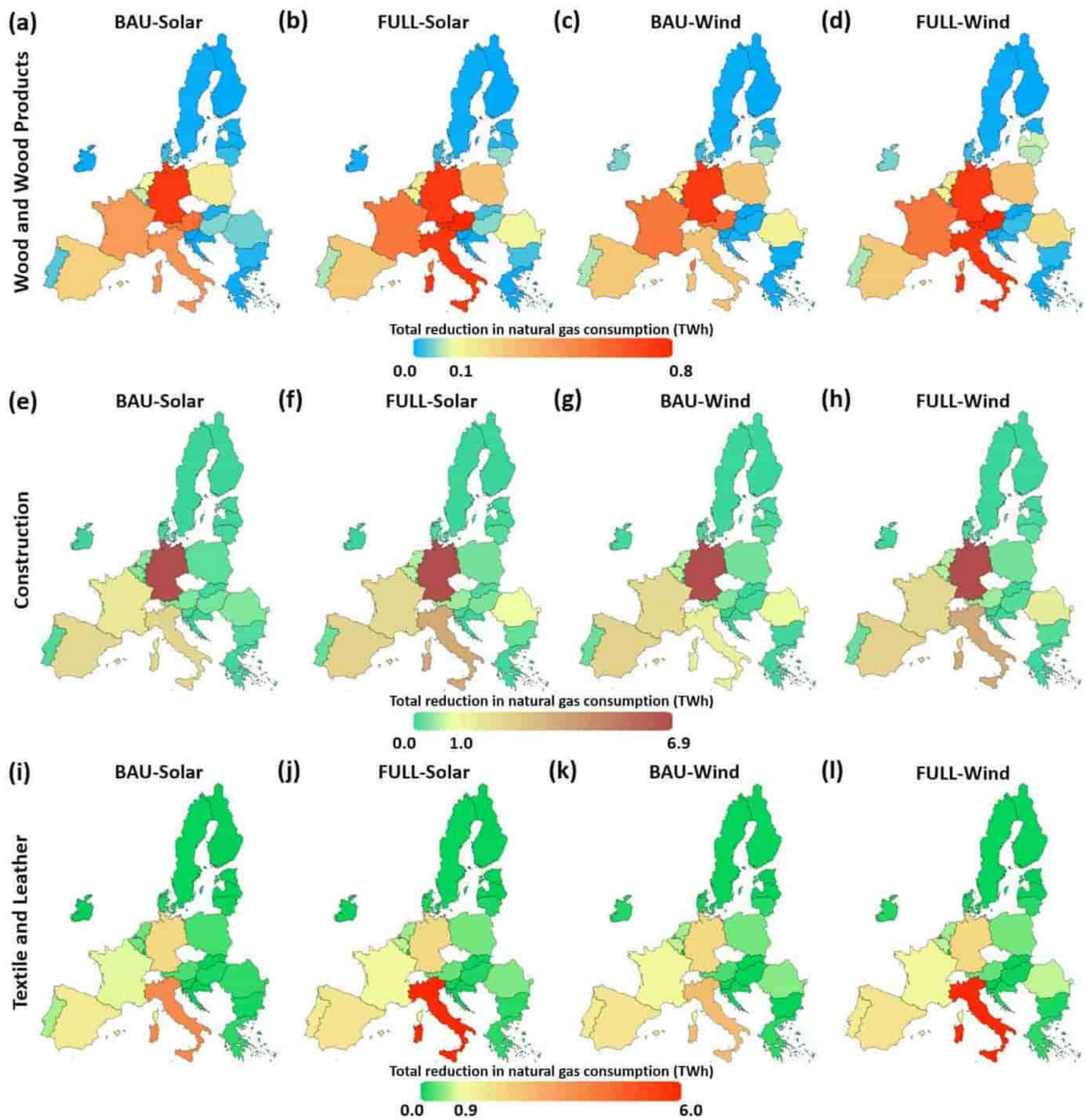

Fig. S4. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the wood and wood product sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the wood and wood product sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the wood and wood product sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the wood and wood product sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the construction* *sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the construction sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the construction sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the construction sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the textile and leather sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the textile and leather sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the textile and leather sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the textile and leather sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

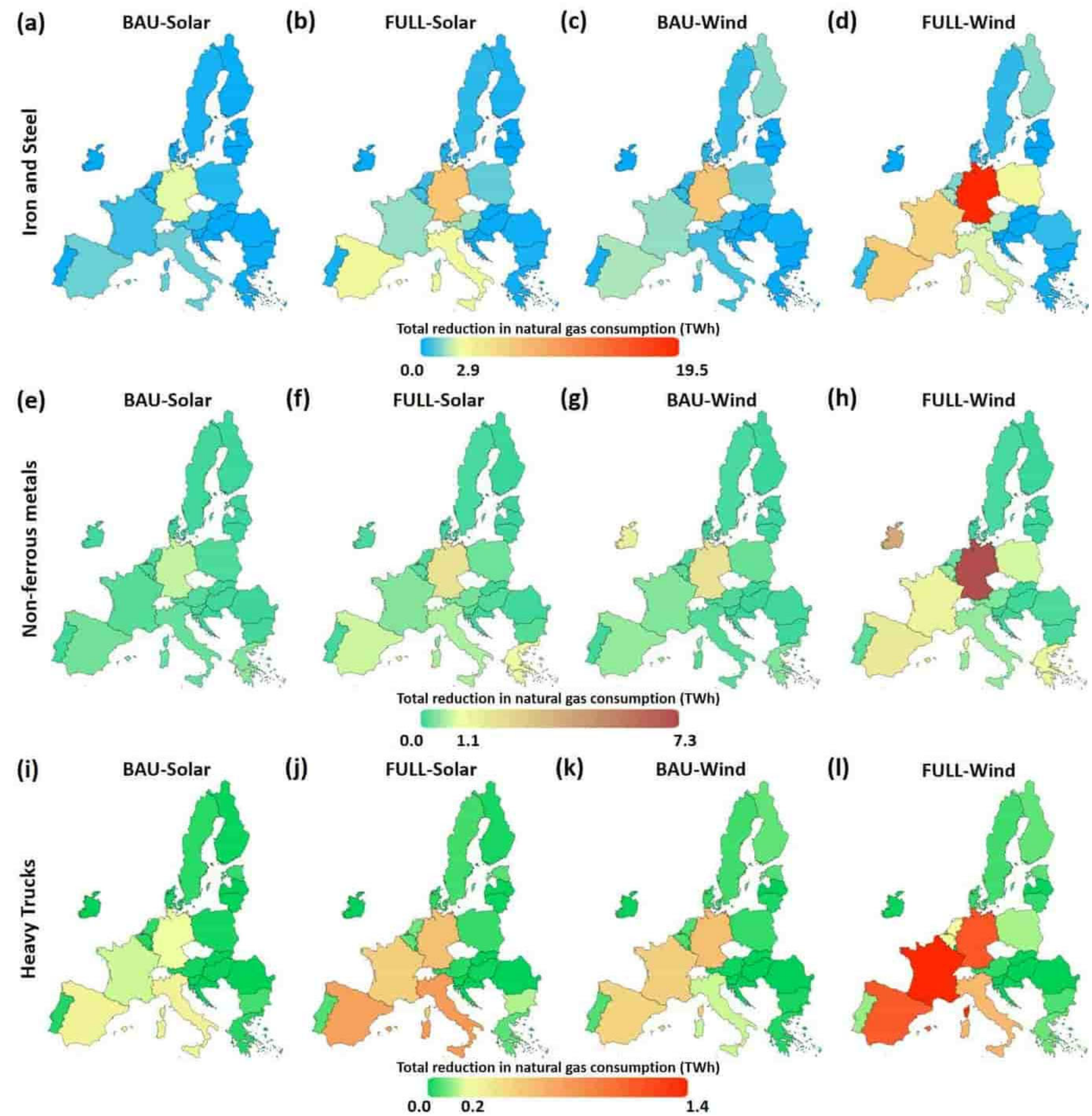

Fig. S5. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the iron and steel sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the iron and steel sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the iron and steel sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the iron and steel sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the non-*

ferrous metal sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations. ***f.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

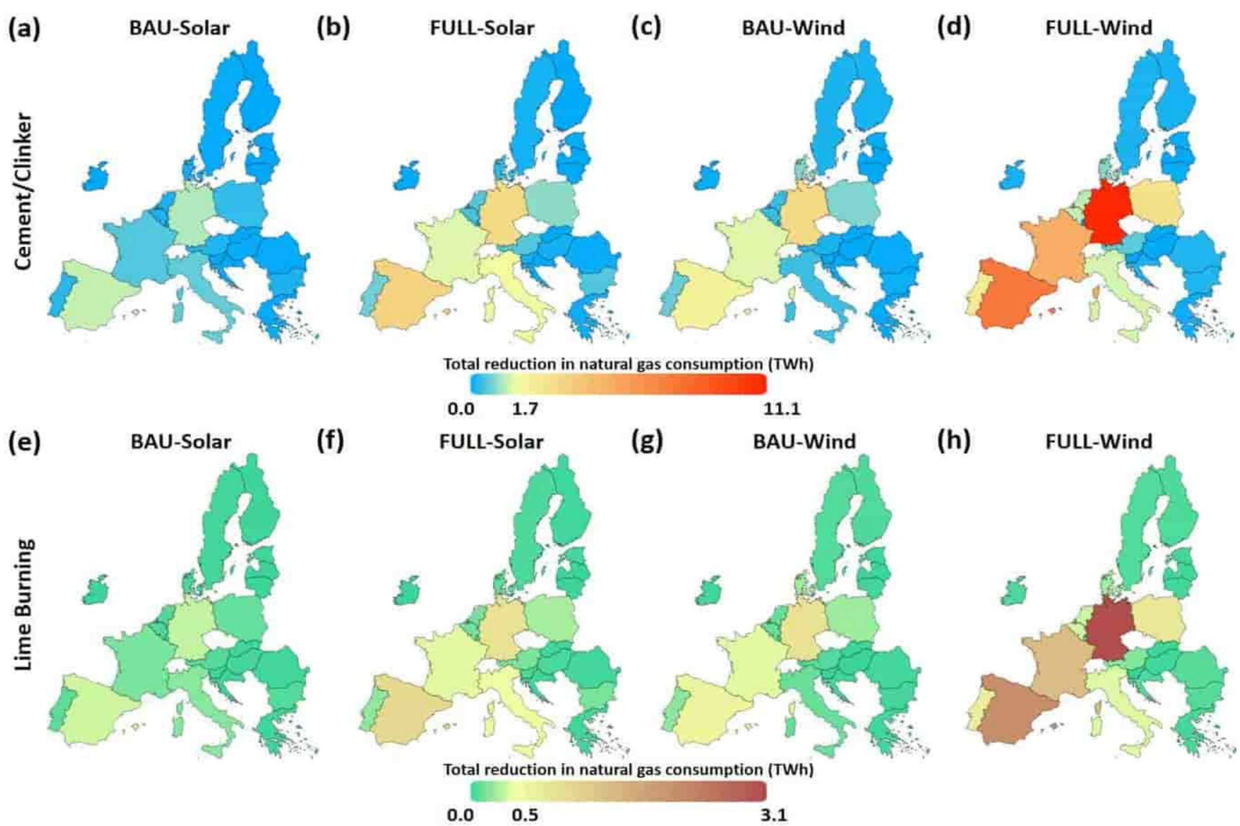

Fig. S6. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the lime-burning sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the lime-burning sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the lime-burning sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the lime-burning sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

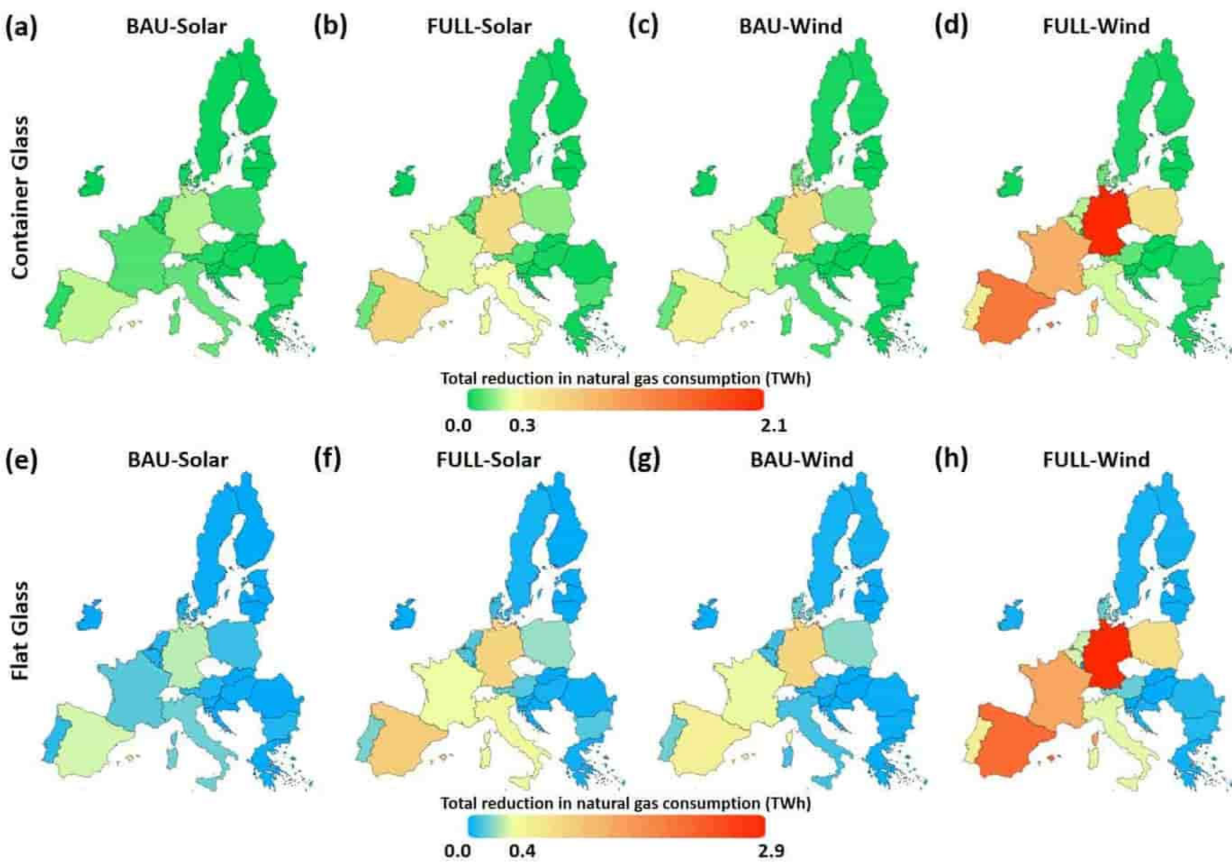

Fig. S7. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the container glass sector based on the use of green hydrogen technologies under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the container glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the container glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the container glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the flat glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the flat glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the flat glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the flat glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

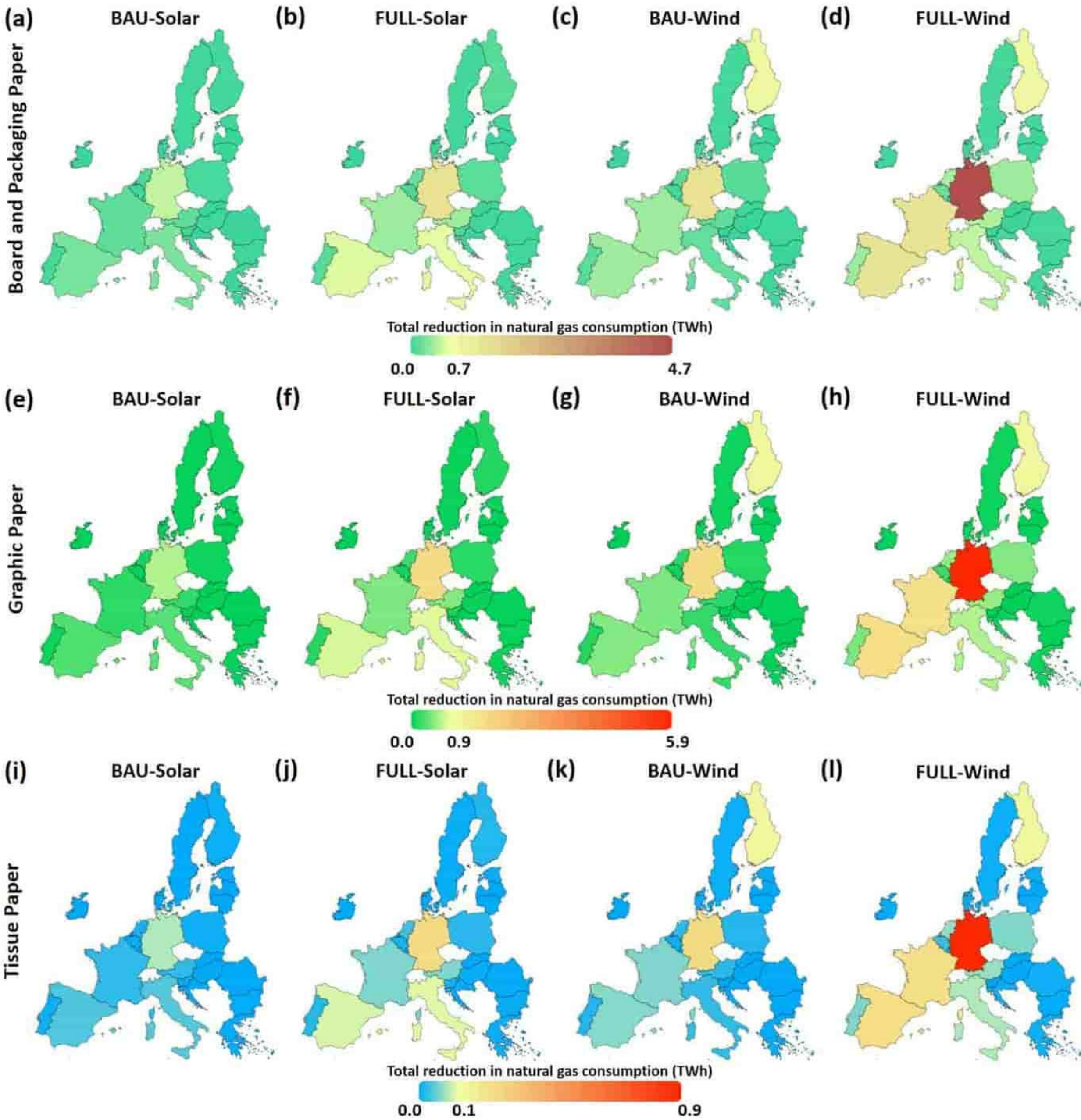

Fig. S8. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for* *growth in wind power installations.* ***e.,*** *the graphic paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the graphic paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the graphic paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the graphic paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the tissue paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the tissue paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the tissue paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the tissue paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

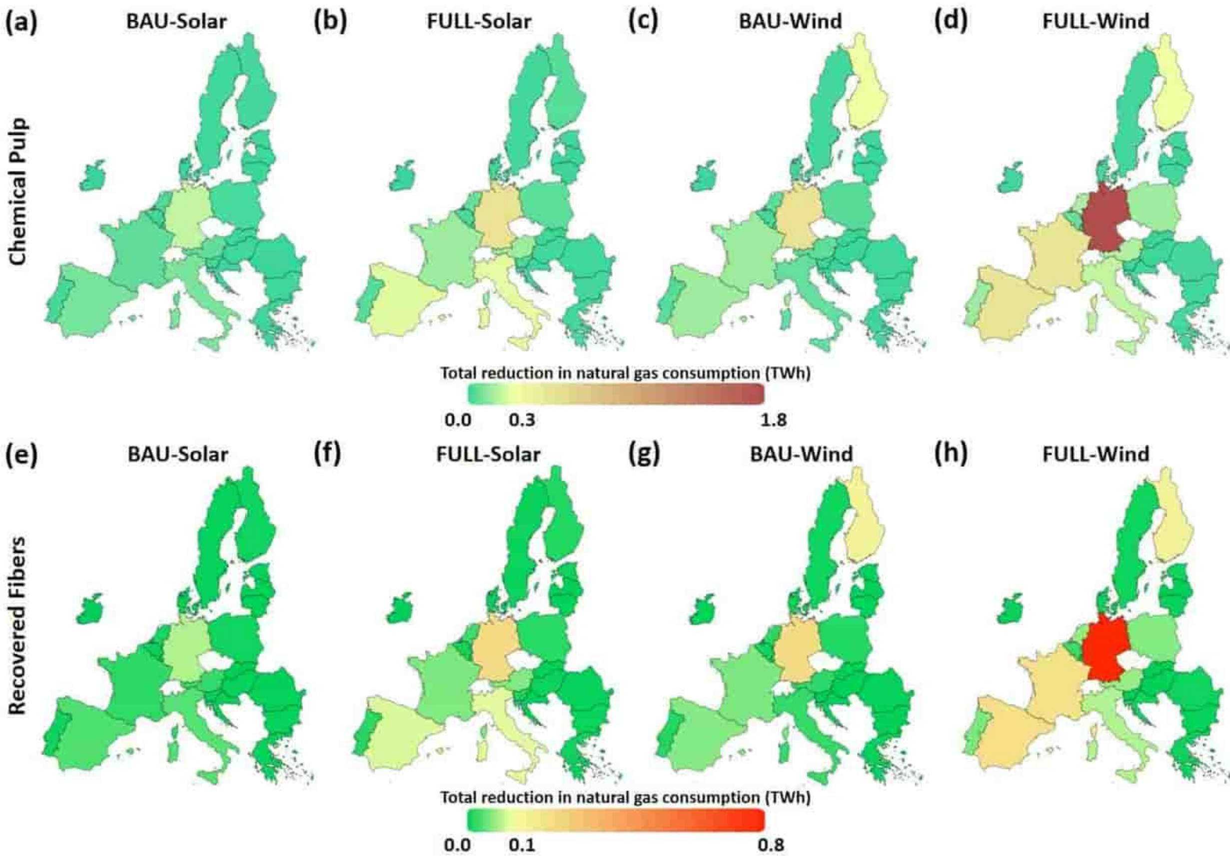

Fig. S9. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

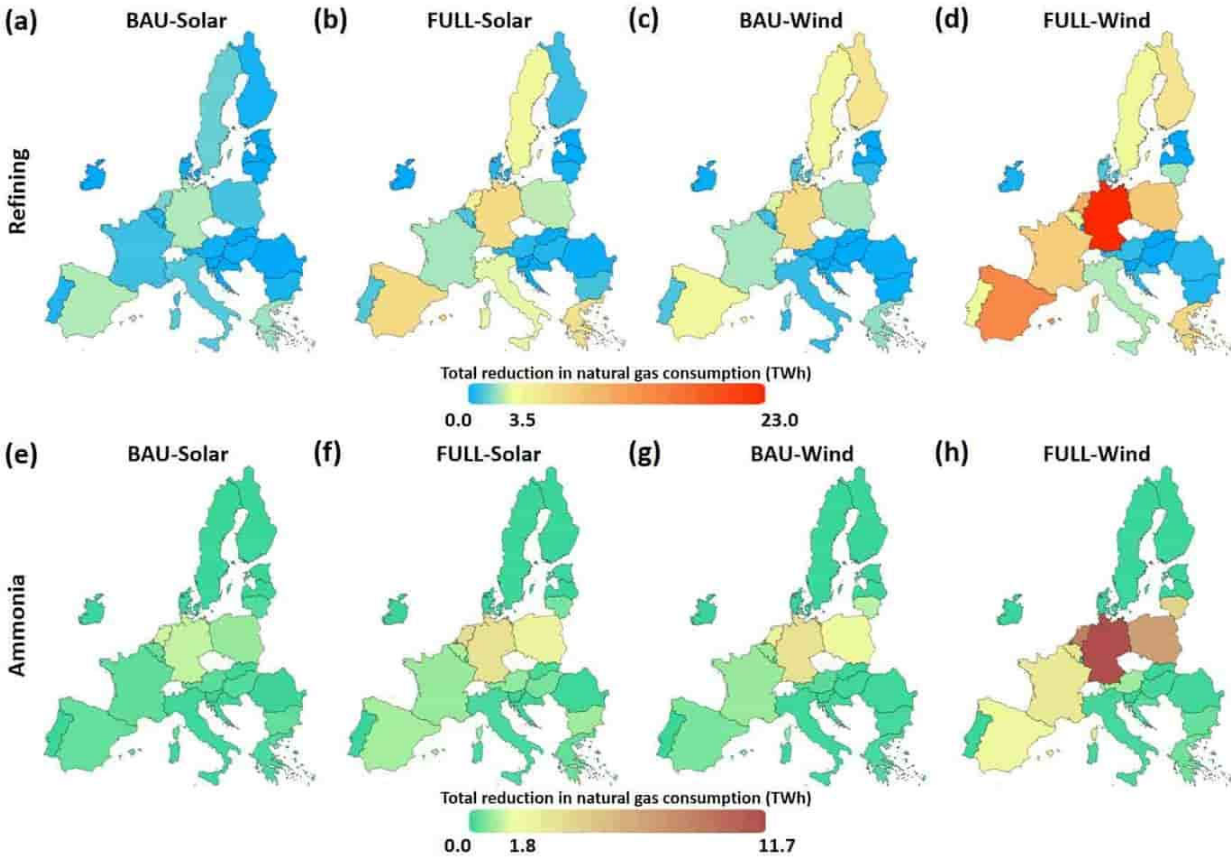

Fig. S10. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in* ***a.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the ammonia sector based* *on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.*

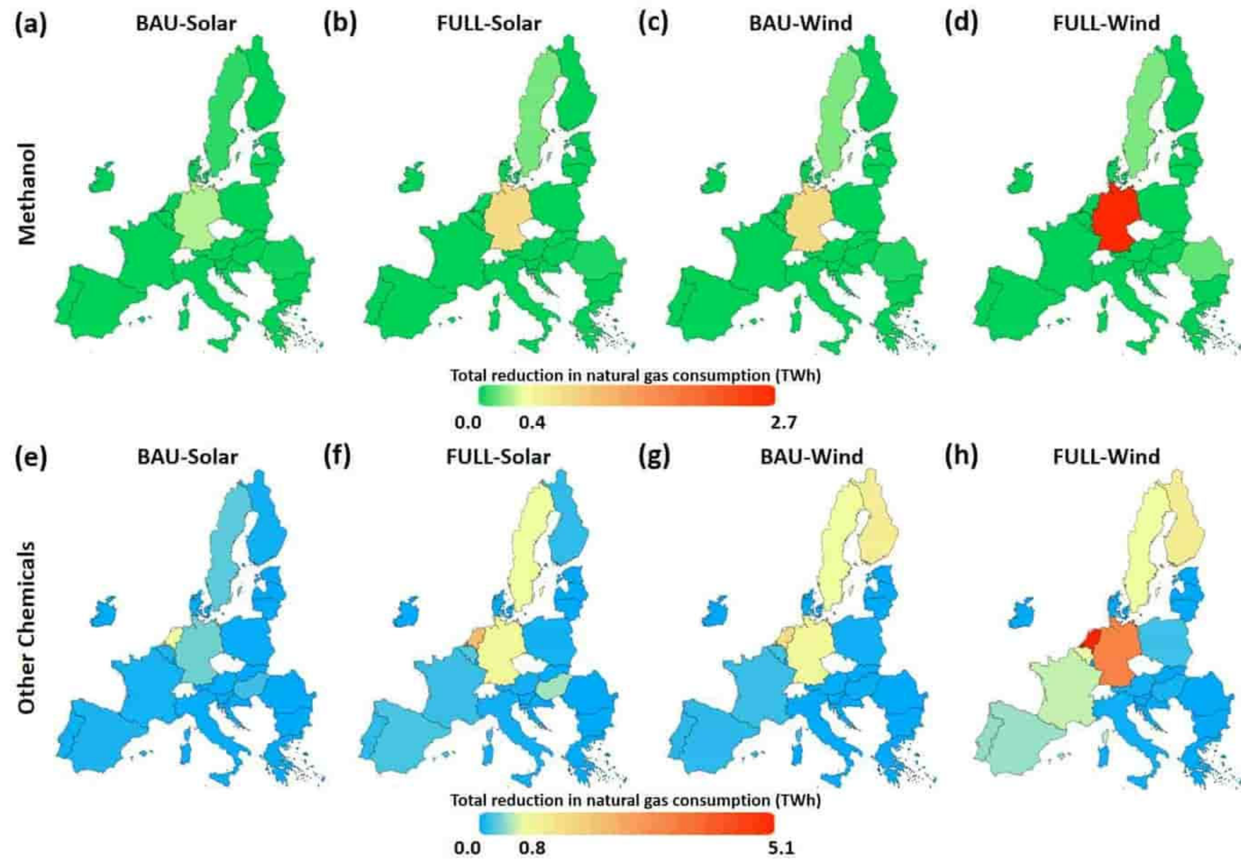

Fig. S11. *Total reduction in natural gas dependence (TWh) in EU member countries by 2050 in **a.,** the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations. **b.,** the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations. **c.,** the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations. **d.,** the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations. **e.,** other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations. **f.,** other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations. **g.,** other chemicals based on* *the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.*

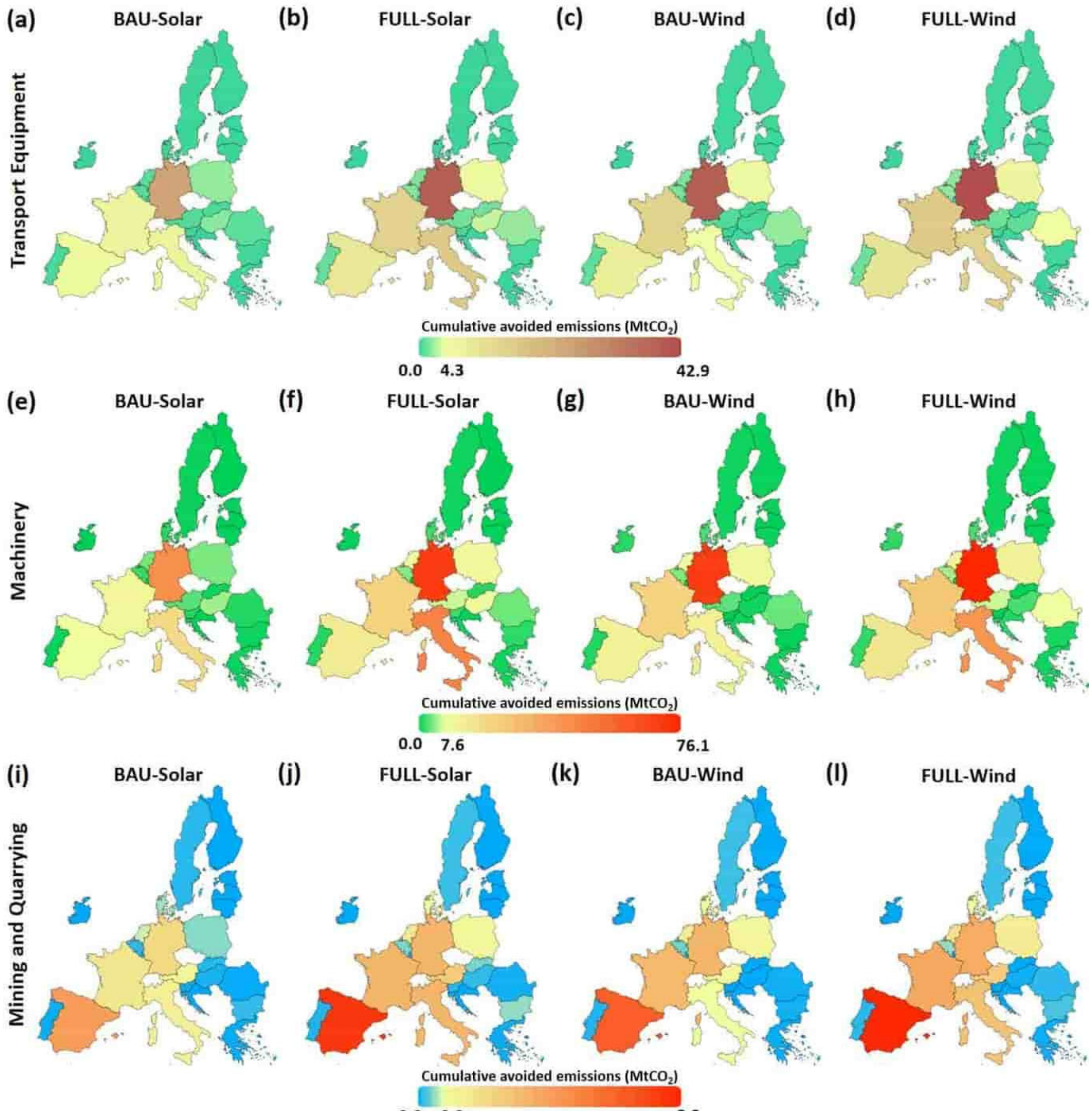

Fig. S12. *Cumulative avoided emissions (MtCO$_2$) in EU member countries by 2050 in* ***a.,*** *the transportation equipment sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the transportation* *equipment sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the transportation equipment sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the transportation equipment sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the machinery sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the machinery sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the machinery sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the machinery sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the mining and quarrying sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the mining and quarrying sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the mining and quarrying sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the mining and quarrying sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

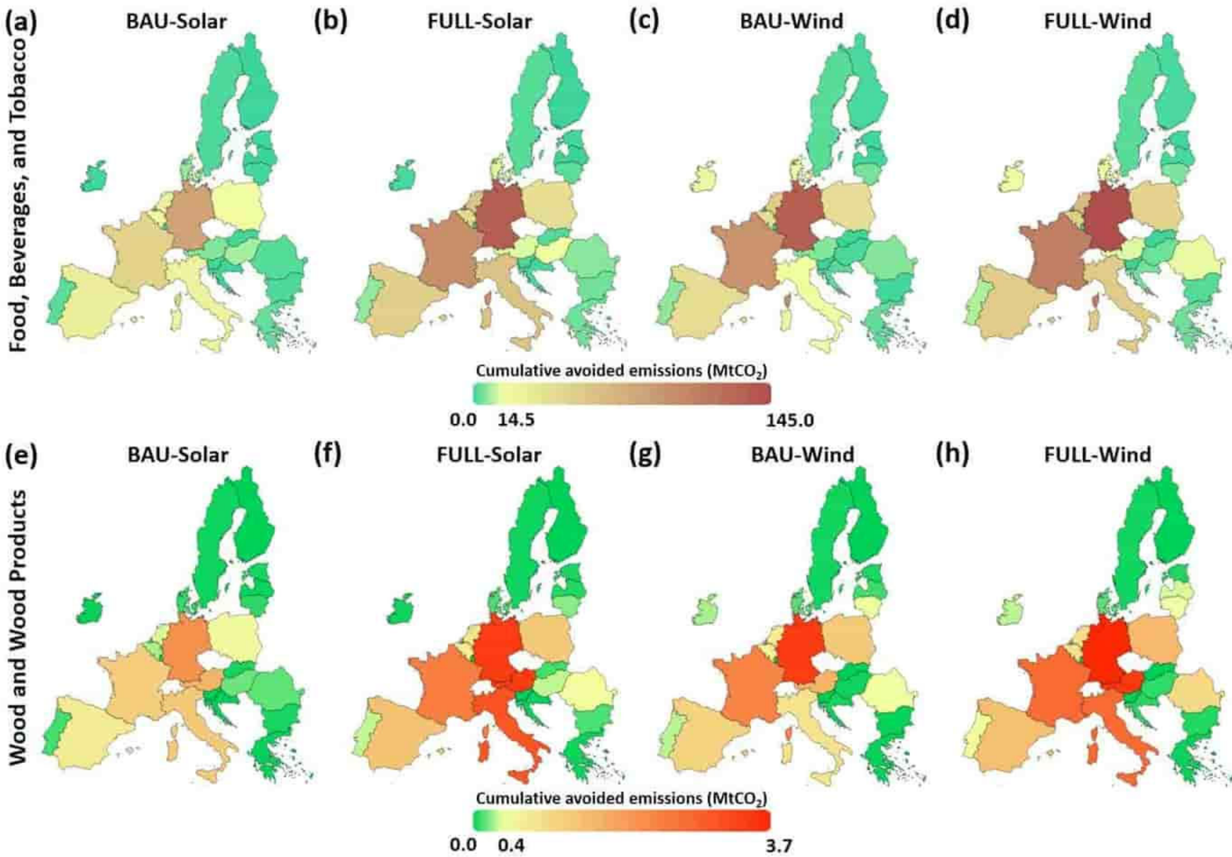

Fig. S13. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in **a.,** the food, beverages, and tobacco sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations. **b.,** the food, beverages, and tobacco sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations. **c.,** the food, beverages, and tobacco sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations. **d.,** the food, beverages, and tobacco sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations. **e.,** the wood and wood products sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations. **f.,** the wood and wood products sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations. **g.,** the wood and wood products sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations. **h.,** the wood and wood products sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

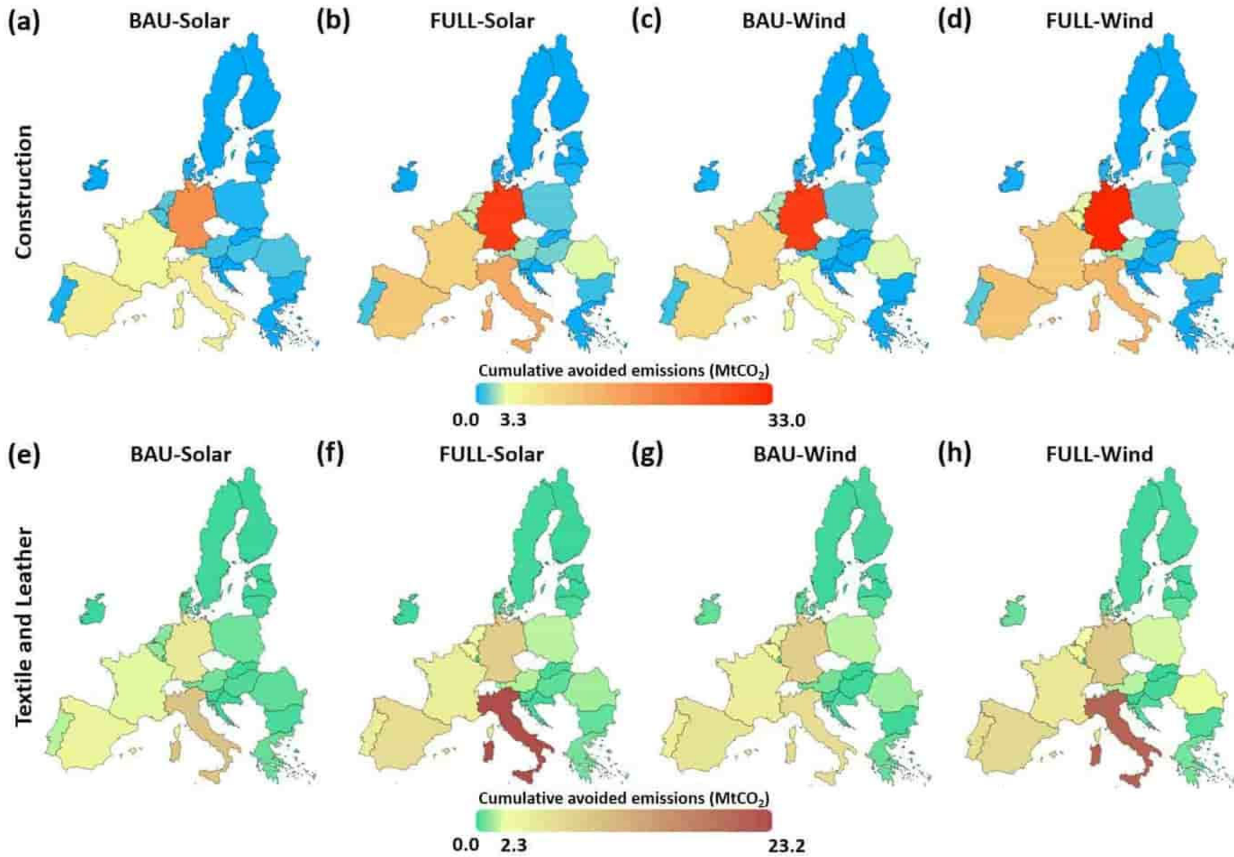

Fig. S14. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in* ***a.,*** *the construction sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the construction sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the construction sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the construction sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the textile and leather sector based on the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the textile and leather sector based on the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the textile and leather sector based on the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the textile and leather sector based on the electrification potential under the FULL implementation scenario for growth in wind power installations.*

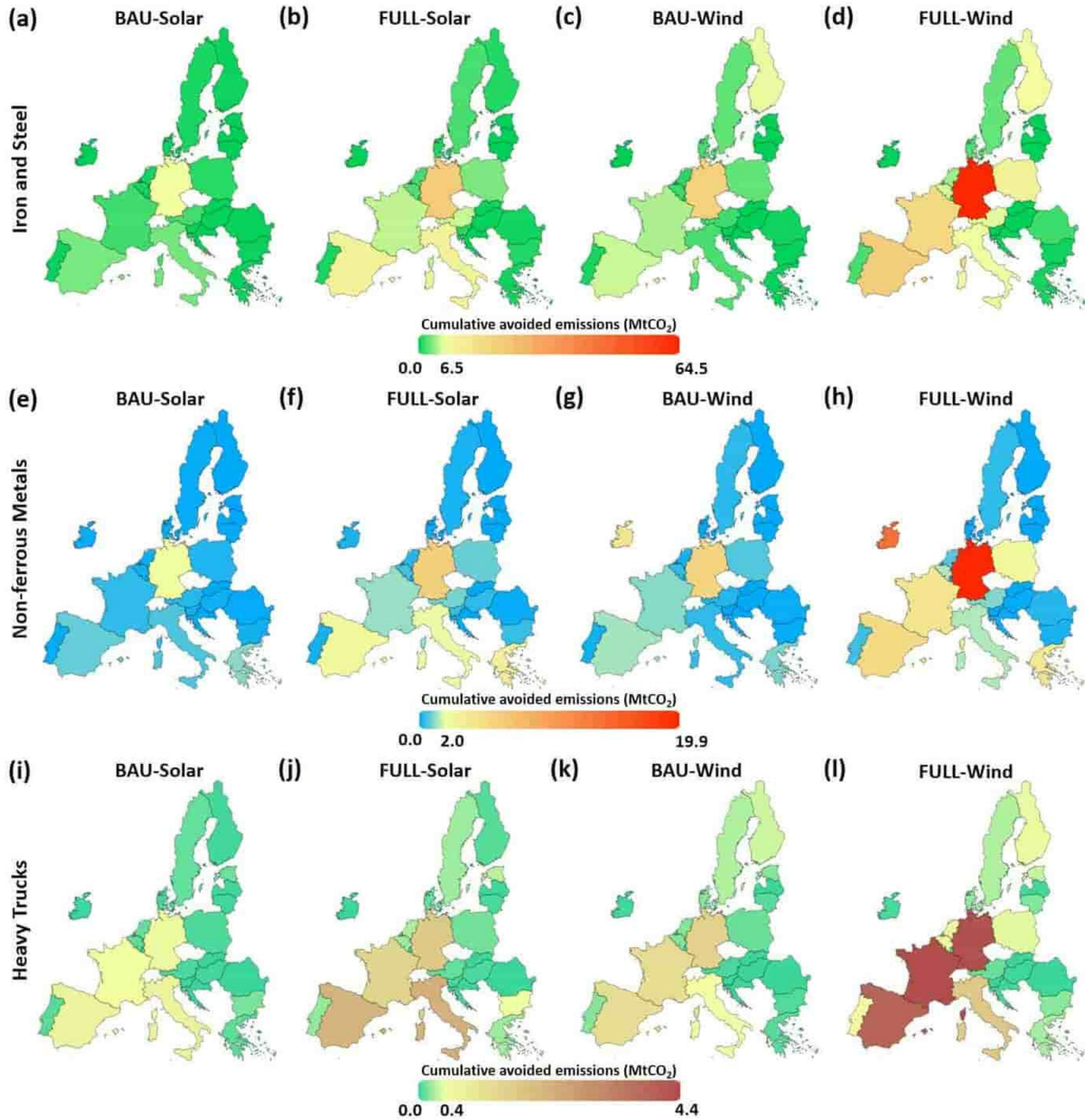

Fig. S15. *Cumulative avoided emissions (MtCO2) in EU member countries by 2050 in* ***a.,*** *the iron and steel sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the iron and steel sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the iron and steel sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the iron and steel sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the non-*

ferrous metal sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations. ***f.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the non-ferrous metal sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the operation of heavy trucks based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

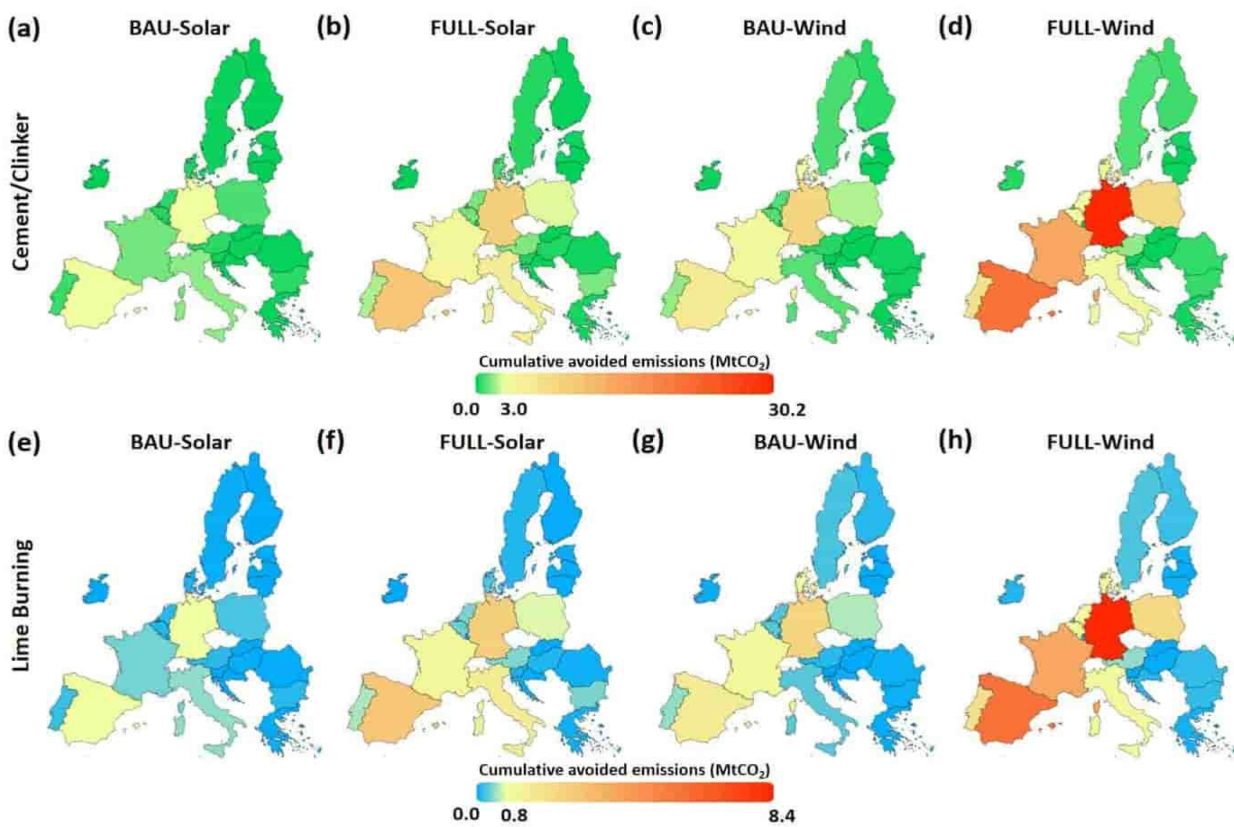

Fig. S16. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in* ***a.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the cement/clinker sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the lime-burning sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the lime-burning sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the lime-burning sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the lime-burning sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

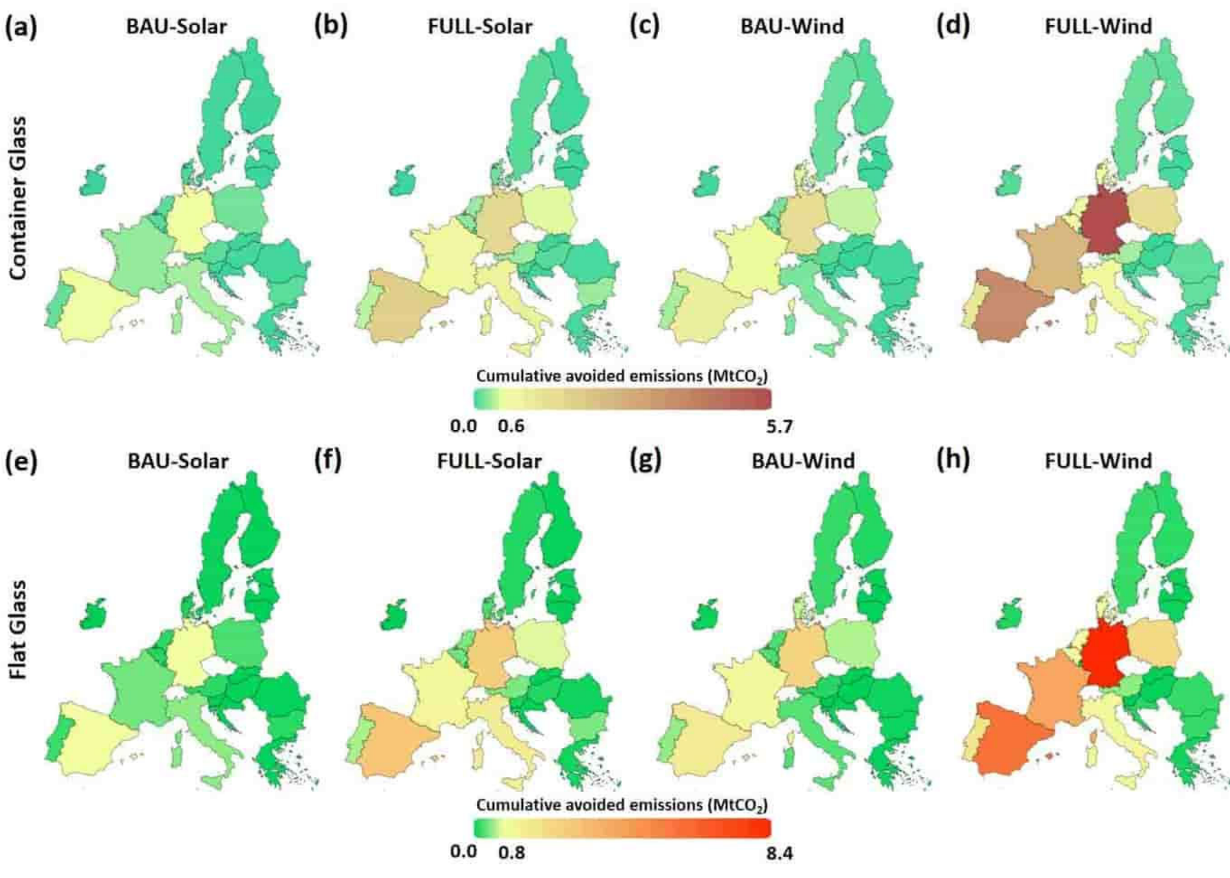

Fig. S17. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in* ***a.,*** *the container glass sector based on the use of green hydrogen technologies under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the container glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the container glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the container glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the flat glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the flat glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the flat glass sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the flat glass sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

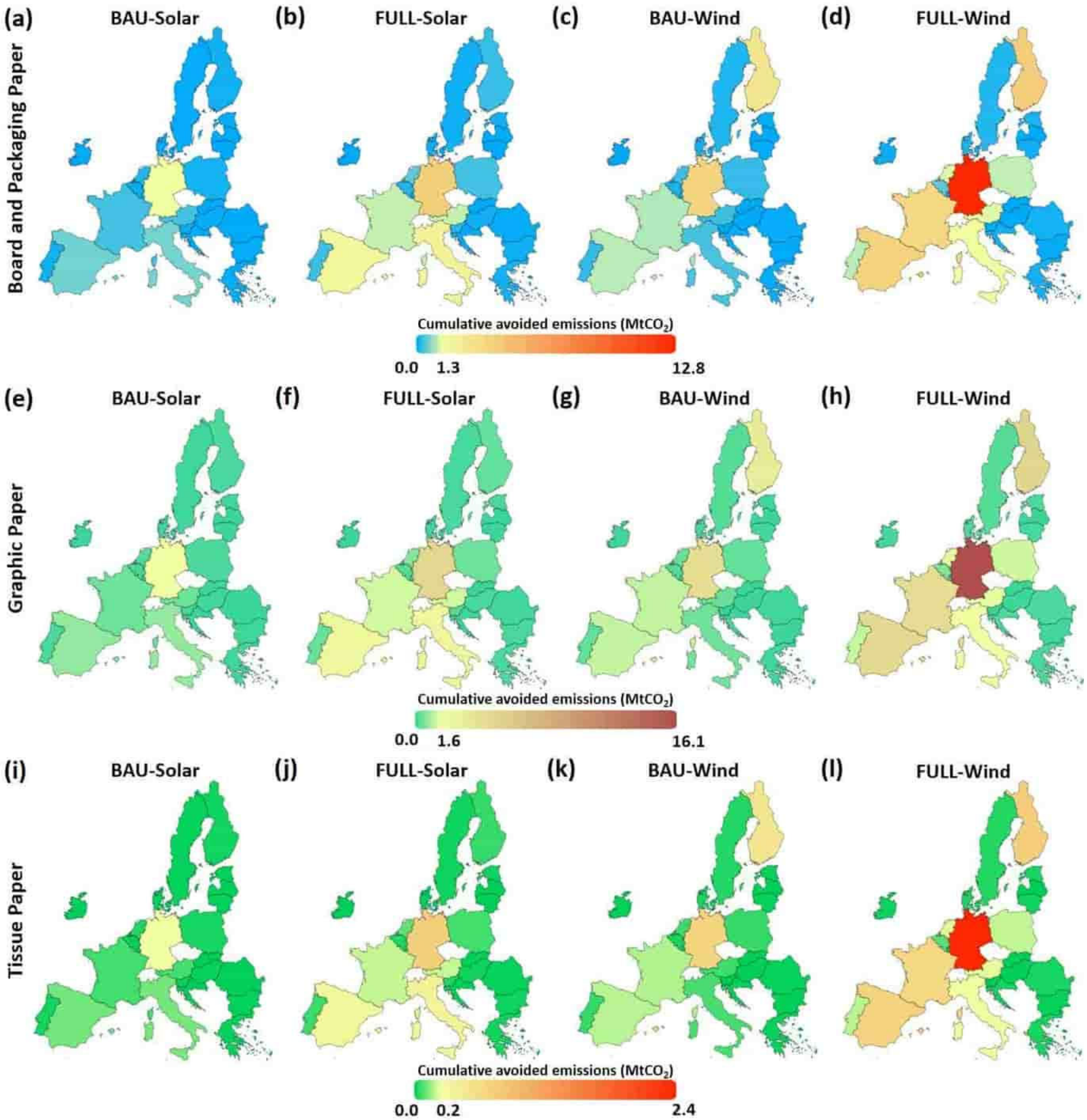

Fig. S18. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in* ***a.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the board and packaging paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind* *power installations.* ***e.,*** *the graphic paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the graphic paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the graphic paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the graphic paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***i.,*** *the tissue paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***j.,*** *the tissue paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***k.,*** *the tissue paper sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***l.,*** *the tissue paper sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

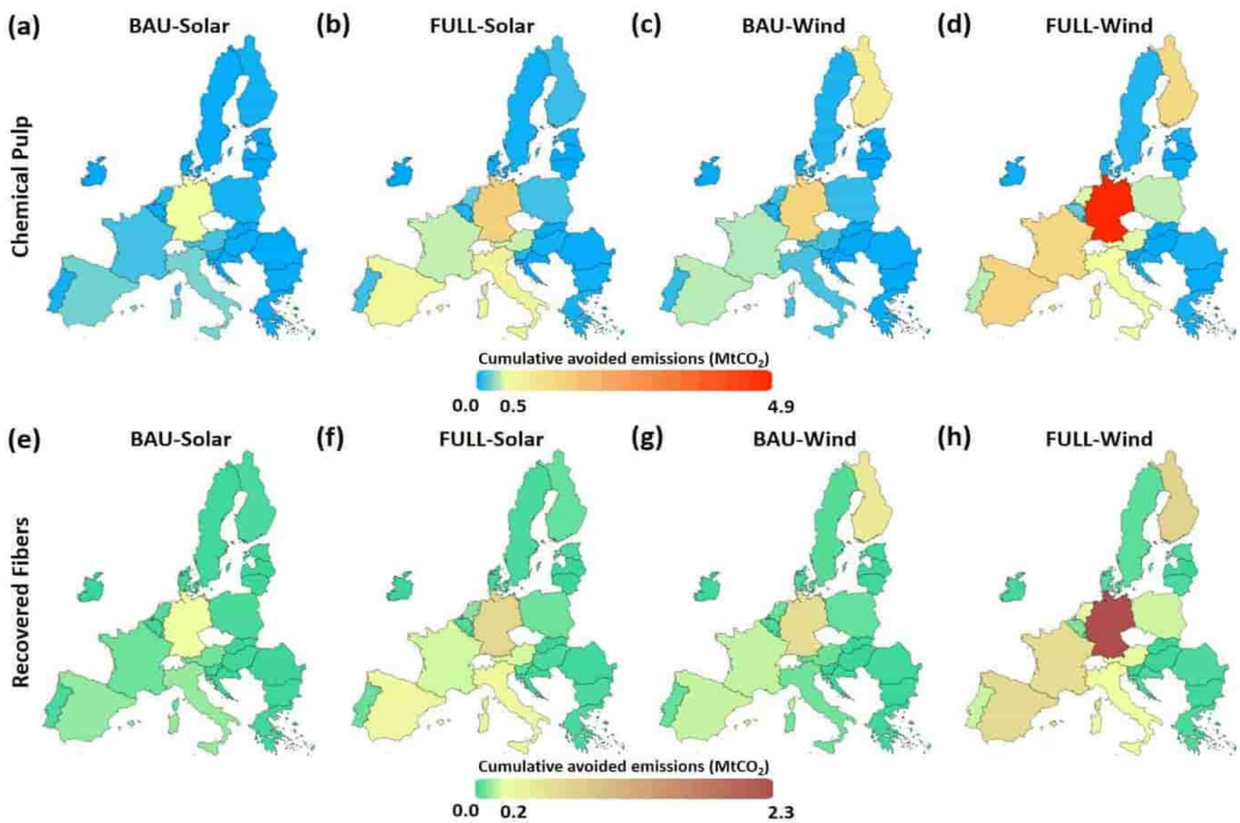

Fig. S19. *Cumulative avoided emissions ($MtCO_2$) in EU member countries by 2050 in* ***a.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the BAU* *implementation scenario for growth in solar power installations.* ***b.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the chemical pulp sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the recovered fibers sector based on the use of green hydrogen technologies under the FULL implementation scenario for growth in wind power installations.*

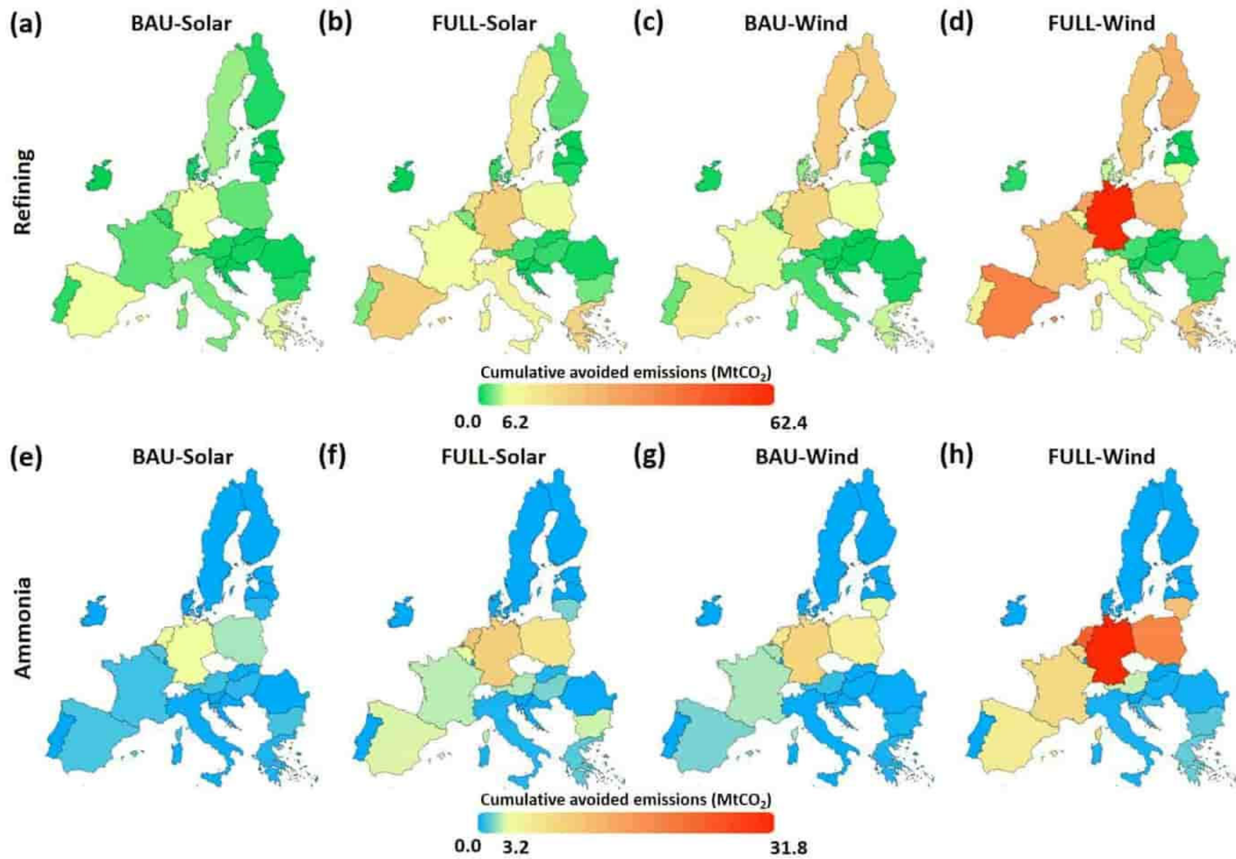

Fig. S20. *Cumulative avoided emissions (MtCO$_2$) in EU member countries by 2050 in* ***a.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen* *under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the refining sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *the ammonia sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.*

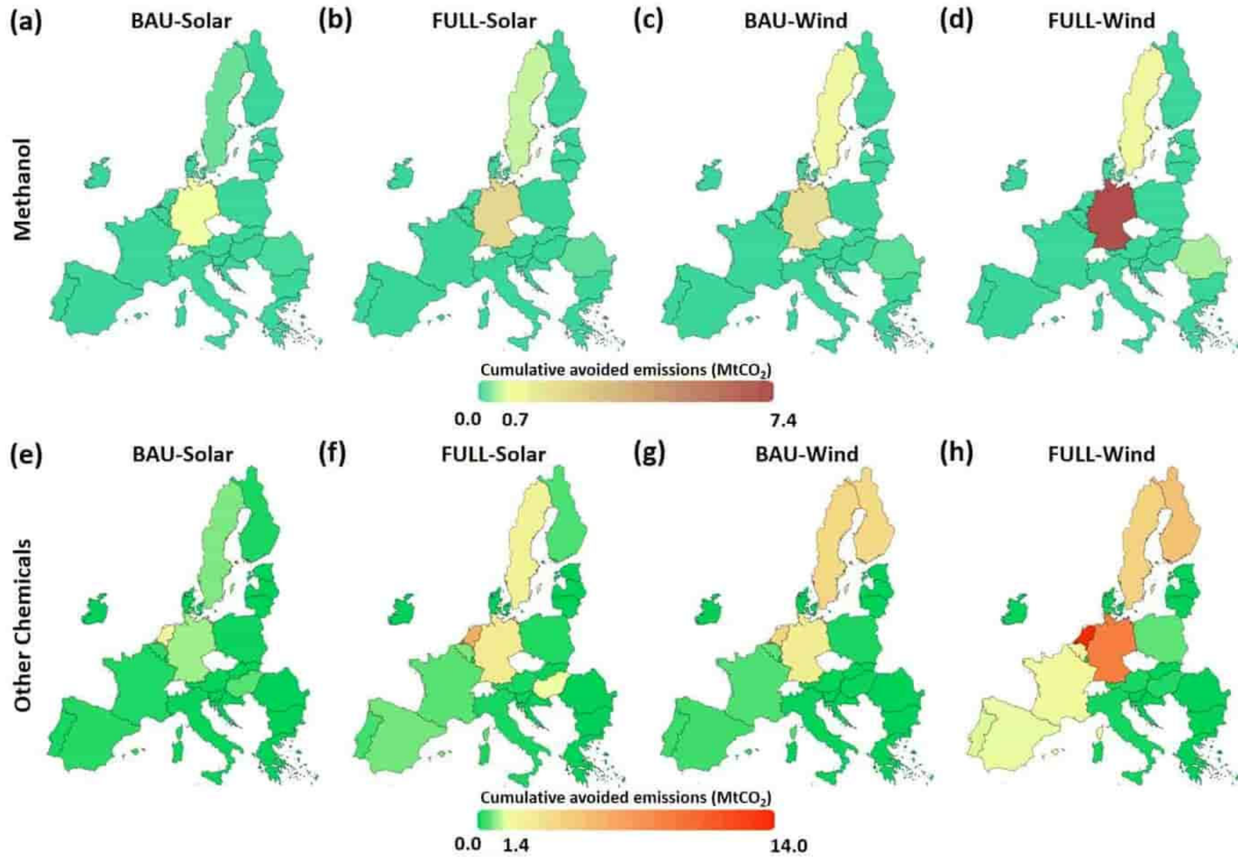

Fig. S21. *Cumulative avoided emissions (MtCO₂) in EU member countries by 2050 in* ***a.,*** *the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *the methanol sector based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *other chemicals based on the use of green hydrogen in place of natural gas-based hydrogen under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *other chemicals based on* *the use of green hydrogen in place of natural gas-based hydrogen under the FULL implementation scenario for growth in wind power installations.*

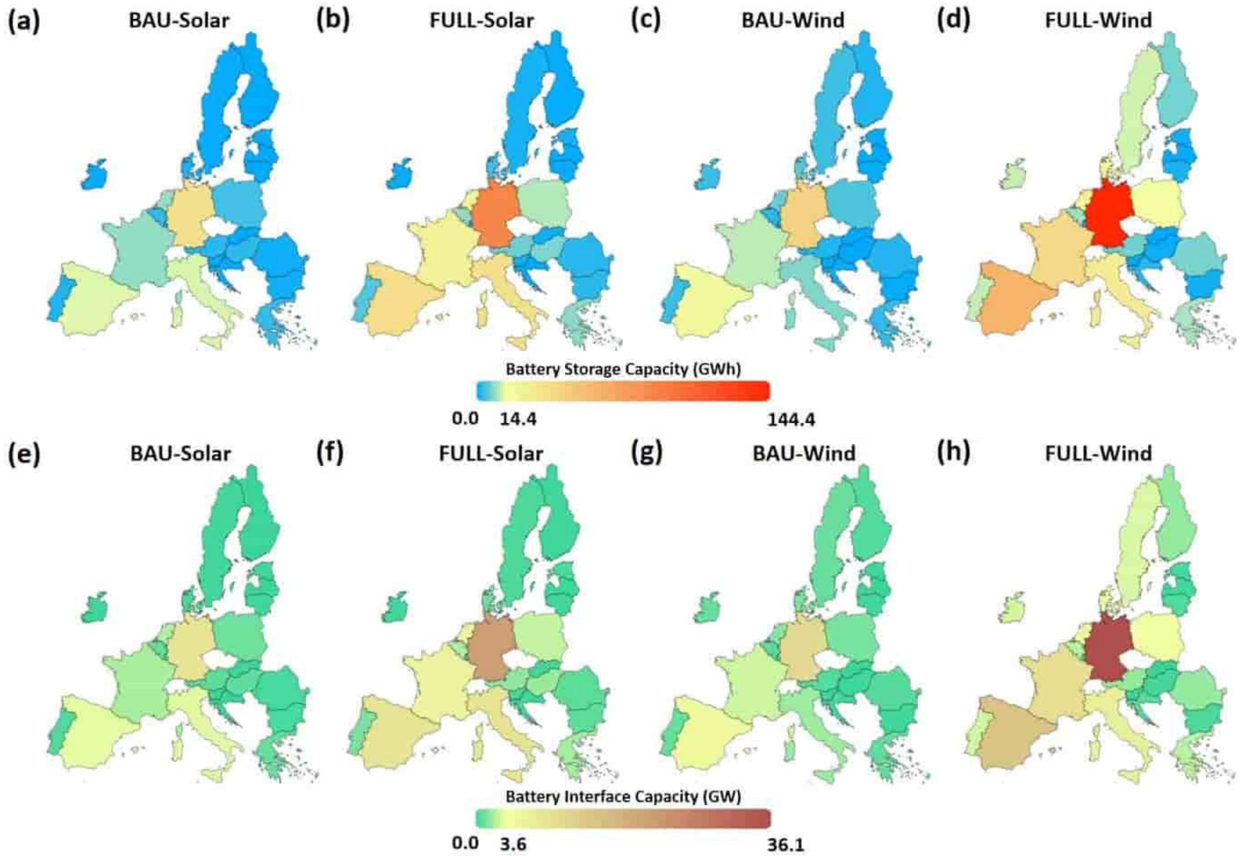

Fig. S56. a., *Battery storage capacity (GWh) to attain the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *Battery storage capacity (GWh) to attain the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *Battery storage capacity (GWh) to attain the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *Battery storage capacity (GWh) to attain the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *Battery interface capacity (GW) to attain the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *Battery interface capacity (GW) to attain the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *Battery interface capacity (GW) to attain the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *Battery interface* *capacity (GW) to attain the electrification potential under the FULL implementation scenario for growth in wind power installations.*

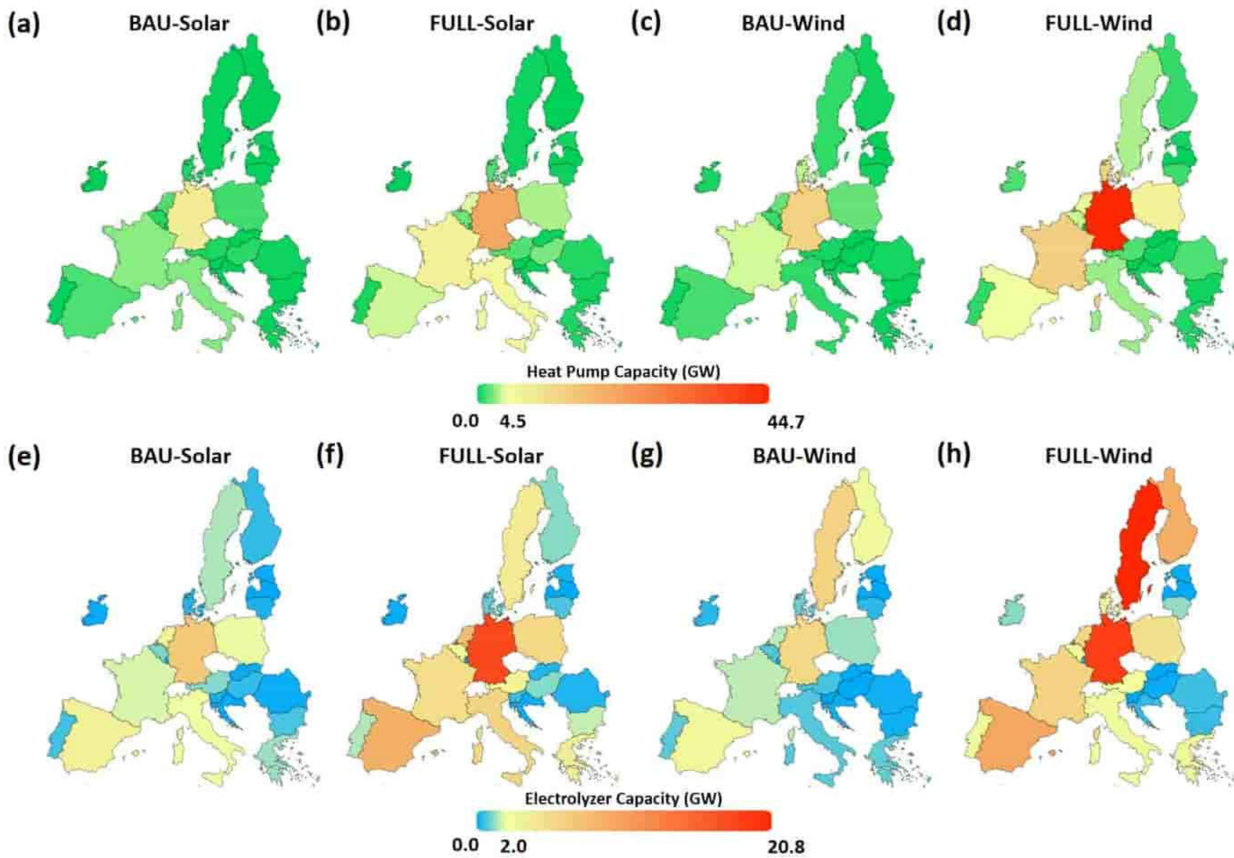

Fig. S57. a., *Heat pump capacity (GW) to attain the electrification potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *Heat pump capacity (GW) to attain the electrification potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *Heat pump capacity (GW) to attain the electrification potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *Heat pump capacity (GW) to attain the electrification potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *Electrolyzer capacity (GW) required for green hydrogen deployment under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *Electrolyzer capacity (GW) required for green hydrogen deployment under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *Electrolyzer capacity (GW) required for green hydrogen deployment under the BAU implementation scenario for growth in wind power installations.* ***h.,*** *Electrolyzer capacity (GW) required for* *green hydrogen deployment under the FULL implementation scenario for growth in wind power installations.*

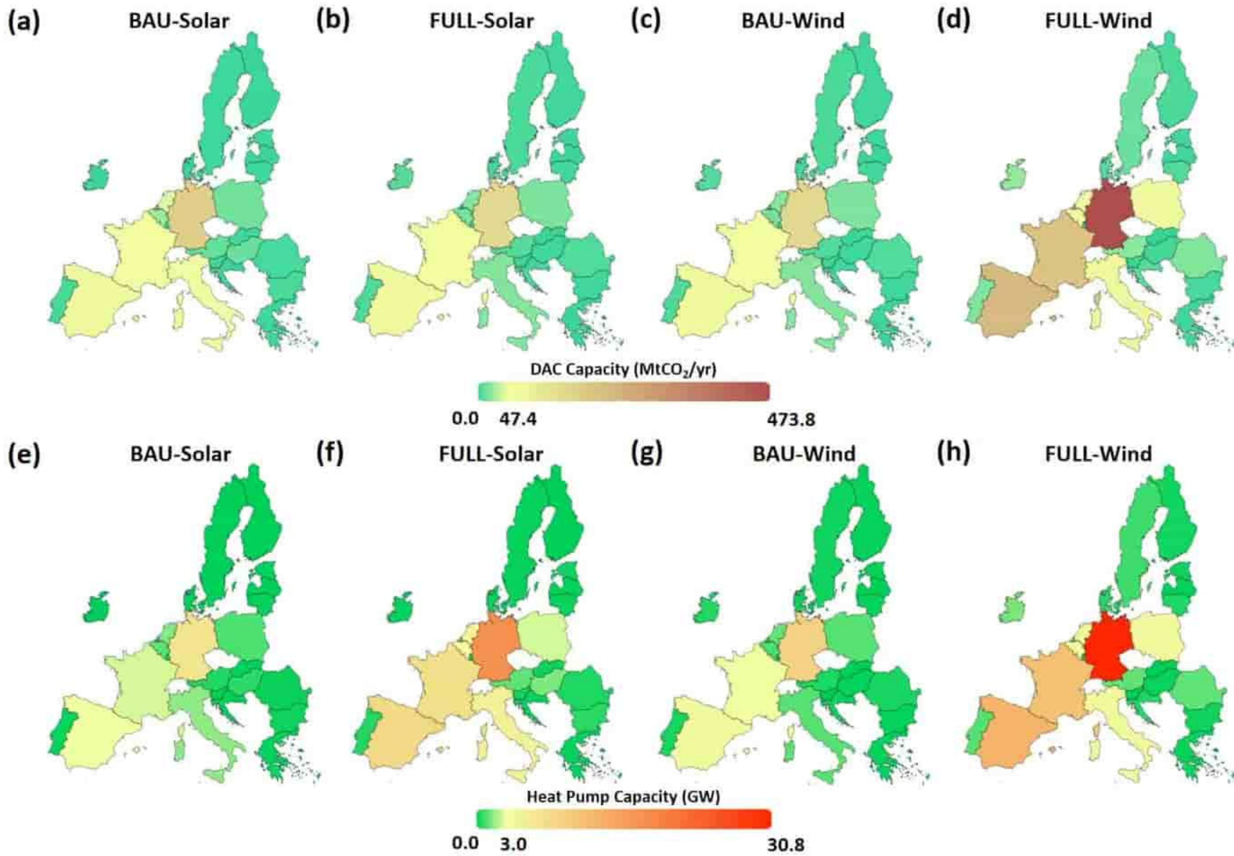

Fig. S58. a., *DAC carbon capture capacity (MtCO_2/yr) across EU countries to attain carbon offsetting potential under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *DAC carbon capture capacity (MtCO_2/yr) across EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *DAC carbon capture capacity (MtCO_2/yr) across EU countries to attain carbon offsetting potential under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *DAC carbon capture capacity (MtCO_2/yr) across EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *Heat pump capacity (GW) across EU countries to attain carbon offsetting potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *Heat pump capacity (GW) across EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *Heat pump capacity (GW) across EU countries to attain carbon offsetting potential under the BAU implementation* *scenario for growth in wind power installations.* ***h.,*** *Heat pump capacity (GW) across EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in wind power installations.*

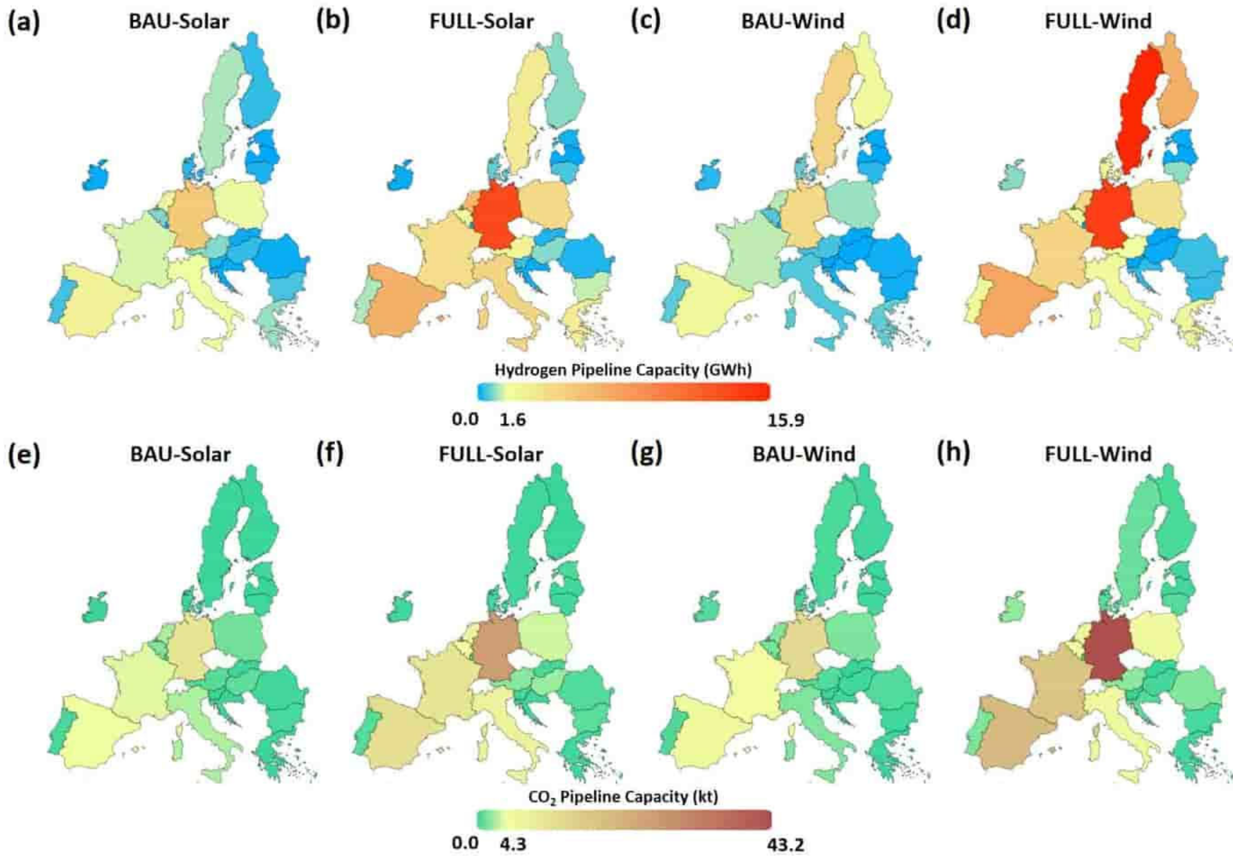

Fig. S59. a., *Hydrogen pipeline capacity (GWh) in different EU countries under the BAU implementation scenario for growth in solar power installations.* ***b.,*** *Hydrogen pipeline capacity (GWh) in different EU countries under the FULL implementation scenario for growth in solar power installations.* ***c.,*** *Hydrogen pipeline capacity (GWh) in different EU countries under the BAU implementation scenario for growth in wind power installations.* ***d.,*** *Hydrogen pipeline capacity (GWh) in different EU countries under the FULL implementation scenario for growth in wind power installations.* ***e.,*** *CO_2 pipeline capacity (kt) in different EU countries to attain carbon offsetting potential under the BAU implementation scenario for growth in solar power installations.* ***f.,*** *CO_2 pipeline capacity (kt) in different EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in solar power installations.* ***g.,*** *CO_2 pipeline capacity (kt) in different EU countries to attain carbon offsetting potential under the BAU implementation scenario for growth in wind power installations.* ***h.,***

CO_2 pipeline capacity (kt) in different EU countries to attain carbon offsetting potential under the FULL implementation scenario for growth in wind power installations.

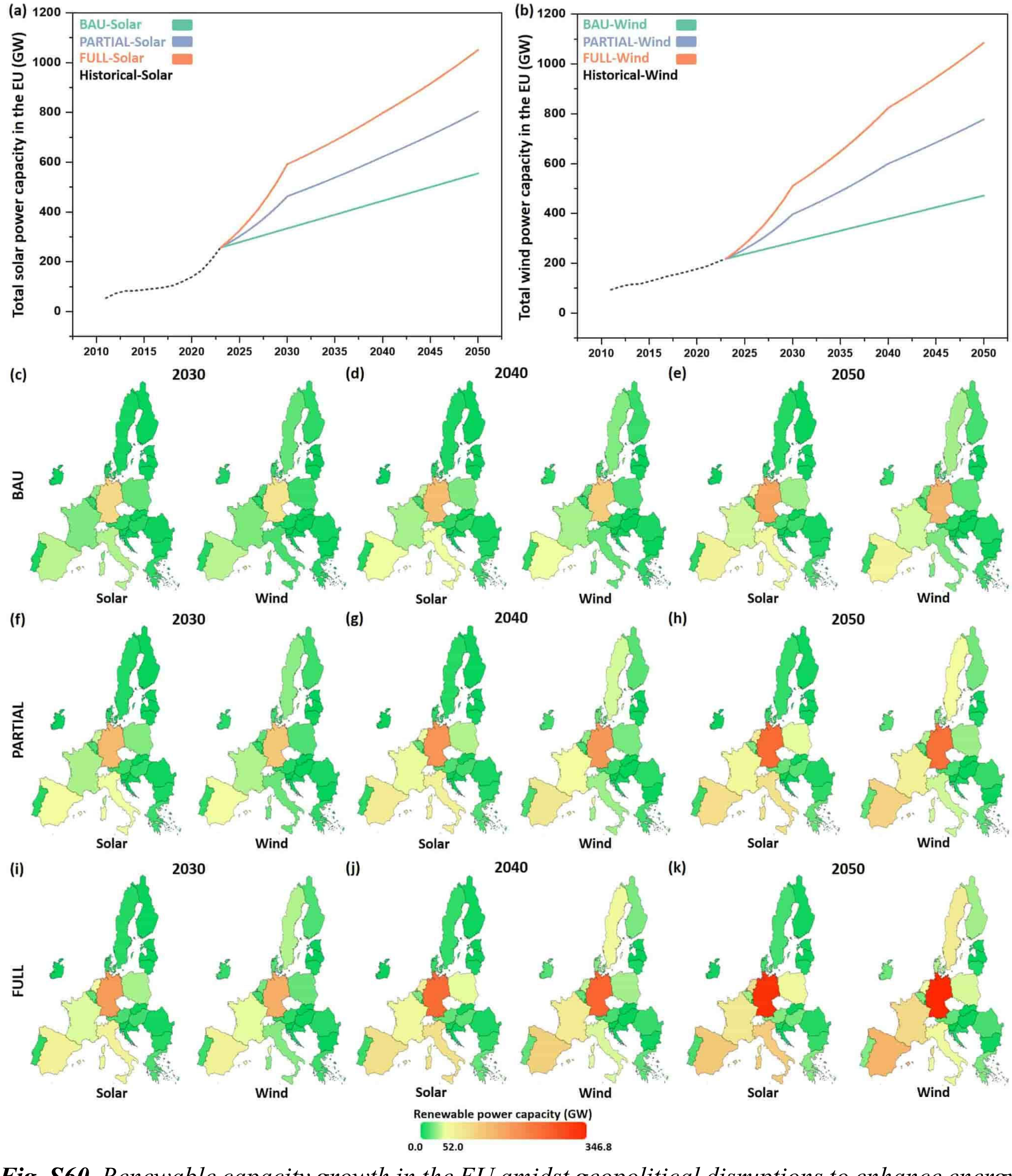

Fig. S60. *Renewable capacity growth in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability* ***a.,*** *Solar power capacity projections in the EU under different scenarios (GW).* ***b.,*** *Wind power capacity projections in the EU under different* *scenarios (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.*

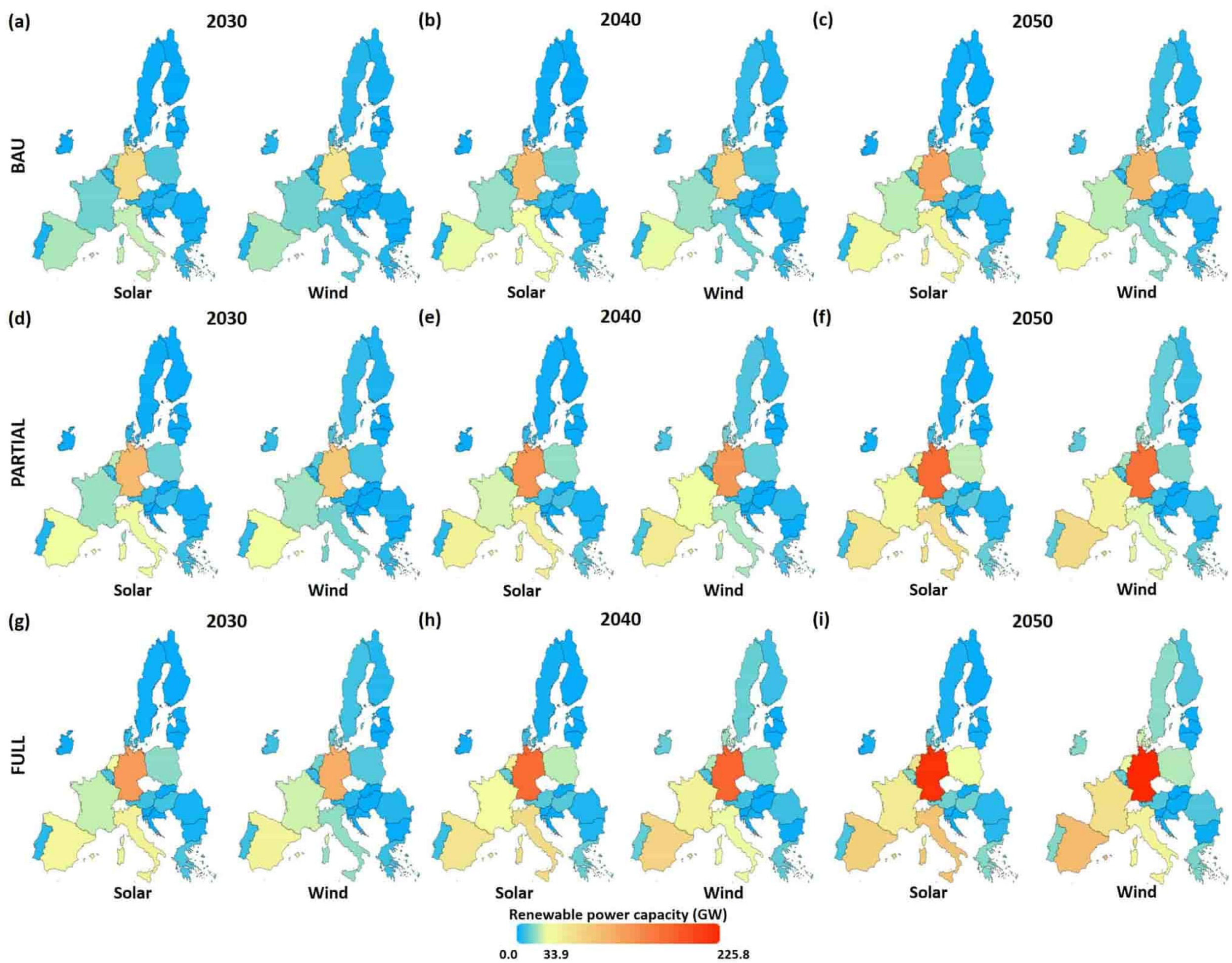

Fig. S63. *Renewable capacity expansion contributing to electrification potential in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability* ***a.,*** *Solar and* *wind power capacity utilized for electrification potential in different EU countries under the BAU 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.*

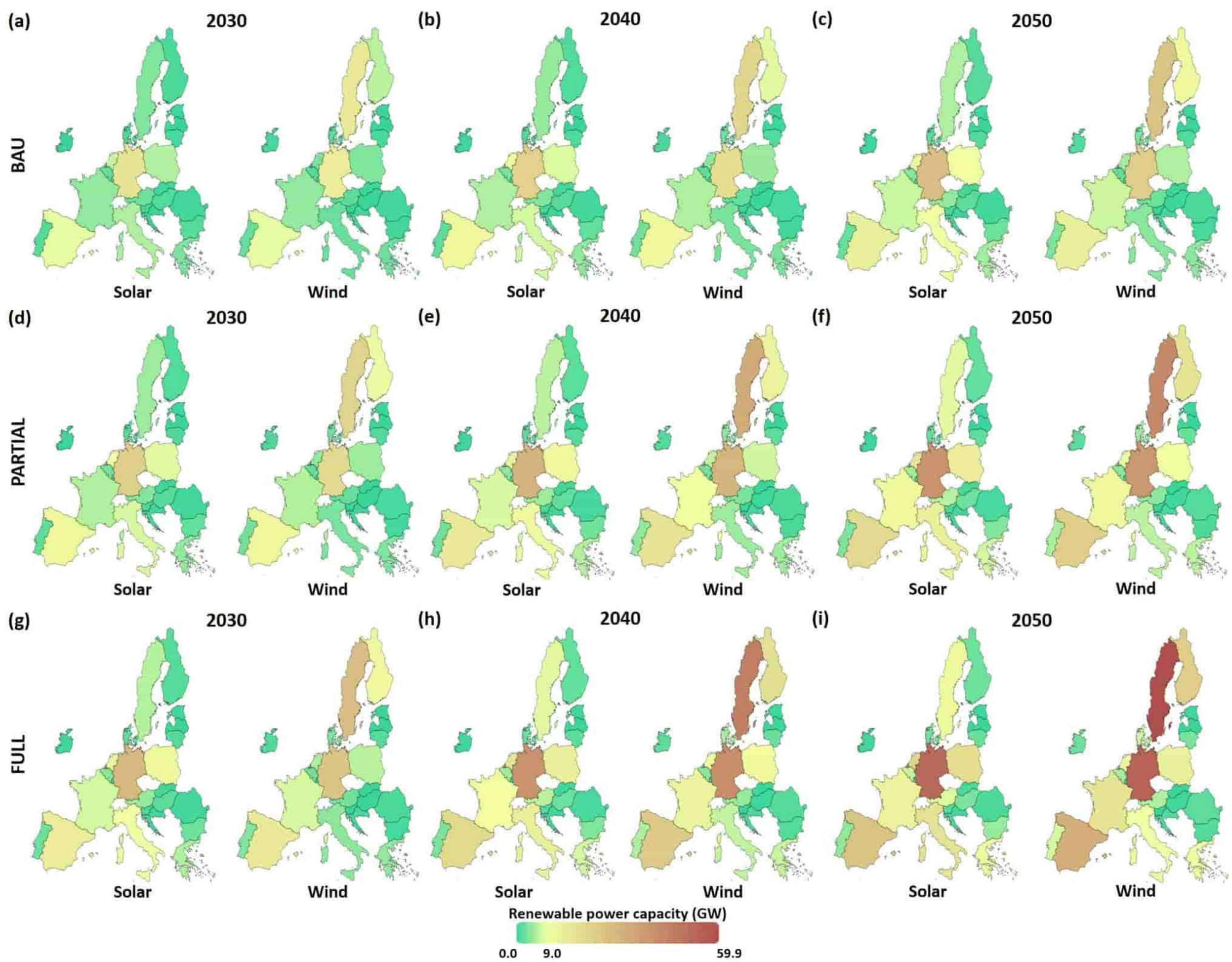

Fig. S64. *Renewable capacity expansion contributing to green hydrogen deployment in the EU amidst geopolitical disruptions to enhance energy security and climate sustainability* ***a.,*** *Solar and wind power capacity utilized for green hydrogen deployment in different EU countries under the BAU implementation 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.*

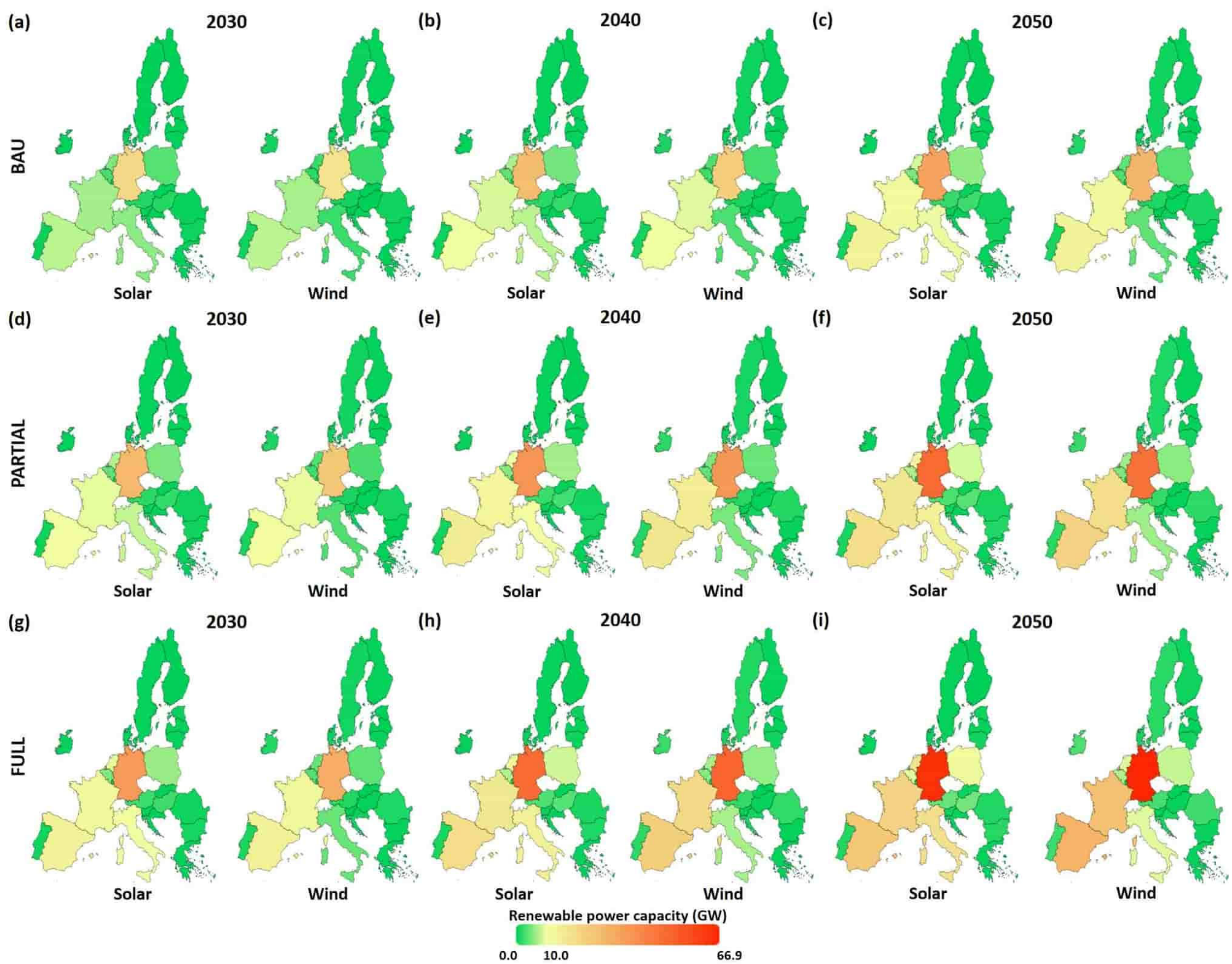

Fig. S65. *Renewable capacity expansion contributing to carbon offsetting potential through DAC systems in the EU amidst geopolitical disruptions to enhance climate sustainability* ***a.,*** *Solar and wind power capacity utilized for carbon offsetting through DAC systems in different EU countries under 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.*

Reviewer 2

Key Results

The manuscript presents an impressive energy modeling study that integrates scenario building and optimization techniques to assess economic implications. The modeling work adds to the existing body of knowledge, distinguishing itself from prior studies through its unique specifications, scope, and results. The findings provide valuable insights into energy system transformations, with potential implications for policy and economic decision-making. The study demonstrates that an accelerated deployment of solar and wind capacity, electrification of consumption, investments in green hydrogen for heavy industry, and direct air capture are economically feasible in the EU.

Validity

While the modeling framework appears robust, I do not have the necessary expertise to assess the soundness of the model itself.

Significance

The research contributes meaningfully to energy transition modeling and economic assessments. However, its broader claims regarding geopolitical and climate mitigation contributions are rather superficial. While the results are relevant to ongoing discussions about EU energy security and emissions reduction strategies, the paper does not provide enough depth in geopolitical analysis or climate mitigation to substantiate this as a significant contribution. The novelty lies primarily in the modeling approach rather than in geopolitical or climate policy insights.

More modest goals would improve the paper. The paper shows interesting results from a novel modelling exercise – this is valuable enough – it does not need to make claims about geopolitics or climate mitigation. Simply mentioning once that the results of the paper will be relevant in the context of the EU trying to reduce reliance on gas imports while keeping its climate targets on track should suffice.

Data and Methodology

The methodological approach seems sound, and the data presentation is comprehensive in the ample supplementary material.

Analytical Approach

The analytical rigor of the modeling exercise appears strong, but the broader discussions on geopolitics and climate mitigation are not fully developed. The statistical and scenario-based *analyses are well-structured, yet the claims about broader policy implications should be either developer or (preferably) pruned. If the authors wish to include policy discussions, they should provide a more in-depth analysis rather than high-level statements.*

Suggested Improvements

Reviewer's Comment (1)

Refocus the scope – The paper currently attempts to contribute to multiple distinct areas, including geopolitics and climate mitigation, but does not provide sufficient depth in these domains. A more modest and focused objective centered on the modeling exercise itself would strengthen the manuscript.

Answer: Thanks for the comment. We agree with the reviewer's feedback to present a more focused objective in this work. To address this, we have implemented the following revisions in the manuscript:

- In the revised Introduction section:
  - While the broader framing includes references to energy security and climate mitigation, the opening paragraph has been revised to clearly articulate the research question centered on detailed scenario-based evaluation and sector-specific interventions.
  - We have also explicitly indicated that this work prioritizes modeling and analytical depth instead of detailed geopolitical nuance to better delineate the scope and contributions of the study.
  - We have strengthened the review of existing literature, particularly studies related to energy transition models in Europe. These paragraphs position the knowledge gap addressed in this work relative to prior assessments and outline the novel contributions through a set of bullet points.
  - To further contextualize these contributions, Table S1 presents a comparative summary of key focus areas, insights from prior literature, and the corresponding contributions of this study.
- While presenting the results of this work, we have ensured that references to geopolitical or climate policy dimensions are now presented in a measured and contextual manner, without overstating their significance relative to the modeling construct.

- The revised Systems Analysis Framework section in the main file emphasizes the methodological structure and analytical components of the modeling framework, reinforcing the study's focus on scenario-based assessment.

Action

- *On pages 2 to 4 of the revised main file:*

"The continued dependence of EU energy demand on fossil fuel supplies underscores the pressing challenge of energy security, particularly in light of recent geopolitical tensions. The Russia-Ukraine conflict, for instance, exemplifies the concerns with surging energy prices[1, 2] and persistent disruptions in fossil fuel supply chains[3]. In this context, a targeted focus on reducing sector-specific natural gas consumption remains critical, given its continued role as a key input across electricity, heating, industrial, and transportation sectors[4], emergence as a principal vulnerability during recent geopolitical disruptions[5], and intertwined implications for the climate crisis. For instance, Russian gas imports, which previously accounted for over 40% of the EU's natural gas supply, represented around 11% in 20244, underscoring the severity of the shift caused by geopolitical tensions. While other energy imports, such as oil, also play a role in the EU's energy mix, analysis by the European Parliament indicates that the EU has numerous options for oil imports, as it is flexibly traded and transported across the world[6]. However, natural gas remains a pressing challenge due to its heavy reliance on pipelines[7], which are time-consuming to develop[8] and highly vulnerable to supply disruptions[9]. Alongside the potential risks to future energy security in the EU[10, 11], climate change persists as an impending crisis. The proximate deadlines for the climate targets, particularly those set for 2030, 2040, and 2050[12, 13], necessitate robust strategies to curtail carbon emissions across diverse sectors. Moreover, the uncertainty surrounding the economic implications of geopolitical tensions, such as higher costs[14] and economic slowdowns[15], necessitates evaluating how varying cost development trajectories affect the competitiveness of sector-specific clean energy strategies across the EU. Therefore, a critical gap persists in the systematic evaluation of strategic interventions driven by renewable capacity expansion, across spatial, sectoral, and temporal horizons in the EU, along with the associated economic implications, thereby necessitating scenario-based assessment to inform infrastructure planning and policy decisions. This analysis aims to address these questions without delving into deep geopolitical nuances.

Empirical assessments demonstrate that renewable energy deployment can act as a substitute for energy imports, with various EU countries exhibiting improved efficiency and productivity through technological innovation and convergence toward renewable energy and energy security goals[16]*. Tracking the evolution of energy security indicators reveals that diversification of primary energy sources, along with the share and diversity of energy imports, are key drivers of improvement, with regional cluster analysis highlighting transferable policy insights*[17]*. Complementary assessments further suggest that sufficiency measures can substantially reduce final energy demand and alleviate pressure on supply-side interventions by 2050*[18]*. These insights are reinforced by policy mechanisms such as REPowerEU 2030*[19, 20]*, and the recently announced targets for 2040*[21]*, which collectively signal a strategic pivot toward renewable energy across electricity, heating, and transportation to reduce natural gas dependence. Nonetheless, recent setbacks in global emissions reduction efforts*[22, 23] *and reduced accessibility to affordable energy in the EU*[24] *reveal the susceptibilities in pre-conflict energy and climate strategies, indicating the need for scenario-based frameworks that align energy security improvements with climate mitigation, using reductions in natural gas consumption as a central metric across diverse renewable deployment pathways.*

Previous studies also examine the European energy transition using modeling frameworks based on least-cost optimization to determine energy system configurations[25, 26, 27]*, or offer insights at the transmission network level*[28]*. These analyses outline the diversity of feasible system designs*[29]*, foster communication across societal levels*[30]*, generate high-level insights for multi-sector system integration*[31]*, and investigate grid constraints*[32]*. Some assessments also focus on individual energy pathways*[33, 34]*, or region-specific crisis responses*[2]*, without directly addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions. Within this broader transition landscape, sectors that are difficult to electrify, such as heavy industries, require complementary technological pathways. Green hydrogen emerges as a promising vector for advancing energy transition and climate mitigation goals*[35, 36]*, supported by the expansion of renewable capacity and offering a critical alternative to natural gas in heavy industries*[37, 38, 39]*. Recent literature highlights the importance of competitive and secure renewable hydrogen to minimize reliance on single suppliers*[40]*. Regional assessments further underscore the role of hydrogen infrastructure during the energy crisis*[41]*, the feasibility of substituting carbon-intensive hydrogen production with renewable-based electrolysis*[42]*, and the potential of hydrogen and* *power-to-liquid pathways to reduce energy-related import costs[43]. Additionally, studies emphasize the role of hydrogen in decarbonizing the European energy system, with projections of substantial hydrogen production by 2050[44, 45]. However, these opportunities require careful policy choices to avoid perpetuating long-standing vulnerabilities[46]. These insights reinforce the need for sector-disaggregated analysis aimed at reducing natural gas consumption and emissions through targeted interventions, evaluated across diverse cost trajectories, to advance EU-wide energy security and decarbonization outcomes.*

While previous studies provide valuable perspectives, also summarized in Table S1 for comparative reference, this work seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation in the EU energy landscape, with the following novel contributions:

- *Develops a comprehensive scenario-based assessment centered on renewable expansion pathways and incorporating targeted strategies, including electrification, green hydrogen deployment, and carbon offsetting, to align the EU's dual goals of energy security and climate sustainability amidst geopolitical disruptions.*
- *Introduces a sector-disaggregated framework targeting reductions in natural gas consumption and emissions across electricity and heating, light and heavy industries, and transportation, capturing the differentiated impacts of transition strategies across spatial and temporal horizons in the EU.*
- *Establishes a robust analytical framework to evaluate the economic feasibility of targeted interventions, incorporating a comprehensive spectrum of technology cost trajectories informed by historical learning rates under varying renewable expansion scenarios."*

- *We have presented the revised text in the Results section in response to Comment 6. To reduce the length of this file, please refer to pages 101-105 for the complete revision.*
- *We have presented the revised text in the Systems Analysis Framework section in response to Comment 1 from Reviewer 1. To reduce the length of this file, please refer to pages 3-6 for the complete revision.*

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Reviewer's Comment (2)

Concise framing of geopolitical discussion – The discussion on EU geopolitics is superficial. Key missing elements include internal gas production, the potential shifts in US LNG exports post-November 2024, and the complexities in defining 'allies.'

Answer: Thanks for the comment. We agree with the reviewer's feedback to strengthen the discussion on geopolitical framing. In the revised manuscript, we address the key issues including internal gas production with the sharp reduction in Russian natural gas supplies, the increase in US LNG exports to Europe and the associated strategic considerations in the long term, and the fluid nature of international alliances. Moreover, we contextualize the findings of this work within this revised framing to present a multi-layered energy strategy that incorporates the complementary components of domestic interventions, intra-EU coordination, and selective international partnerships.

Action

- *On page 19 of the revised main file:*

*"The EU's energy landscape faces a pivotal moment due to the evolving geopolitical events of recent years. While domestic natural gas production in the EU declined by 9% in the first nine months of 2022[87] and by 18.6% in 2023 compared to the previous year[88], a defining shift occurred with the sharp reduction in imports from Russia, falling from over 40% in 2021 to around 11% by 2024[4], triggered by the geopolitical fallout of the conflict. This disruption prompted an urgent reassessment of energy security strategies across member states[89]. For instance, the EU diversified its energy imports, notably increasing natural gas supplies from the US by 138.6% over the same period[4]. However, this reconfiguration introduced new strategic complexities. Recent shifts in US foreign policy discourse signal a potential inclination to frame energy exports as essential geopolitical levers[90], such as in trade negotiations[91], thereby highlighting strategic considerations surrounding the long-term reliability of US energy supplies[92]. Moreover, the evolving geopolitical landscape reveals that international alliances are increasingly fluid[93], shaped by shifting strategic interests. In this context, the findings of this work underscore the need for a multi-layered strategy, combining domestic electrification and green hydrogen deployment in the investigated scenarios (**Figs. 1** and **3**) which can reduce up to 61.3% of gross inland consumption of natural gas by 2050, which can be further improved with coordinated intra-EU trade and selective international partnerships. While regional integration within the EU can unlock clean electricity and hydrogen*

*trade opportunities by leveraging surplus capacities in specific member states (**Figs. S23** and **S24**), the extent of reliance on external suppliers must be approached pragmatically. In order to avoid substituting one dependency for another, residual sector-specific substitution needs (**Fig. S25**) should guide the design of essential future trade strategies to prevent a recurrence of past vulnerabilities. For example, in sectors such as electricity and heating, light industries, and segments of the road transportation sector, clean energy electrification through international corridors can play a significant role. In contrast, for hard-to-abate sectors like heavy industries, green hydrogen carriers represent more effective alternatives to reduce natural gas reliance."*

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Reviewer's Comment (3)

Reduce length and repetition – The manuscript is unnecessarily long and at times repetitive, particularly in discussions on geopolitics and climate mitigation. Streamlining the text would enhance readability and focus.

Answer: Thanks for the comment. Following the reviewer's feedback, we have streamlined the text throughout the manuscript, particularly in discussions on geopolitics and climate mitigation, to reduce repetition and enhance clarity.

Action

- *We have presented the revised text in the Introduction section in response to Comment 1. To reduce the length of this file, please refer to pages 86-89 for the complete revision.*
- *We have presented the revised text in the Results section in response to Comment 6. To reduce the length of this file, please refer to pages 98-102 for the complete revision.*
- *We have presented the complete revised text in the Discussion section in response to Comment 6 from Reviewer 4. To reduce the length of this file, please refer to pages 182-186 for the complete revision.*

Reviewer's Comment (4)

Clarify terminology – The term 'offsetting' is used in a way that differs from its conventional meaning in emissions trading. The authors should align this term with standard usage or provide a clear definition.

Answer: Thanks for the comment. Following the reviewer's feedback, we have defined "offsetting" in the context of this analysis as referring specifically to the deployment of DAC systems powered by clean electricity, and have included the relevant citations.

Action

- *On page 5 of the revised main file:*

"The proposed scenarios allow the sector-specific evaluation of reducing natural gas consumption, where renewable capacity expansion supports electrification, green hydrogen deployment, and the potential for carbon offsetting through Direct Air Capture (DAC) systems[53, 54, 55]*, directly contributing to the EU's dual goals of energy security and climate change mitigation."*

- *On page 28 of the revised main file:*

"In order to address residual natural gas consumption, the analysis incorporates carbon offsetting using solid-sorbent DAC systems, which can operate solely on electricity derived from clean energy sources[133] *and require low regeneration temperatures*[134]*."*

References

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Reviewer's Comment (5)

Update discussion points – Certain statements in the discussion section undermine the strength of the modeling work, either due to outdated claims or overly optimistic assertions:

Outdated: The role of targeted subsidies and feed-in tariffs has been well-established for over a decade; revising this statement to reflect current policy dynamics would be beneficial.

Wishful thinking: The assertion that fostering symbiotic relationships with supplier countries will enable green energy transitions is an idealized perspective that has proven difficult to achieve in practice.

Inaccurate: The manuscript refers to 'international agreements such as COP28,' but the COP is a decision-making body, not an international agreement. This should be corrected.

Answer: Thanks for the comment. We agree with the reviewer's feedback on updating the discussion points. In the revised manuscript, we have removed references to targeted subsidies and feed-in tariffs and instead expanded the discussion on the design and implementation of carbon credit systems, highlighting how the proposed strategies align with equity objectives and the planned targets for this decade under policy instruments such as the EU Emissions Trading System (ETS). We have also revised the reference to COP28 to accurately reflect its role as a decision-making body. The revised manuscript also avoids the assertion of symbiotic relationships and now presents the findings within a revised framing of a multi-layered energy strategy that incorporates domestic interventions, intra-EU coordination, and selective international partnerships.

Action

- *We have presented the revised text addressing the updated discussion points in response to Comment 6 from Reviewer 1 and Comment 2. To reduce the length of this file, please refer to pages 34-35 and 96-97 for the complete revision.*

Reviewer's Comment (6)

Clarity and Context

The paper's clarity can be improved by streamlining discussions and avoiding redundant explanations. The results should be contextualized appropriately, avoiding overstated or oversimplified claims about geopolitical or climate policy contributions. A brief mention of how the findings relate to EU energy security and climate targets should suffice, without making it a central claim.

Answer: Thanks for the comment. Following the reviewer's suggestion, we have revised all results sub-sections to eliminate redundant discussion and streamline the presentation of findings. We have also ensured that references to geopolitical or climate policy contributions are presented in a measured and contextual manner, without overstating their significance. The relationship between the results and EU energy security or climate targets is now mentioned appropriately where relevant.

Action

- *On page 8 of the revised main file:*

*"The findings presented in **Fig. 1**a illustrate the reductions in EU-wide natural gas consumption through electrification strategies targeting the electricity and heating sector, light industries, and road transportation. Specifically, we evaluate the percentage decrease in gross inland natural gas consumption compared to 2023 levels, using this as a central metric to assess the alignment of energy security improvements with long-term climate mitigation goals. To complement this aggregate assessment, **Fig. S26** presents changes in natural gas import dependency rate, offering additional insight into potential shifts in supply-side exposure across scenarios. The BAU-solar and BAU-wind scenarios lead to reductions of 15.5% and 29.4%, respectively, while the FULL-solar and FULL-wind scenarios achieve greater reductions of 32.6% and 50.9% by 2050. The PARTIAL scenarios yield intermediate outcomes, with reductions ranging from 24.8% to 46.3%, representing a transitional trajectory between incremental and accelerated renewable deployment. The inclusion of the PARTIAL-solar and PARTIAL-wind scenarios is particularly relevant for illustrating moderate expansion pathways, where the EU may encounter constraints related to infrastructure planning[56], policy uncertainty[20], or regional deployment feasibility[57, 58]. These reductions in natural gas consumption translate into substantial cumulative avoided emissions (**Fig. 1**b), with the FULL-wind scenario enabling up to 6.0 $GtCO_2$ of mitigation*

potential by 2050. The results for the PARTIAL (2.3 $GtCO_2$ to 4.9 $GtCO_2$) and BAU scenarios (1.3 $GtCO_2$ to 2.7 $GtCO_2$) highlight the differentiated impact of scenario ambition on long-term mitigation pathways. ***Figs. 1****o and p illustrate a sectoral breakdown of the total reduction in natural gas consumption across the EU, encompassing electricity and heating, light industries, and the road transportation sector.* ***Figs. S31-S55*** *evaluate system-level operational challenges by presenting frequency distributions of normalized net-load ramp rates, which reflect how increased renewable integration influences temporal flexibility requirements across EU countries under different scenarios.*

Across the different scenarios, the sector-specific contributions to climate benefits are disaggregated in ***Figs.*** *1c-n. For the electricity and heating sector (****Figs.*** *1c-f), Germany, France, Italy, Spain, and the Netherlands exhibit the greatest mitigation potential, with Germany alone contributing up to 1770.0 $MtCO_2$ by 2050 under the FULL-wind scenario. Similarly, results for the light industrial sector (****Figs.*** *1g-j) reveal that countries such as Germany, France, and Spain, can cumulatively avoid up to 515.0 $MtCO_2$ under the BAU scenarios and 591.2 $MtCO_2$ under the FULL implementation scenarios by 2050. The analysis extends to the road transportation sector (****Figs. 1****k-n), where electrification of passenger cars, light commercial vehicles, buses, and coaches in countries like France, Italy, and Spain enables total emissions reductions ranging from 3.9 $MtCO_2$ to 21.4 $MtCO_2$. Lastly, the detailed sectoral breakdowns across EU countries, capturing the spatial heterogeneity in reductions in natural gas consumption (****Figs. S1-S4****) and avoided emissions (****Figs. S12-S14****), offer a basis for targeted policy interventions by entities such as the European Commission, helping identify where deployment efforts can yield the highest impact.* ***Figs. S56*** *and* ***S57*** *further illustrate the regional distribution of the required technological infrastructure across the EU under the investigated scenarios.”*

- *On page 11 of the revised main file:*

“In order to evaluate the economic implications of strategic scenarios, this work assesses the levelized cost of electricity (LCOE), levelized cost of heat (LCOHe), and the total cost of electrification potential under three cost development trajectories categorized as slow, nominal, and fast. These trajectories reflect varying learning rates informed by historical trends[59], capturing uncertainties in future cost competitiveness. ***Figs. 2****a and b illustrate the spatial variation in LCOE in 2024 and under a fast trajectory in 2050 for solar and wind power expansion,*

incorporating battery storage. The average LCOE across EU countries is \$0.16/kWh for solar and \$0.08/kWh for wind, based on country-level estimates, which drops by 60.9% and 46.0% in 2050, respectively. ***Figs. 2****c and d present the corresponding spatial variation in LCOHe driven by solar and wind power installations.* ***Fig. 2****e presents the total cost of electrification potential across different scenarios (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind) under varying cost trajectories through 2050. In the FULL-wind scenario, the total cost reaches \$173.2 bn under the slow trajectory but declines by 13.7% under the fast trajectory. The comparison highlights the role of accelerated cost reductions, potentially driven by policy support and investment incentives, in enhancing economic feasibility. Similarly, under the PARTIAL-solar and PARTIAL-wind scenarios, total electrification costs reach \$62.7 bn and \$102.3 bn, respectively, by 2050 under the nominal trajectory. These intermediate pathways illustrate a cost-effective middle ground between ambitious deployment targets and economic feasibility across the EU. Moreover, the results show that in pathways with dominant wind capacity (e.g., FULL-wind), the incremental cost of solar expansion becomes marginal, offering flexibility in deployment strategy. To contextualize the cost estimates presented in* ***Fig. 2****, an additional analysis is conducted across the EU and disaggregated NUTS-2 regions within Germany (****Figs. S27-S30****), comparing LCOE outcomes across different configurations based on economic parameters and the inclusion of battery storage."*

- *On page 13 of the revised main file:*

*"****Fig. 3****a presents the reduction in EU natural gas reliance through green hydrogen deployment in heavy industry and the operation of heavy trucks under different solar and wind capacity expansion scenarios. Under the FULL-wind scenario, up to 10.3% of gross inland natural gas consumption can be avoided by 2050, while the PARTIAL-wind scenario yields a moderate reduction of 7.1%, reflecting its transitional positioning. In comparison, the BAU-wind and BAU-solar scenarios result in more limited reductions of 3.6% and 1.7%, respectively. These findings emphasize that while the FULL scenarios provide the greatest system-level impact, the PARTIAL configurations represent viable intermediate pathways and serve as reference points for moderate policy ambition. Cumulative emissions reductions associated with green hydrogen deployment are shown in* ***Fig. 3****b. The FULL-wind scenario enables up to 947.5 $MtCO_2$ of avoided emissions by 2050, indicating a 203.7% increase over the BAU-wind scenario. The PARTIAL-wind scenario achieves 640.0 $MtCO_2$ of avoided emissions, further reinforcing its relevance in bridging*

feasibility with policy ambition. Contributions from solar-powered hydrogen production remain substantial as well, with the FULL-solar scenario yielding 395.3 $MtCO_2$ in cumulative avoided emissions by 2050.

The sectoral disaggregation in ***Fig. 3****c shows that these benefits are concentrated in energy-intensive industries such as iron and steel, non-ferrous metals, non-metallic minerals, refining, chemicals, and heavy trucks in the road transportation sector. This breakdown is further supported by* ***Fig. 3****g, which illustrates the reduction in natural gas consumption across detailed heavy industrial sectors under both BAU and FULL scenarios. Additional sector-specific insights for individual EU countries are depicted in* ***Figs. S5-S11*** *and* ***Figs. S15-S21*** *in the Supplementary Information.* ***Figs. 3****d and e illustrate that rapid advancements in the cost-competitiveness of solar and wind power installations can reduce the levelized cost of hydrogen (LCOH) by up to 60.2% under the fast cost trajectory by 2050. These trends are further reflected in the total hydrogen production costs presented in* ***Fig. 3****f. Across all scenarios, the total cost of hydrogen production remains below $49.6 bn by 2050, with the FULL-wind scenario contributing the most to overall expenditure due to higher output volumes."*

- *On page 16 of the revised main file:*

"In addition to emissions reductions through electrification and green hydrogen utilization, carbon offsetting via DAC powered by solar and wind power expansion offers complementary decarbonization benefits. As depicted in ***Fig. 4****a, the FULL-wind scenario enables up to 6.0 $GtCO_2$ in cumulative CO_2 removal by 2050, while the PARTIAL-wind scenario achieves 3.8 $GtCO_2$. The FULL-solar and PARTIAL-solar scenarios yield comparatively lower contributions of 1.8 $GtCO_2$ and 1.2 $GtCO_2$, respectively. These results suggest that even moderate capacity expansion pathways, such as PARTIAL-wind and PARTIAL-solar, can support substantial removal volumes within more constrained deployment conditions.* ***Figs. 4****c-f illustrate country-level variations in CO_2 removal volumes under the BAU and FULL scenarios. Countries such as Germany, France, Spain, and the Netherlands exhibit higher capture outputs, reflecting a combination of aggressive renewable expansion and DAC infrastructure deployment. The spatial distribution of storage capacity utilization (****Figs. 4****g-j) further highlights regional variation in saturation levels by 2050, reinforcing the importance of country-specific strategies to align renewable expansion for carbon offsetting strategy with geological storage feasibility.* ***Figs. S58-S59*** *complement this analysis by*

depicting the technological requirements, such as DAC unit capacities, heat pump installations, and CO_2 pipeline infrastructure, needed to operationalize carbon removal strategies across EU countries under the investigated scenarios.

Despite the notable CO_2 removal potential, ***Fig. 4****b highlights that total carbon capture costs remain high, ranging from \$21.9 bn under the BAU-solar scenario to \$177.4 bn under the FULL-wind scenario by 2050, even under a fast cost-reduction trajectory. These figures reflect the capital-intensive nature of DAC infrastructure, which dominates total cost outcomes and results in only marginal variation across the slow, nominal, and fast trajectories for renewable capacity expansion. The PARTIAL-solar and PARTIAL-wind scenarios yield projected costs of \$41.0 bn and \$114.3 bn, respectively, illustrating intermediate investment levels with substantial CO_2 removal outcomes.* ***Figs. 4****k and l present the levelized cost of carbon capture (LCOC) for solar- and wind-powered DAC infrastructure. Under the fast trajectory, the LCOC declines by up to 41.5% across EU member states by 2050, reflecting steady improvements in cost-effectiveness. While variation across cost trajectories remains limited, the long-term decline highlights opportunities for strategic investments to support carbon removal as part of a broader decarbonization portfolio."*

<u>References</u>

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References

The manuscript appropriately cites prior modeling exercises

Reviewer's Expertise

I do not have the necessary expertise to evaluate the technical soundness of the energy model itself. My assessment focuses on the clarity, relevance, and contextual framing of the paper's claims.

In conclusion, the manuscript presents valuable modeling work that contributes meaningfully to energy economics. However, its broader claims on geopolitics and climate mitigation should either be substantiated or simplified, and the discussion should be more concise and precise. Refining the focus to highlight the novelty of the modeling approach while streamlining extraneous discussions would significantly improve the manuscript.

Reviewer 3

The paper presents a comprehensive study with valuable insights into energy planning within the European Union. However, after review, I consider the paper requires revisions before it can be accepted for publication. My feedback is as follows:

Reviewer's Comment (1) and (2)

1. Terminology Consistency: The terms energy autonomy, energy resilience, and energy security are used interchangeably throughout the paper. While they share common elements, they have distinct meanings in the given context. I recommend selecting a single definition and ensuring consistency in its usage throughout the paper. This is particularly important for the title, where energy autonomy is used, despite energy security being the more frequently discussed term.

2. Title Re-evaluation: I consider energy security is more widely used than energy autonomy. Additionally, the term decarbonization potential appears to refer to cumulative emissions, but this could be misleading. The figure of 20.1 $GtCO_2$ is presented, yet it is unclear whether this refers to CO_2 emissions only or CO_2 equivalent. Moreover, this number is not referenced later in the manuscript.

Answer: Thanks for the comment. In line with the reviewer's feedback, we have revised the manuscript to ensure consistent use of the term "energy security" and avoid using overlapping terminology such as "energy autonomy" and "energy resilience." We chose to retain "energy security" in alignment with the terminology consistently used by the European Commission (European Commission, 2025). Additionally, we have also updated the title to reflect this consistency and to emphasize the strategic framing of energy security alongside climate mitigation. The emissions figure refers to CO_2 emissions only.

References

European Commission. (2025). *EU energy policy.* https://energy.ec.europa.eu/index_en, (accessed June 10, 2025).

Action

- *We have revised the manuscript to ensure consistent use of the term "energy security," replacing overlapping terms such as "energy autonomy" and "energy resilience," and updated the title to "Aligning EU Energy Security and Climate Mitigation through Targeted Transition Strategies."*

Reviewer's Comment (3)

3. Literature Review and Research Gap: The introduction does not sufficiently demonstrate a literature review identifying the research gap. It should explicitly state how this methodology is novel compared to previous studies using similar scenario analysis and optimization frameworks, such as TIMES, MESSAGE, OSeMOSYS, PyPSA, or Calliope.

Answer: Thanks for the comment. We agree with the reviewer's feedback to better demonstrate the literature review and identify the research gap in comparison to previous studies using scenario analysis and optimization frameworks. To address this:

- We have strengthened the review of existing literature to establish the knowledge gap addressed in this work compared to existing assessments and outline the novel contributions through a set of bullet points.
- To further contextualize these contributions, Table S1 presents a comparative summary of key focus areas, insights from prior literature, and the corresponding contributions of this study.

Action

- *We have presented the revised text in the Introduction section and the comparative summary table in response to Comment 1 from Reviewer 1. To reduce the length of this file, please refer to pages 1-9 for the complete revision.*

Reviewer's Comment (4)

4. Scenario Definition: The paper conceptualizes three scenarios (BAU, PARTIAL, and FULL), but later presents six scenarios in the graphs (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, FULL-wind). Please clarify this distinction in the introduction to enhance understanding.

Answer: Thanks for the comment. In the revised Introduction section, we have described the scenario structure by distinguishing between the three overarching scenarios (BAU, PARTIAL, FULL) and their disaggregation into BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind.

Action

- *On page 4 of the revised main file:*

"We explore overarching scenarios for the policy-driven growth of solar and wind power capacities in the EU, categorized as FULL, PARTIAL, and BAU implementation. The FULL scenario fulfills the REPowerEU policy targets by 2030[19, 20], with subsequent progression to achieve the EU's strategic targets for an accelerated decline in emissions by 2040[21] and net zero by 2050[47]. On the other end of the spectrum, the BAU scenario considers that the EU maintains the growth in solar and wind power capacities prior to the recent geopolitical disruptions. Lastly, the PARTIAL scenario follows an average increment between the FULL and BAU implementation scenarios to weigh the pros and cons of both cases. We focus on solar and wind power installations as part of the clean energy sources, recognizing their growing significance in enhancing energy security in light of geopolitical challenges[20, 48] and their critical role in meeting climate targets[49]. Recognizing the distinct technological characteristics[50], economic implications[51], and spatial heterogeneity of solar and wind energy potential across the EU[52], we further disaggregate each scenario into technology-specific variants, including BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind, to enable a more granular assessment of individual contributions to energy security and climate mitigation. The proposed scenarios allow the sector-specific evaluation of reducing natural gas consumption, where renewable capacity expansion supports electrification, green hydrogen deployment, and the potential for carbon offsetting through Direct Air Capture (DAC) systems[53, 54, 55], directly contributing to the EU's dual goals of energy security and climate change mitigation. Furthermore, to assess the economic feasibility of the proposed energy transition, these pathways are overlaid with slow, nominal, and fast cost

trajectories reflecting a comprehensive spectrum of potential improvements in the cost-effectiveness of renewable energy installations."

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Reviewer's Comment (5)

5. Presentation of Results: The results for the PARTIAL scenario are barely discussed. While it represents an intermediate state between BAU and FULL, it still requires analysis to justify its inclusion. Otherwise, its purpose in the study remains unclear.

Answer: Thanks for the comment. We agree with the reviewer's observation and have revised the Results section to illustrate a more detailed analysis of the PARTIAL scenarios, emphasizing their role as intermediate pathways between BAU and FULL scenarios.

Action

- *On page 8 of the revised main file:*

*"The BAU-solar and BAU-wind scenarios lead to reductions of 15.5% and 29.4%, respectively, while the FULL-solar and FULL-wind scenarios achieve greater reductions of 32.6% and 50.9% by 2050. The PARTIAL scenarios yield intermediate outcomes, with reductions ranging from 24.8% to 46.3%, representing a transitional trajectory between incremental and accelerated renewable deployment. The inclusion of the PARTIAL-solar and PARTIAL-wind scenarios is particularly relevant for illustrating moderate expansion pathways, where the EU may encounter constraints related to infrastructure planning[56], policy uncertainty[20], or regional deployment feasibility[57, 58]. These reductions in natural gas consumption translate into substantial cumulative avoided emissions (**Fig. 1**b), with the FULL-wind scenario enabling up to 6.0 GtCO$_2$ of mitigation potential by 2050. The results for the PARTIAL (2.3 GtCO$_2$ to 4.9 GtCO$_2$) and BAU scenarios (1.3 GtCO$_2$ to 2.7 GtCO$_2$) highlight the differentiated impact of scenario ambition on long-term mitigation pathways."*

- *On page 11 of the revised main file:*

*"**Fig. 2**e presents the total cost of electrification potential across different scenarios (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind) under varying cost trajectories through 2050. In the FULL-wind scenario, the total cost reaches \$173.2 bn under the slow trajectory but declines by 13.7% under the fast trajectory. The comparison highlights the role of accelerated cost reductions, potentially driven by policy support and investment incentives, in enhancing economic feasibility. Similarly, under the PARTIAL-solar and PARTIAL-wind scenarios, total electrification costs reach \$62.7 bn and \$102.3 bn, respectively, by 2050 under the nominal trajectory. These intermediate pathways illustrate a cost-effective middle ground between ambitious deployment targets and economic feasibility across the EU."*

- *On page 13 of the revised main file:*

*"**Fig. 3**a presents the reduction in EU natural gas reliance through green hydrogen deployment in heavy industry and the operation of heavy trucks under different solar and wind capacity expansion scenarios. Under the FULL-wind scenario, up to 10.3% of gross inland natural gas consumption can be avoided by 2050, while the PARTIAL-wind scenario yields a moderate reduction of 7.1%, reflecting its transitional positioning. In comparison, the BAU-wind and BAU-solar scenarios result in more limited reductions of 3.6% and 1.7%, respectively. These findings emphasize that while the FULL scenarios provide the greatest system-level impact, the PARTIAL configurations represent viable intermediate pathways and serve as reference points for moderate policy ambition. Cumulative emissions reductions associated with green hydrogen deployment are shown in **Fig. 3**b. The FULL-wind scenario enables up to 947.5 MtCO_2 of avoided emissions by 2050, indicating a 203.7% increase over the BAU-wind scenario. The PARTIAL-wind scenario achieves 640.0 MtCO_2 of avoided emissions, further reinforcing its relevance in bridging feasibility with policy ambition."*

- *On page 16 of the revised main file:*

*"As depicted in **Fig. 4**a, the FULL-wind scenario enables up to 6.0 GtCO_2 in cumulative CO_2 removal by 2050, while the PARTIAL-wind scenario achieves 3.8 GtCO_2. The FULL-solar and PARTIAL-solar scenarios yield comparatively lower contributions of 1.8 GtCO_2 and 1.2 GtCO_2, respectively. These results suggest that even moderate capacity expansion pathways, such as PARTIAL-wind and PARTIAL-solar, can support substantial removal volumes within more constrained deployment conditions.*

*Despite the notable CO_2 removal potential, **Fig. 4**b highlights that total carbon capture costs remain high, ranging from \$21.9 bn under the BAU-solar scenario to \$177.4 bn under the FULL-wind scenario by 2050, even under a fast cost-reduction trajectory. These figures reflect the capital-intensive nature of DAC infrastructure, which dominates total cost outcomes and results in only marginal variation across the slow, nominal, and fast trajectories for renewable capacity expansion. The PARTIAL-solar and PARTIAL-wind scenarios yield projected costs of \$41.0 bn and \$114.3 bn, respectively, illustrating intermediate investment levels with substantial CO_2 removal outcomes."*

References

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Reviewer's Comment (6)

6. Clarification of a Key Variable: The variable Reduction in natural gas reliance (%) in the EU needs further explanation. For example, does this metric refer to the reduction in final energy consumption of imported natural gas as a proportion of total energy consumption?

Answer: Thanks for the comment. The variable "Reduction in natural gas reliance (%) in the EU" refers to the percentage decrease in gross inland natural gas consumption relative to 2023 levels, which represents the most recent EU-wide consumption data published by Eurostat (Eurostat, 2023). This metric is intended to reflect the overall shift in natural gas consumption over time, which also aligns with the previous commitments by the member states (European Council, 2022; IEA, 2022). Following the reviewer's suggestion regarding imports specifically, the revised manuscript also evaluates the reduction in natural gas import dependency rate (in percentage points) across scenarios, as depicted in **Fig. S26**. This metric also aligns with the prior reporting by Eurostat (Eurostat, 2022). We have revised the text in the main file to incorporate this distinction and ensure that both dimensions of natural gas reliance are appropriately represented.

References

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Action

- *On page 8 of the revised main file:*

*"The findings presented in **Fig. 1**a illustrate the reductions in EU-wide natural gas consumption through electrification strategies targeting the electricity and heating sector, light*

industries, and road transportation. Specifically, we evaluate the percentage decrease in gross inland natural gas consumption compared to 2023 levels, using this as a central metric to assess the alignment of energy security improvements with long-term climate mitigation goals. To complement this aggregate assessment, ***Fig. S26*** *presents changes in natural gas import dependency rate, offering additional insight into potential shifts in supply-side exposure across scenarios."*

- *On page 44 of the revised SI file:*

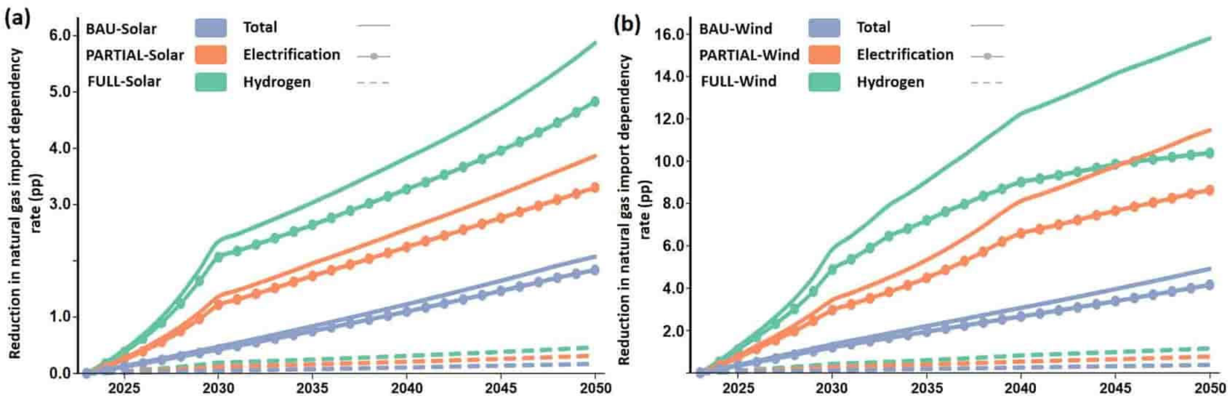

Fig. S26 a., *Total reduction in natural gas import dependency rate (percentage points) across the BAU-Solar, PARTIAL-Solar, and FULL-Solar scenarios through 2050, disaggregated by the individual impact from electrification and green hydrogen deployment.* ***b.,*** *Total reduction in natural gas import 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.*

Reviewer's Comment (7)

7. Energy Security Considerations: The paper suggests that increased renewable energy deployment enhances energy security. However, no data is provided on the operational flexibility of the power system. Higher shares of renewables introduce challenges in ensuring adequacy and reliability. What specific definition of energy security is being used in this context?

Answer: Thanks for the comment. We agree with the reviewer's concern regarding the grid integration challenges associated with increased shares of renewable energy sources, particularly in the context of operational adequacy and system reliability. While this work defines the context of energy security primarily in terms of reductions in natural gas consumption, aligning with the framing of previous policy measures (European Council, 2022; European Commission, 2022), we also evaluate the frequency distribution of net-load ramp rates, normalized to peak load, across various EU countries under different implementation scenarios and time horizons. This metric captures the temporal variability introduced by high renewable penetration and provides insights into the flexibility requirements needed to ensure system reliability alongside energy security goals.

References

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Action

- *On pages 51 to 76 of the revised SI file:*

"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 ***Figs. S31-S55****. 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."

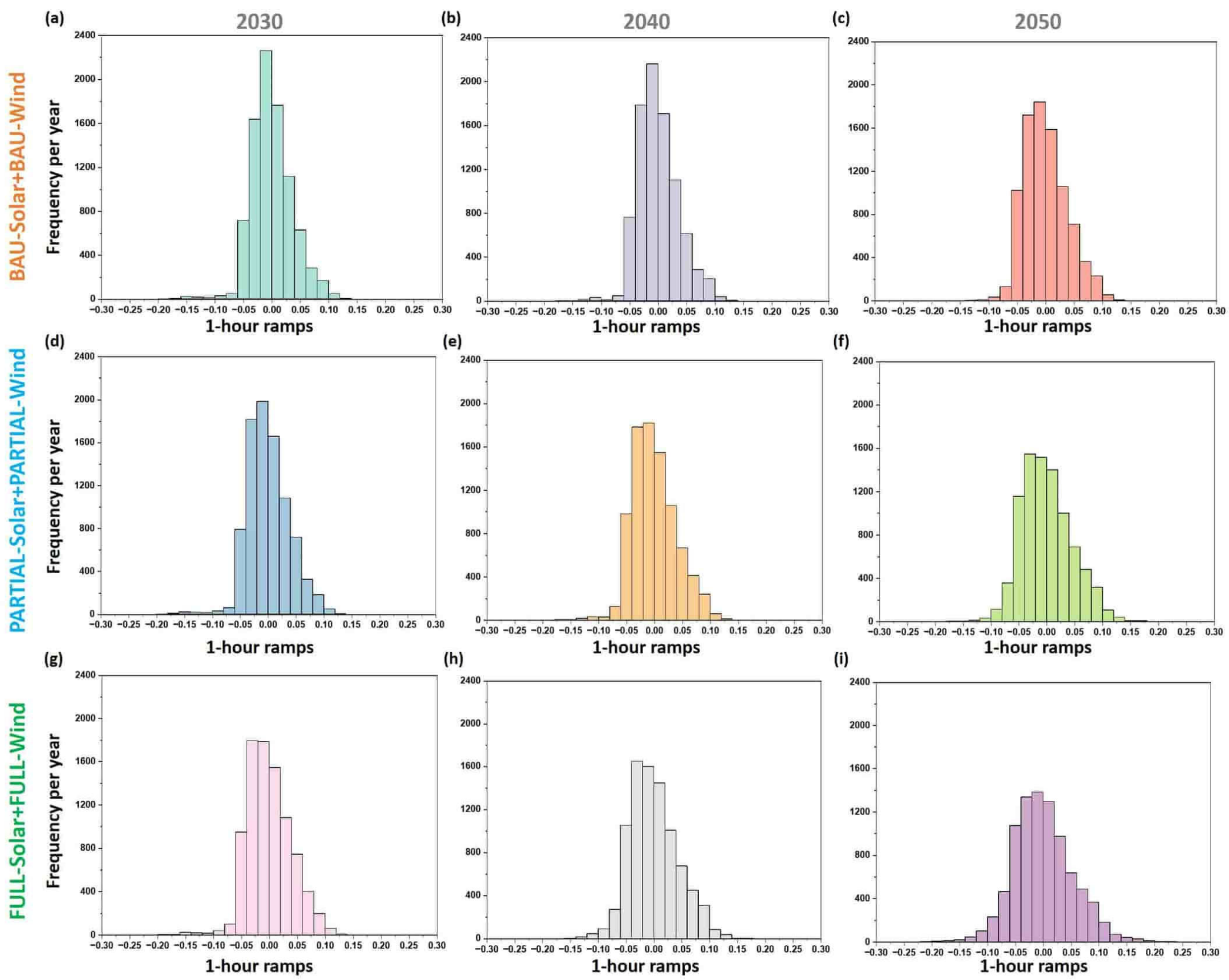

Fig. S31. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Germany*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

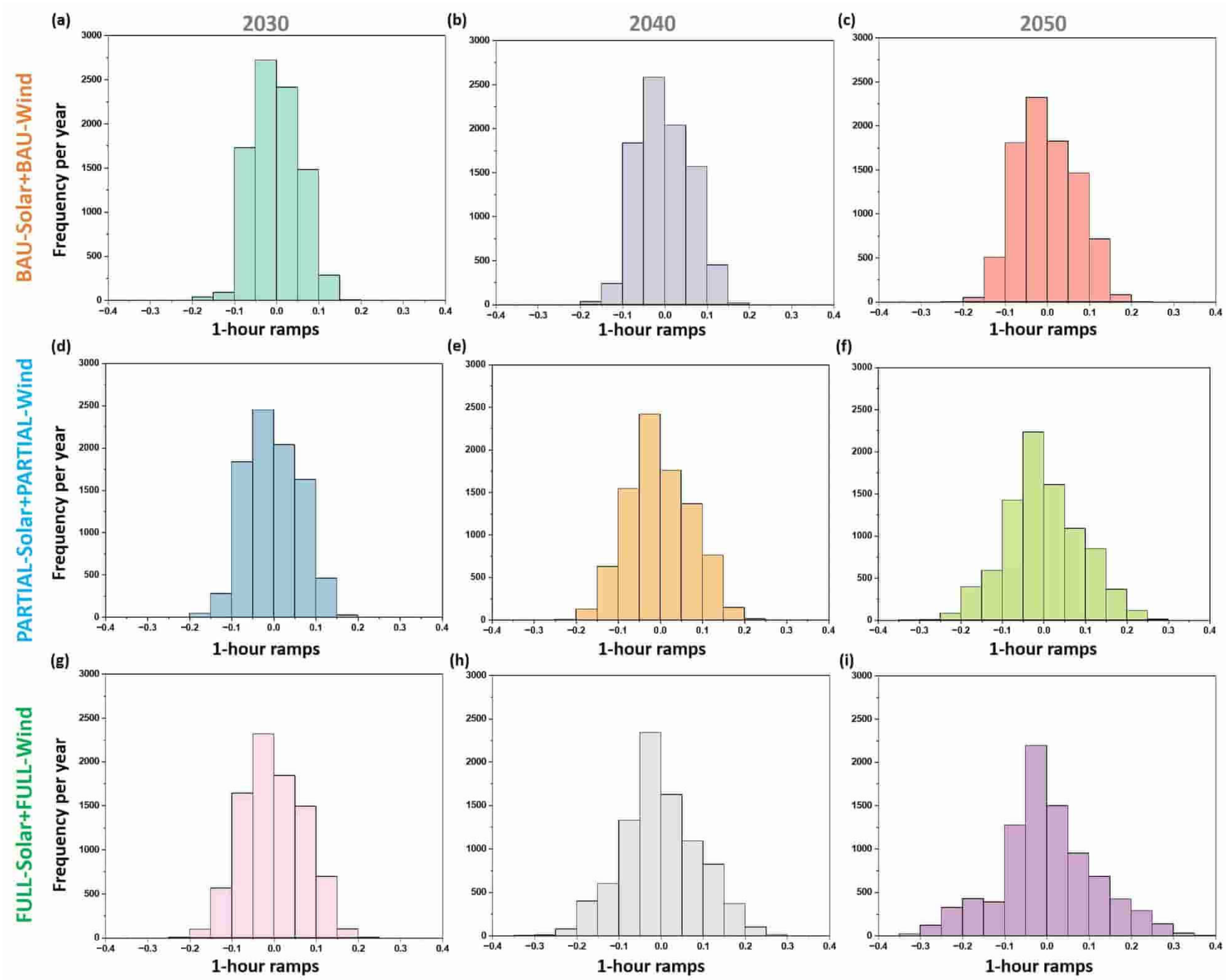

Fig. S32. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Italy*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

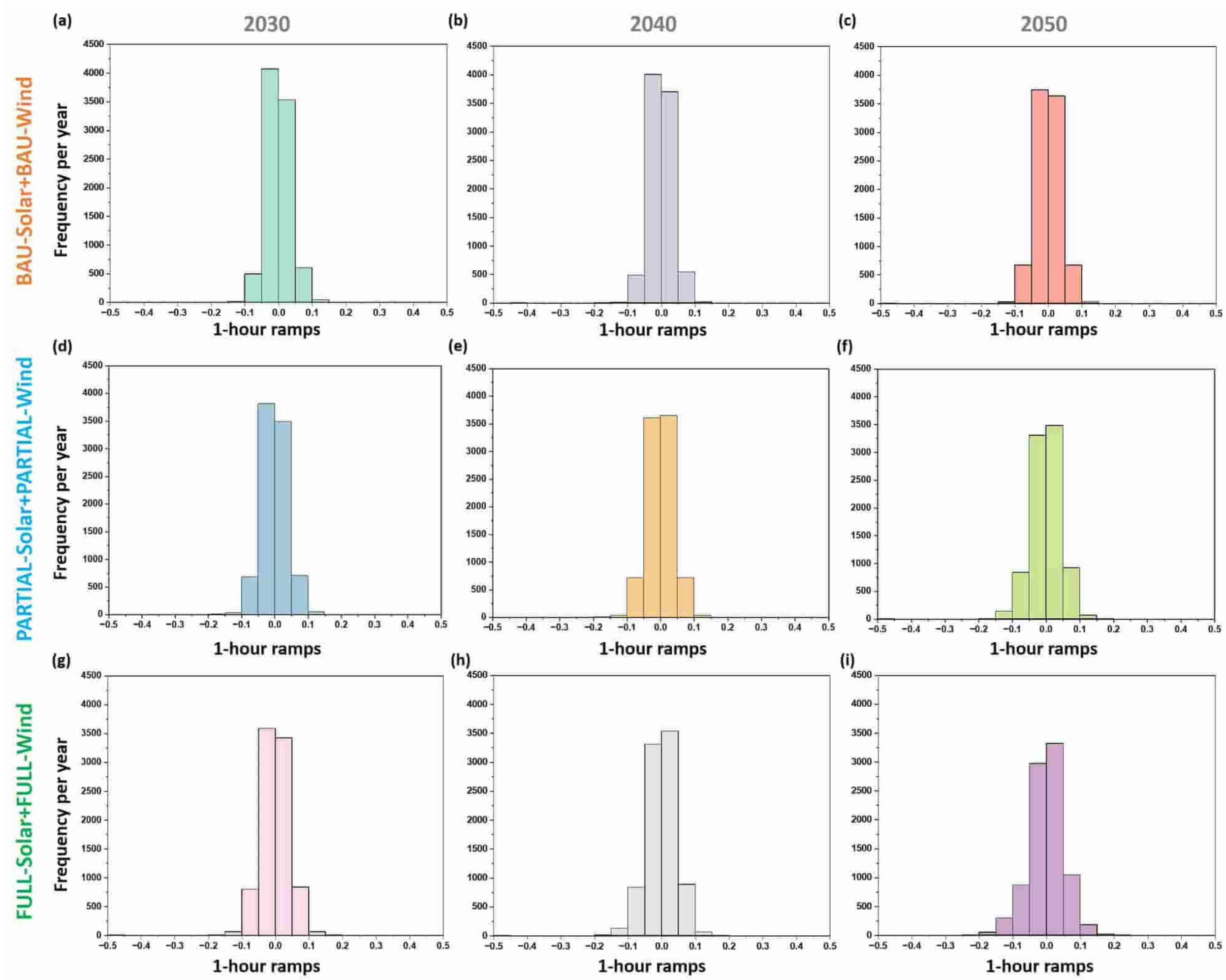

Fig. S33. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***France*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

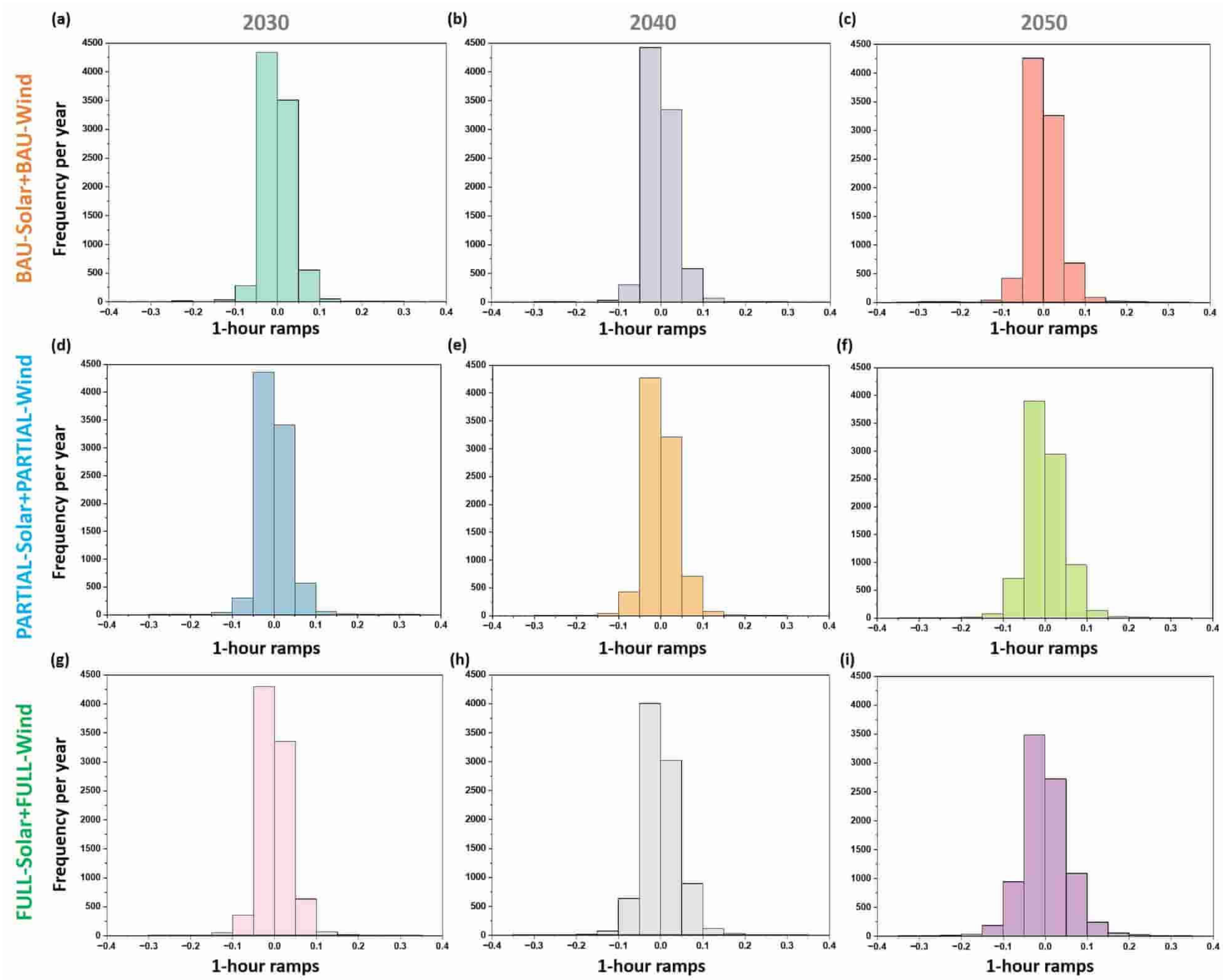

Fig. S34. *Frequency distribution for hourly net-load ramps normalized to the peak load in the **Netherlands** under **a.,** BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **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.*

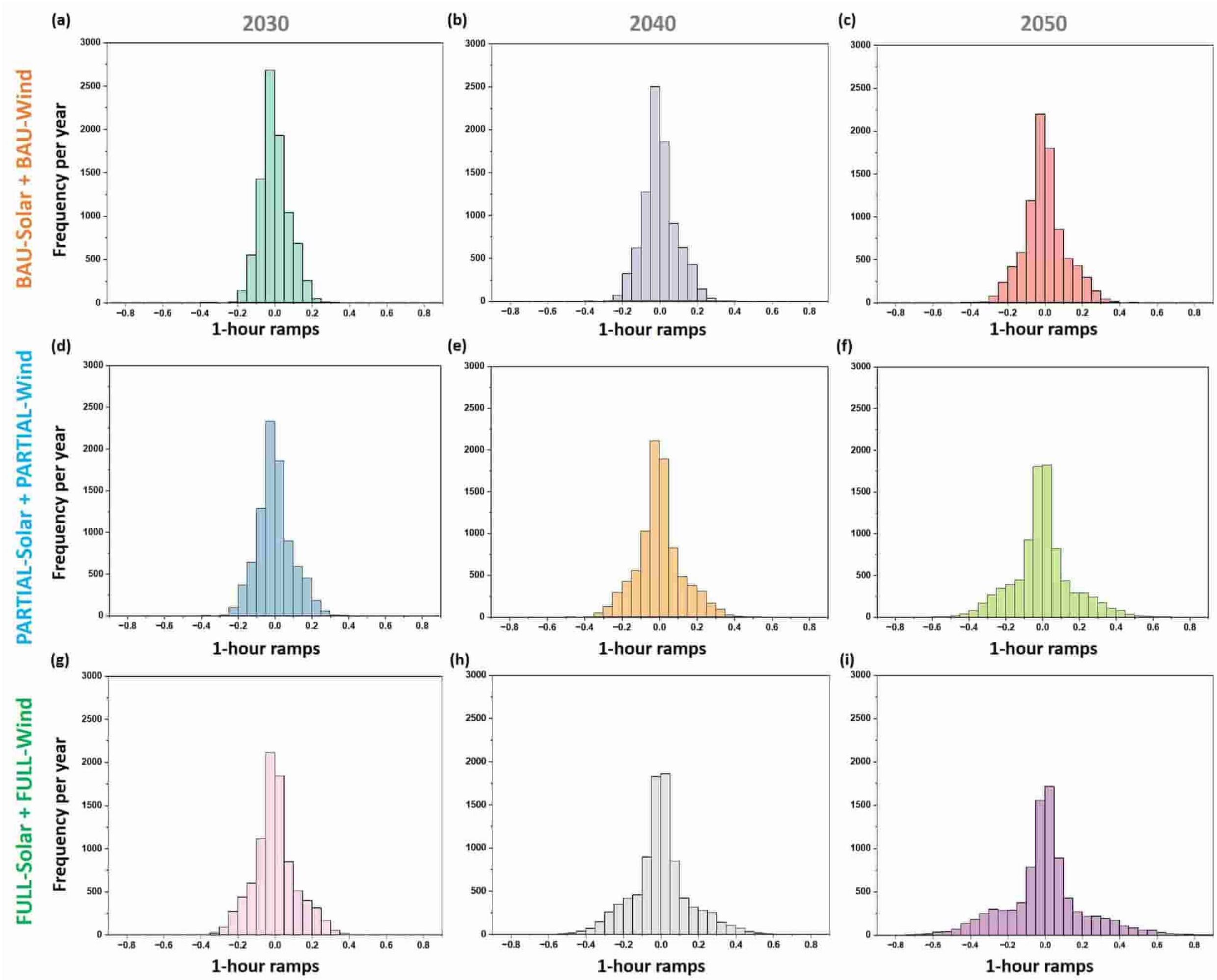

Fig. S35. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Spain*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

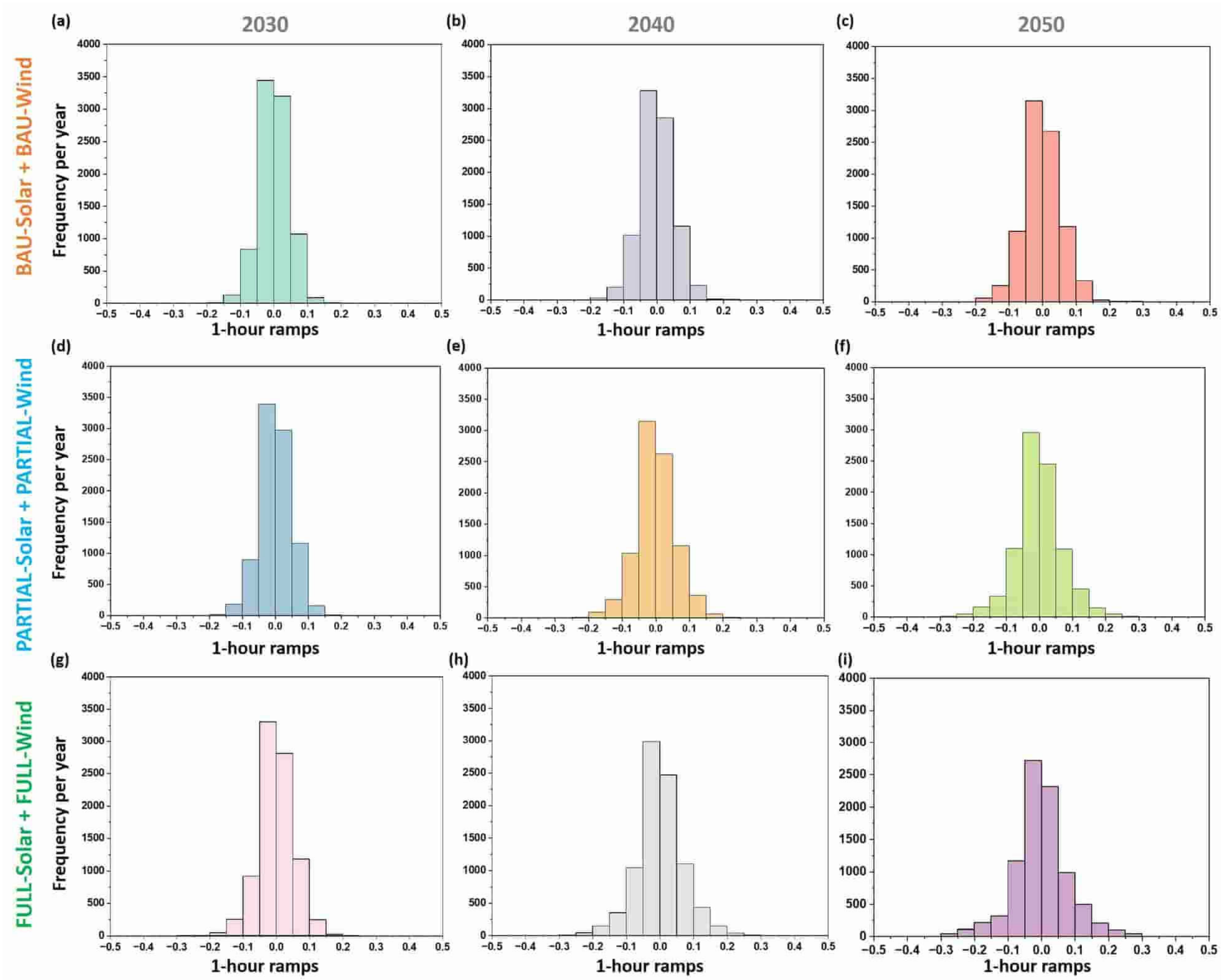

Fig. S36. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Poland*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

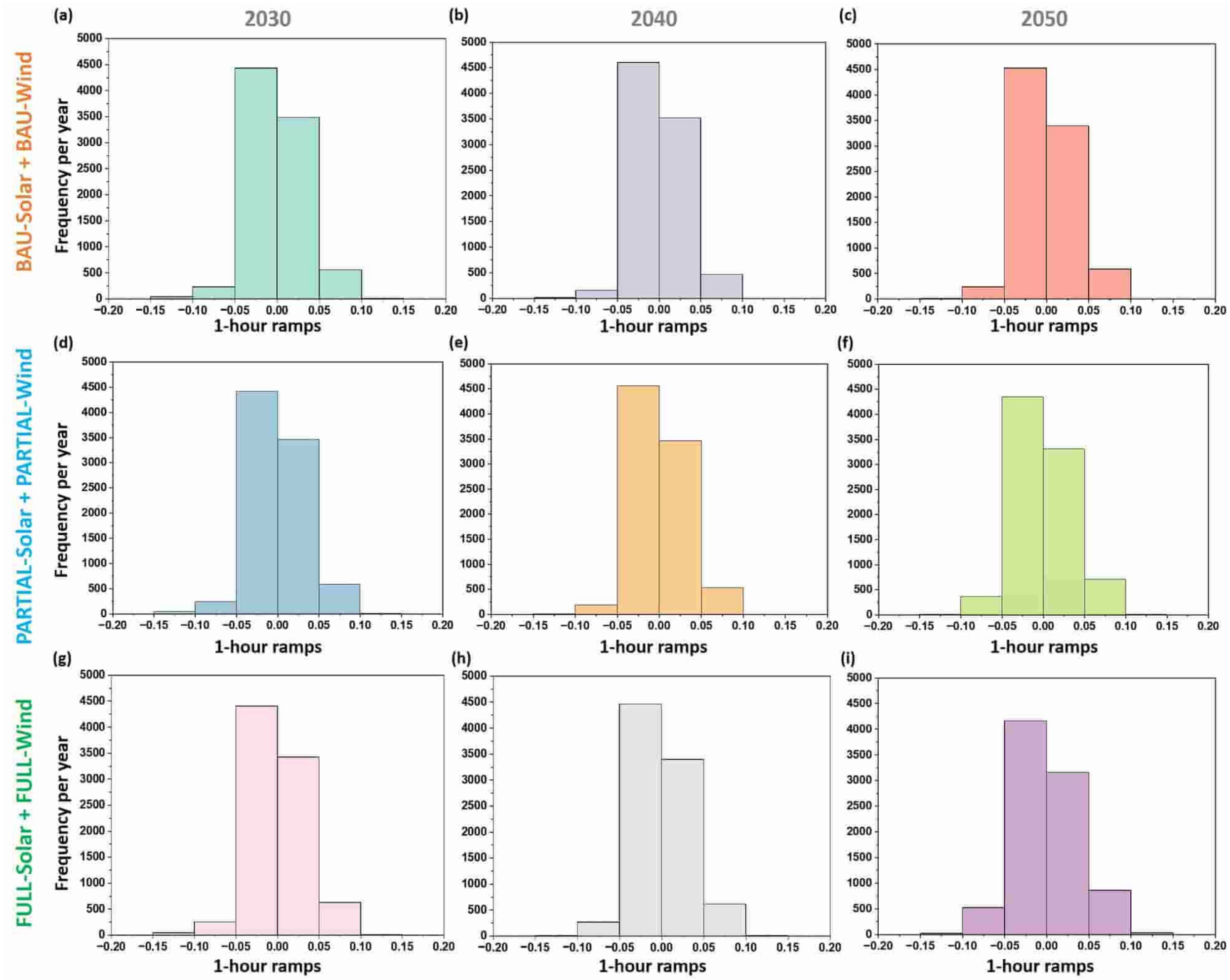

Fig. S37. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Belgium*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

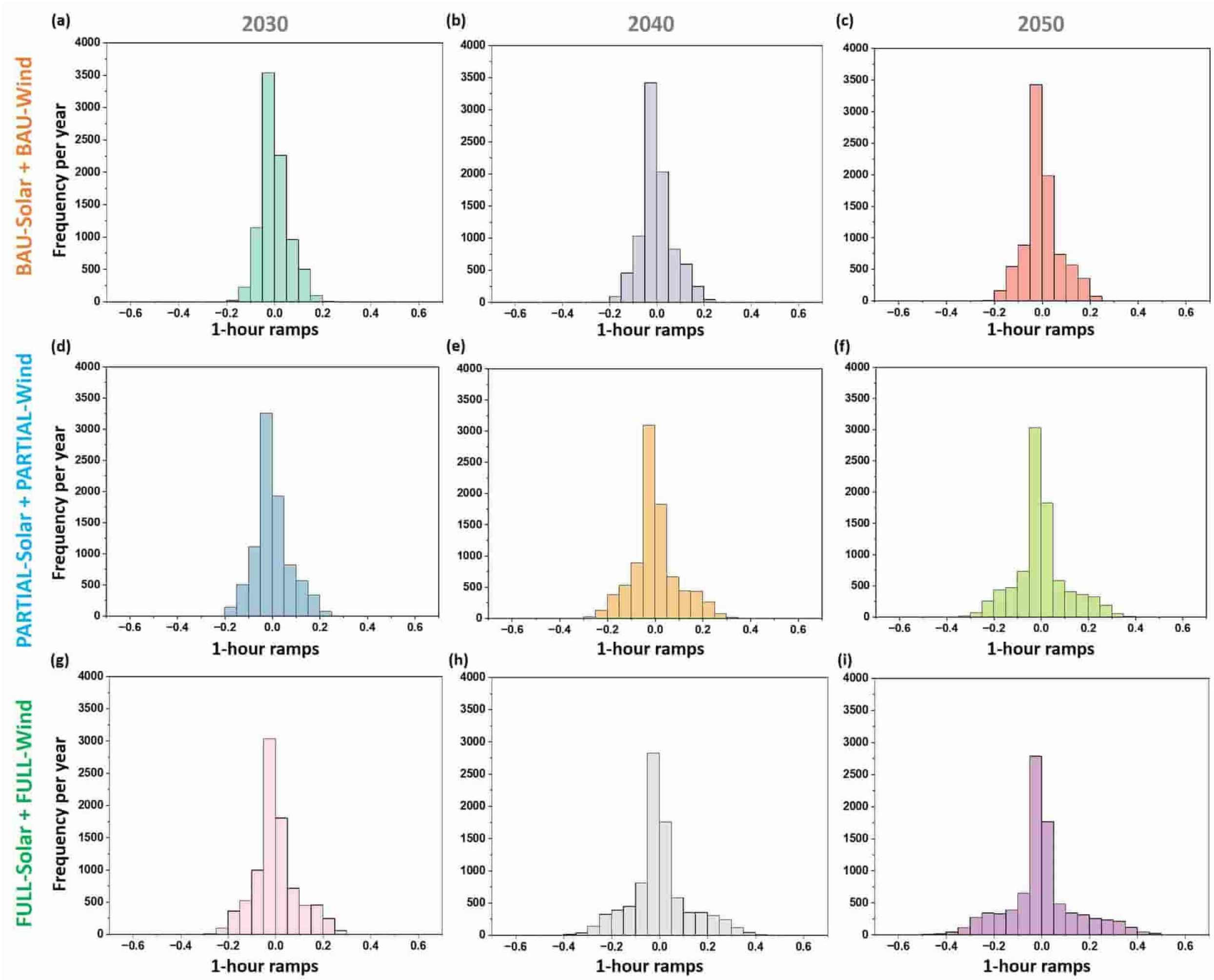

Fig. S38. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Greece*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

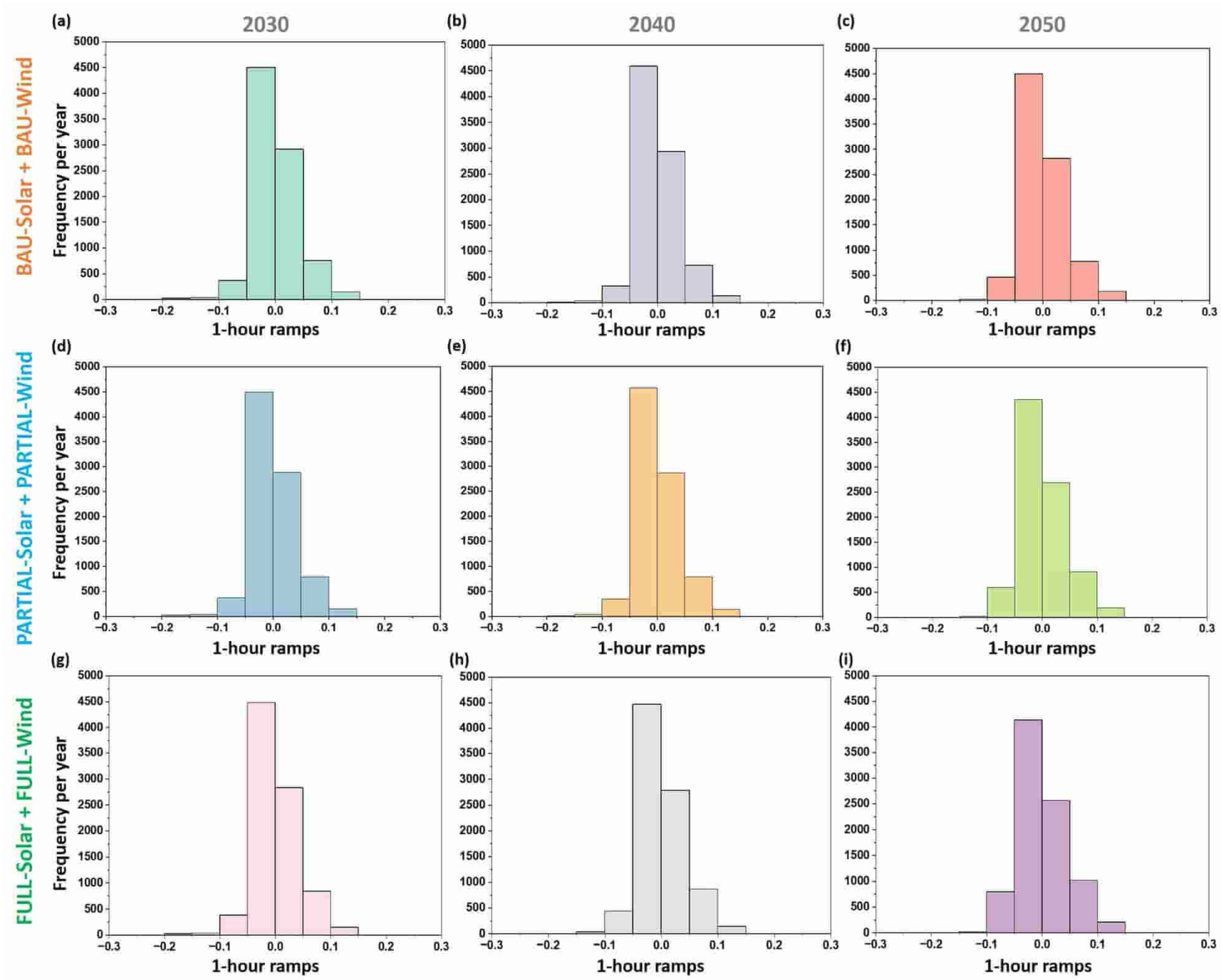

Fig. S39. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Austria*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

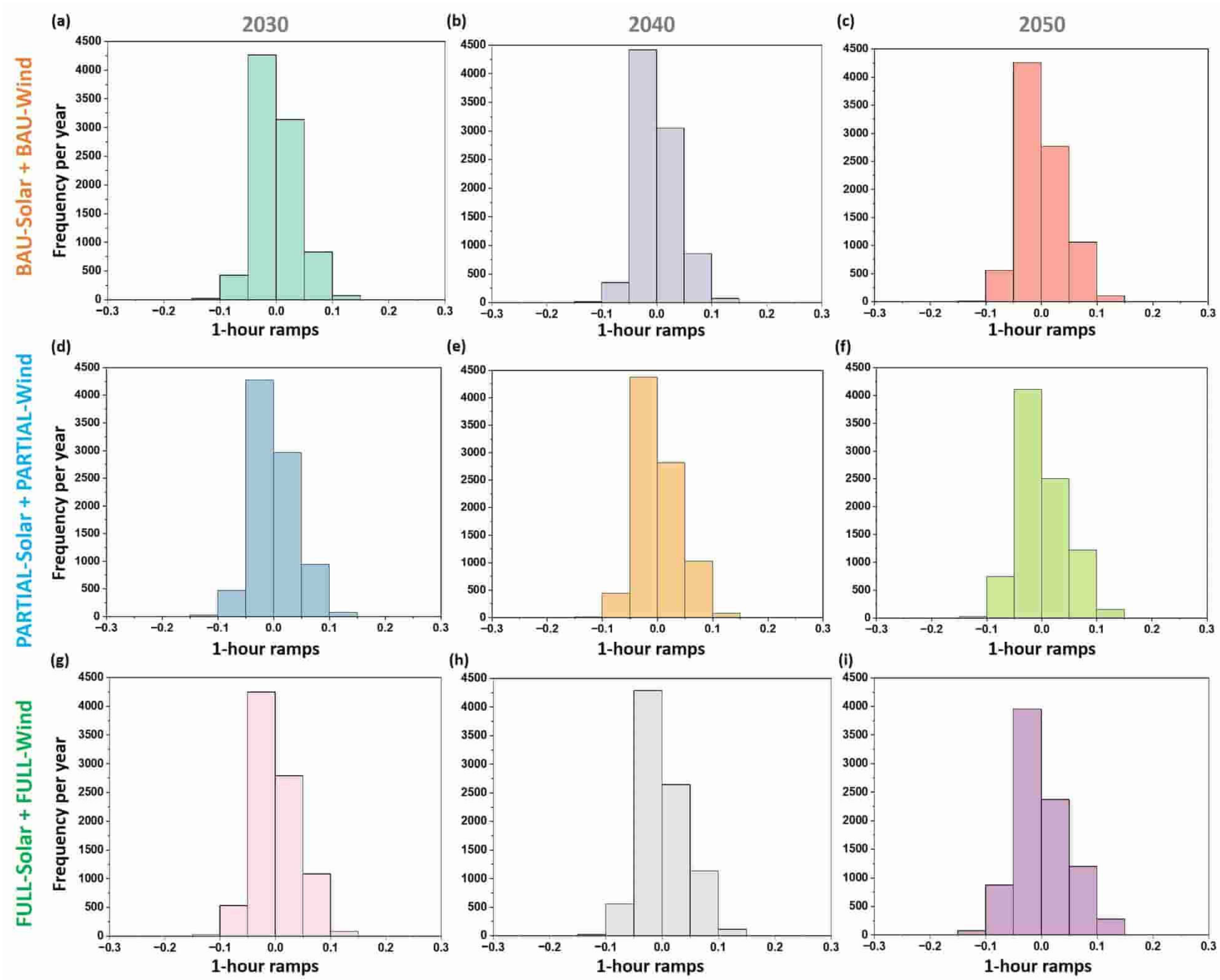

Fig. S40. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Hungary*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

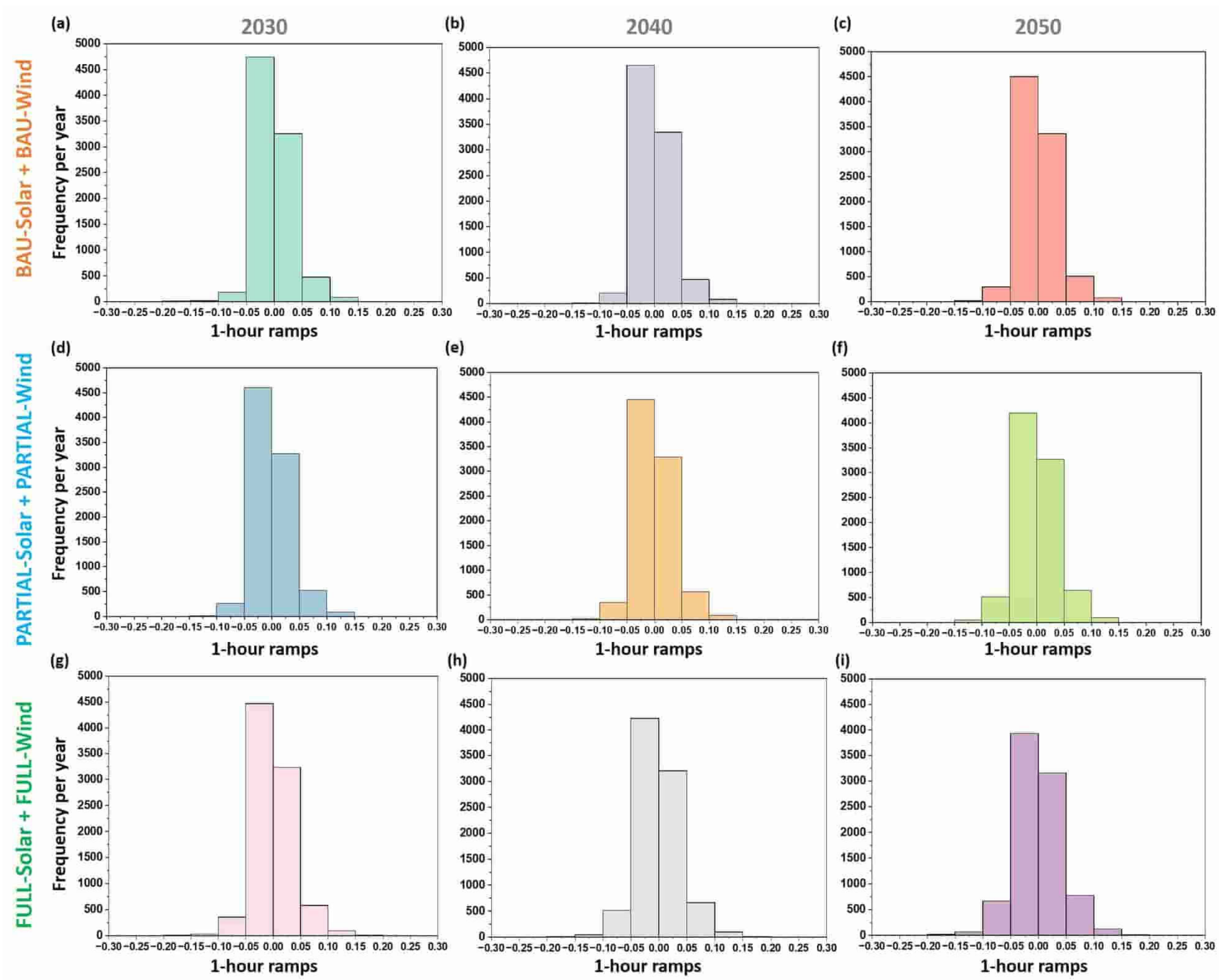

Fig. S41. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Czechia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

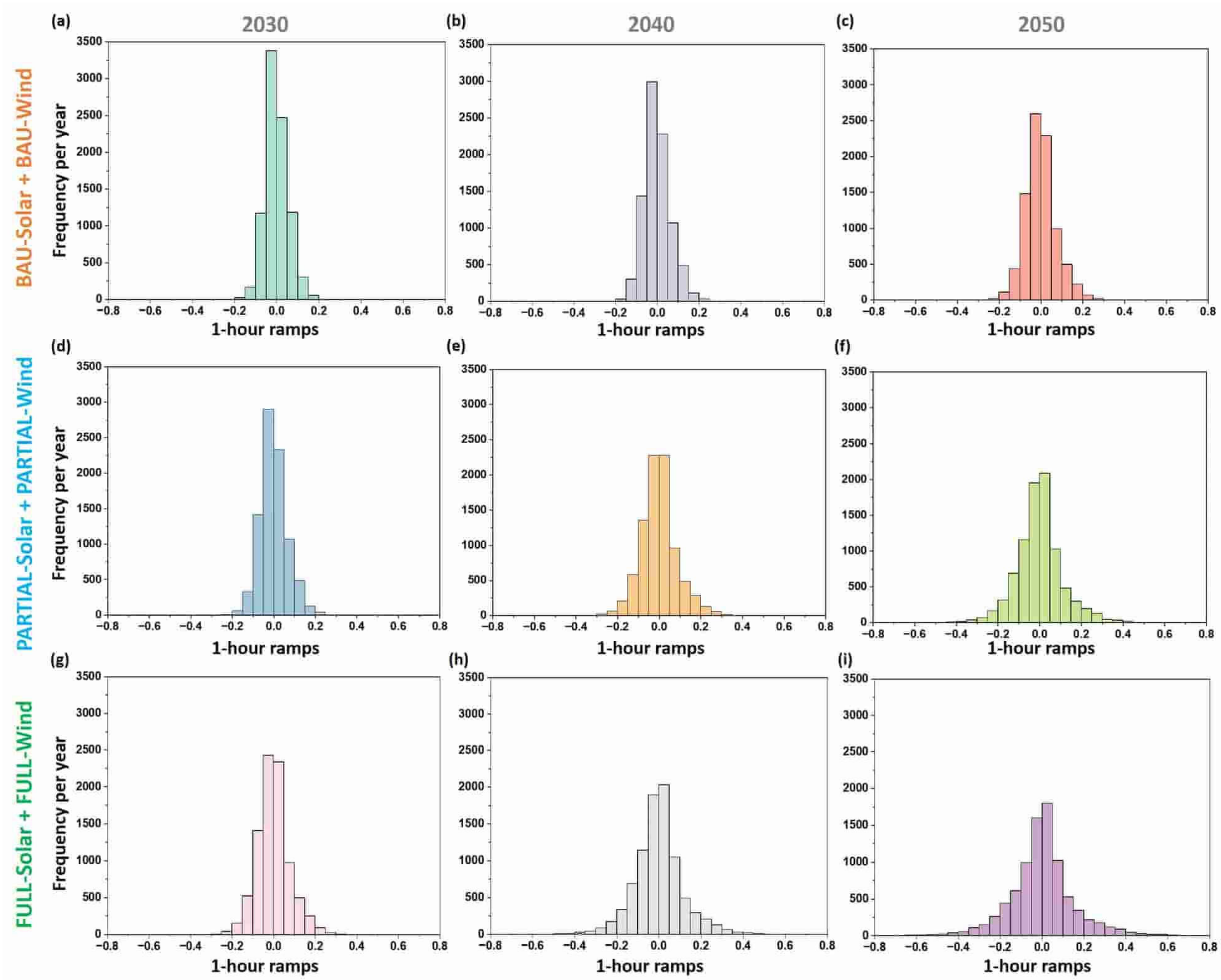

Fig. S42. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Portugal*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

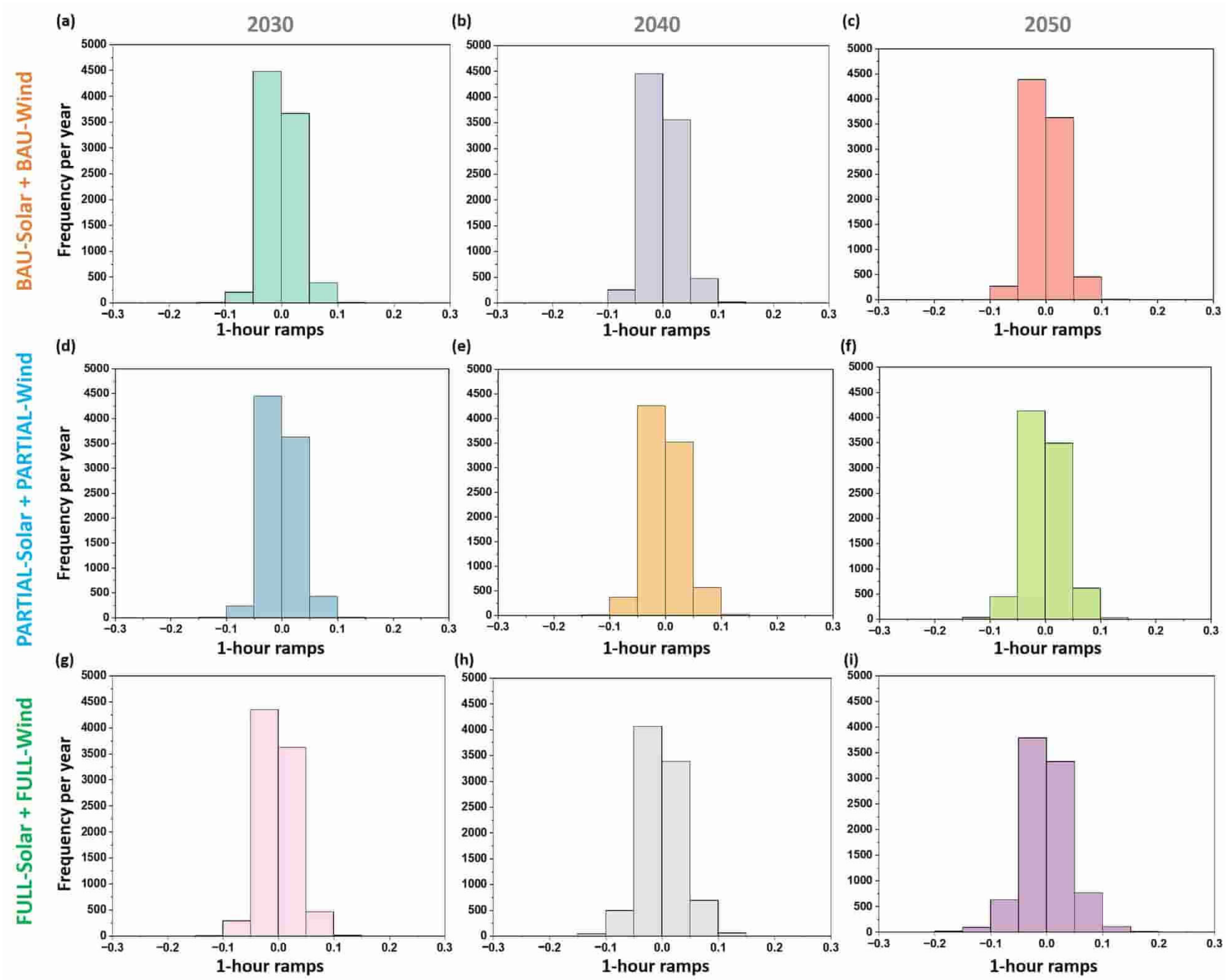

Fig. S43. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Sweden*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

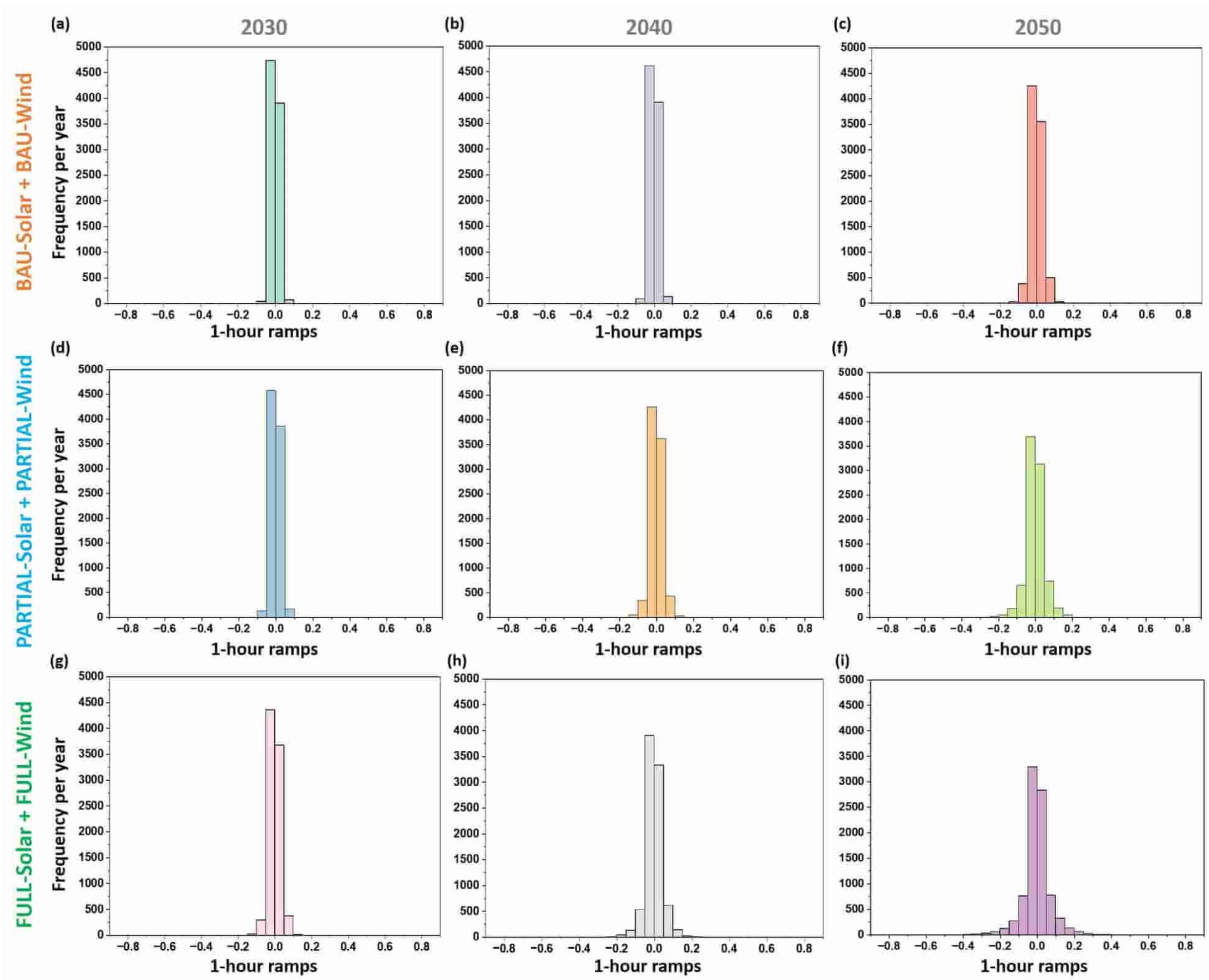

Fig. S44. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Denmark*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

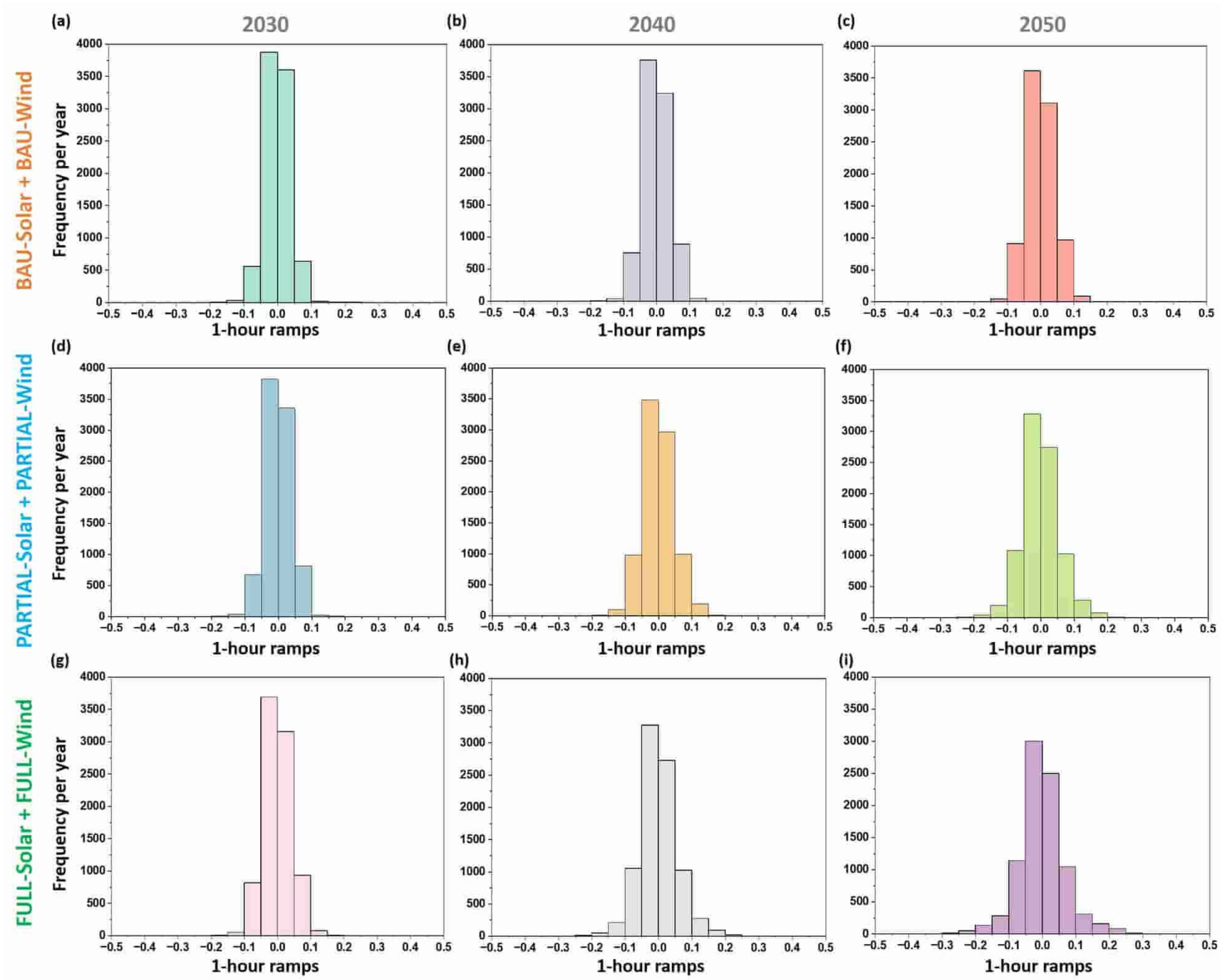

Fig. S45. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Romania*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

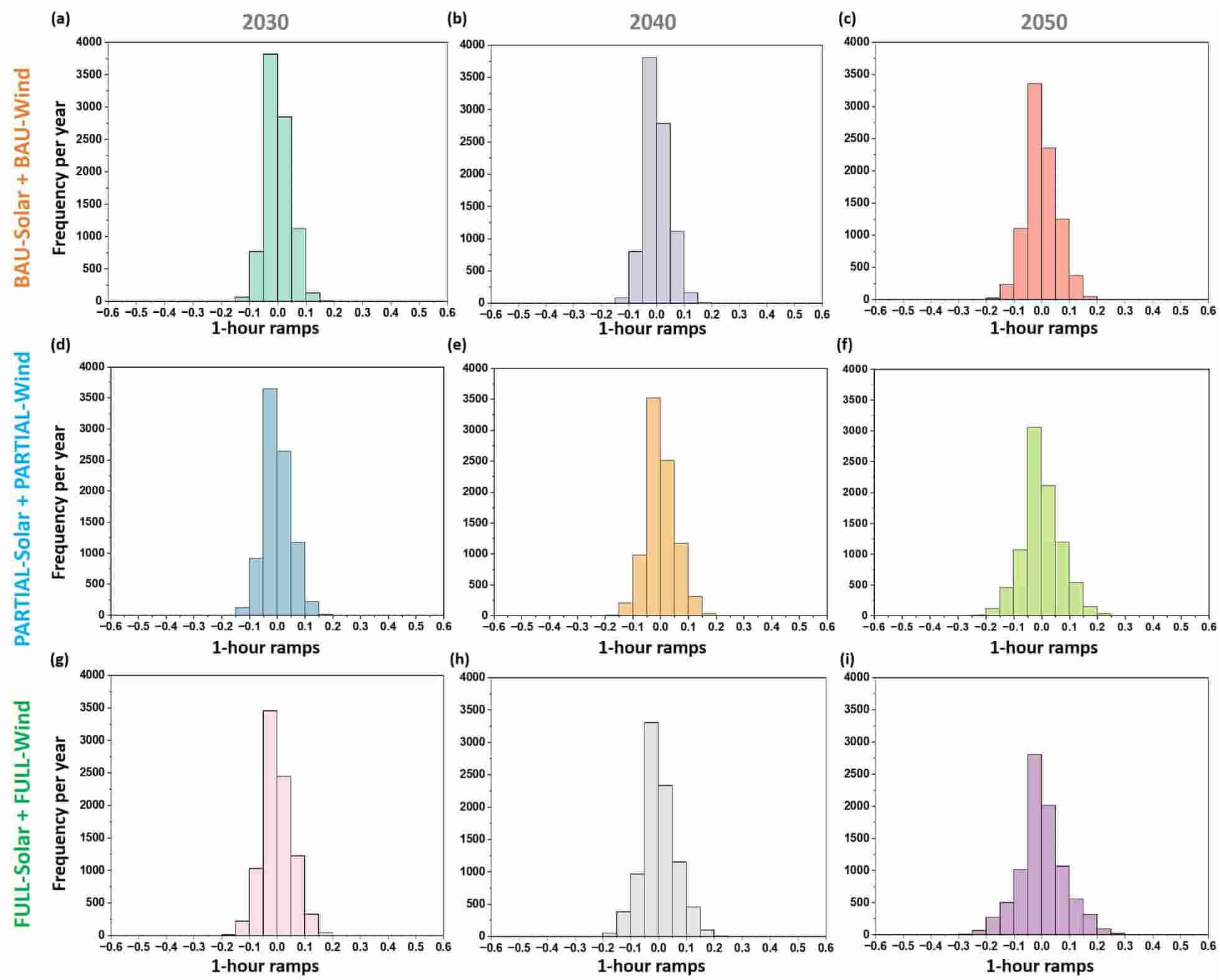

Fig. S46. *Frequency distribution for hourly net-load ramps normalized to the peak load in **Bulgaria** under **a.,** BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** 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.*

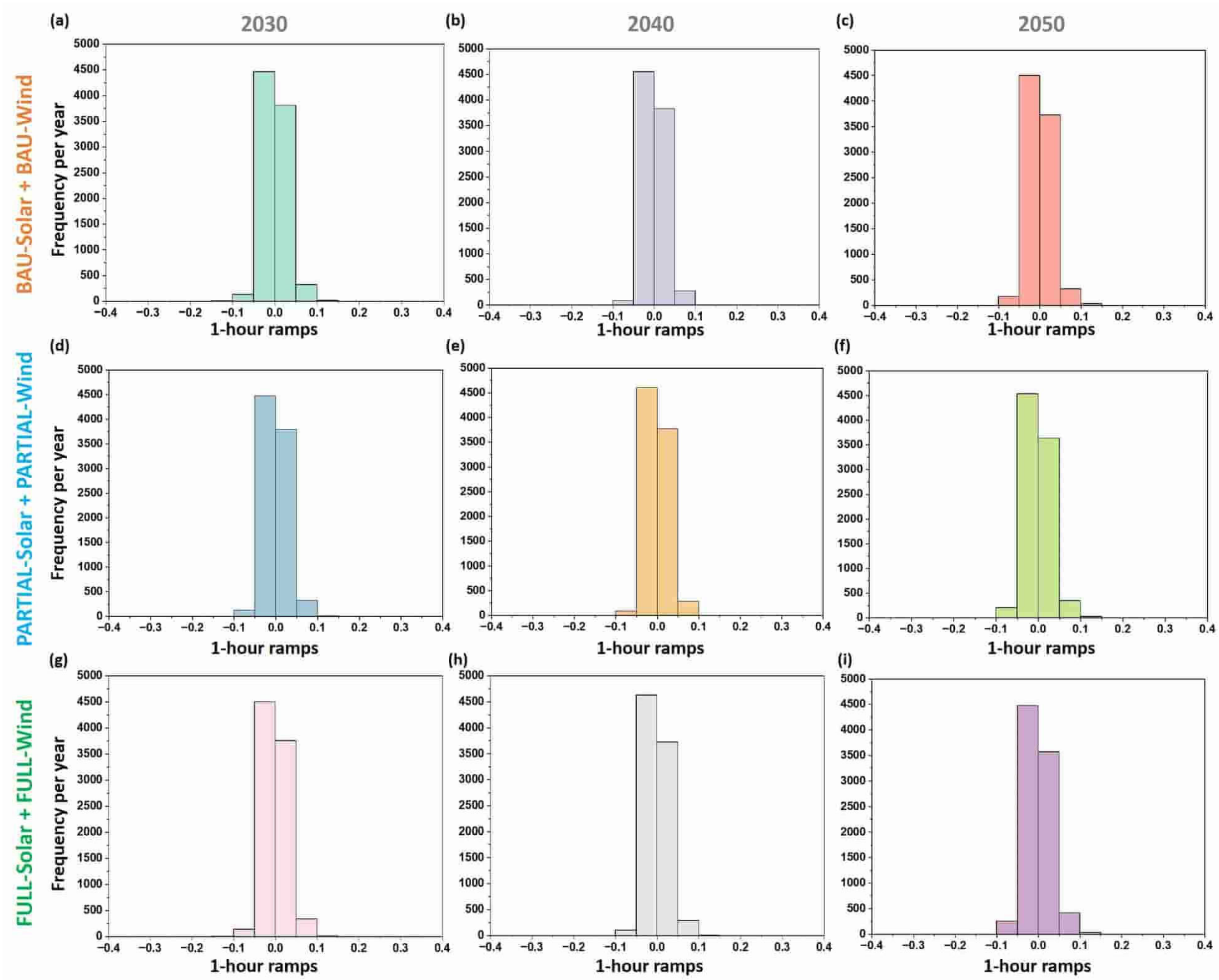

Fig. S47. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Slovakia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

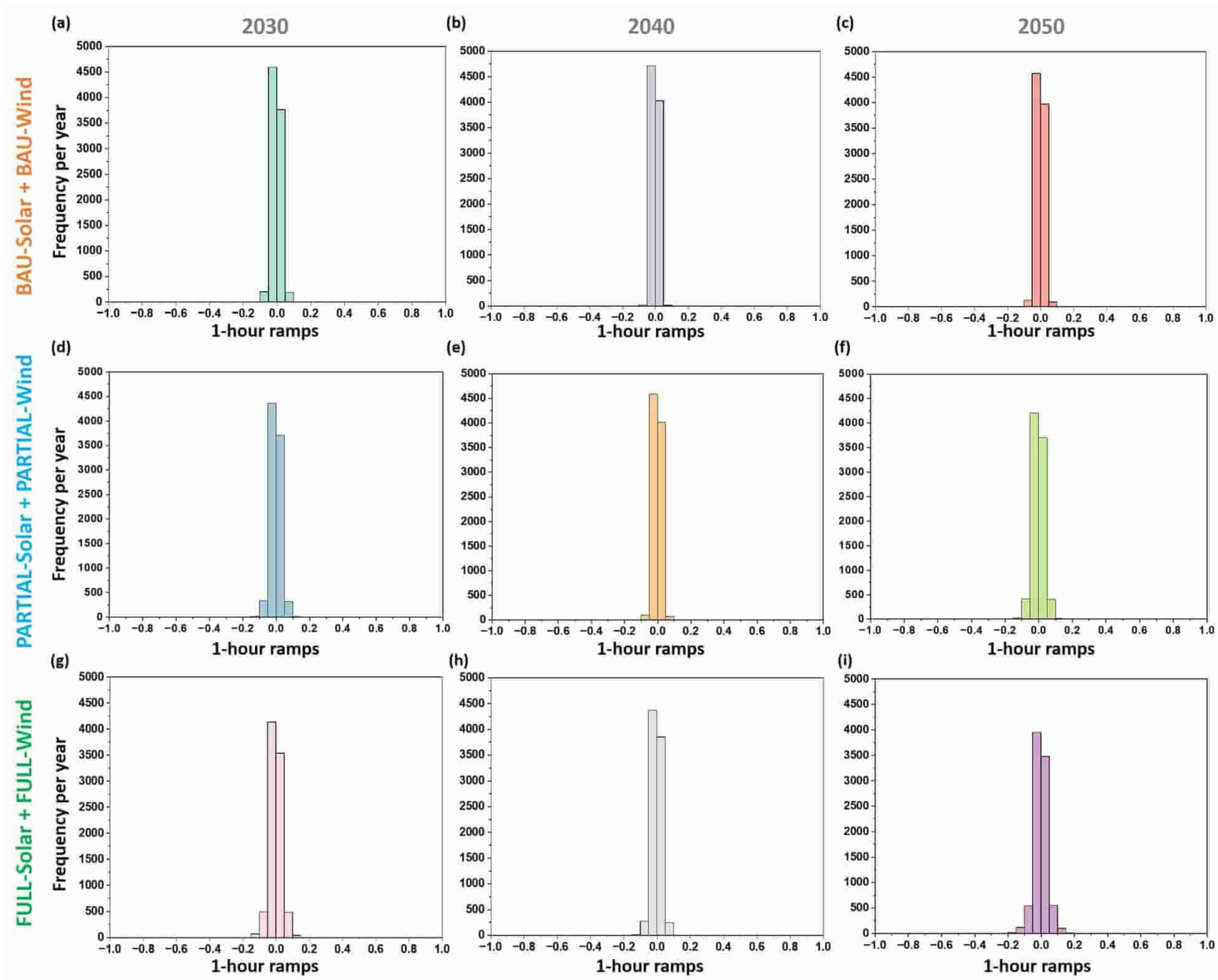

Fig. S48. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Estonia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

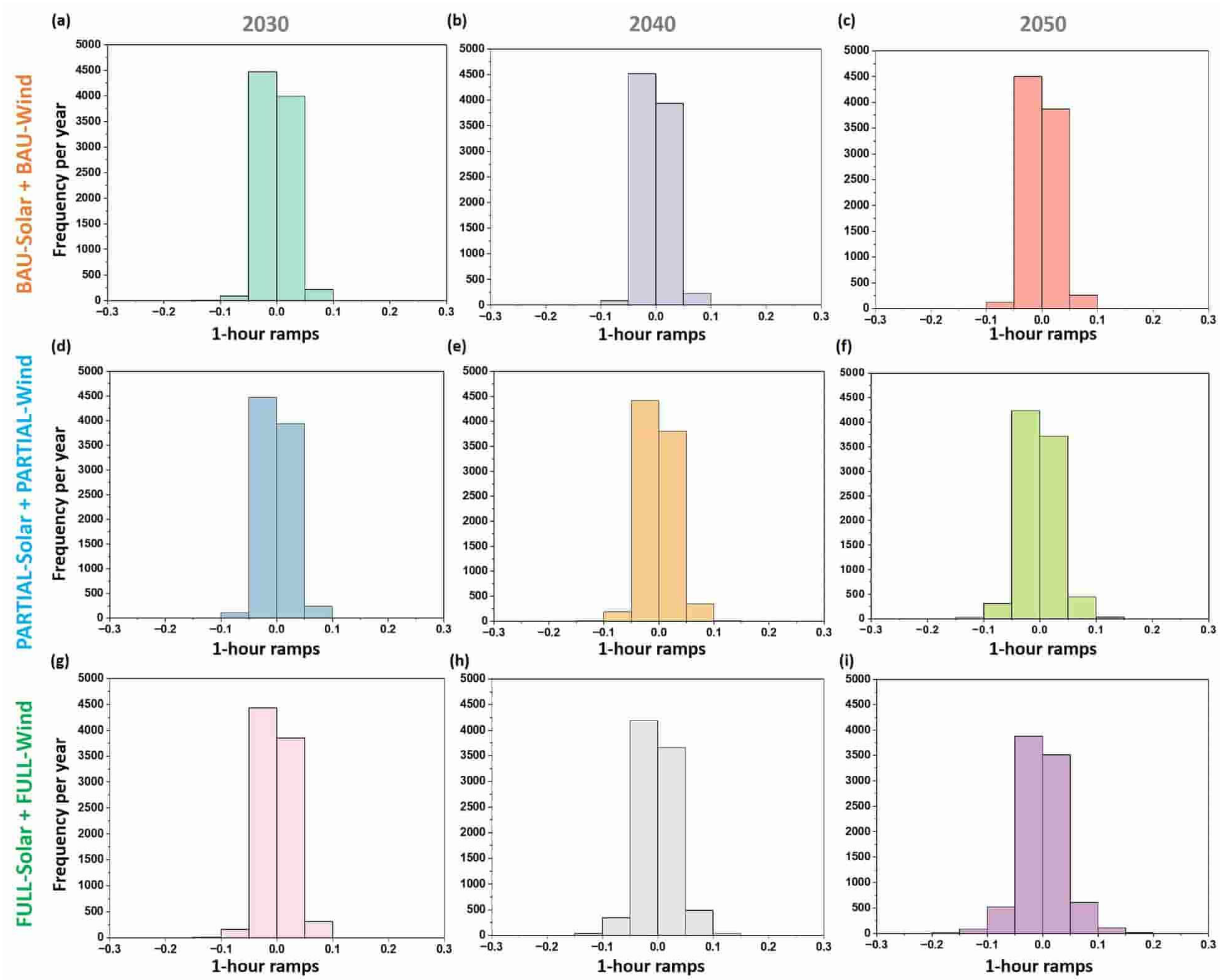

Fig. S49. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Finland*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

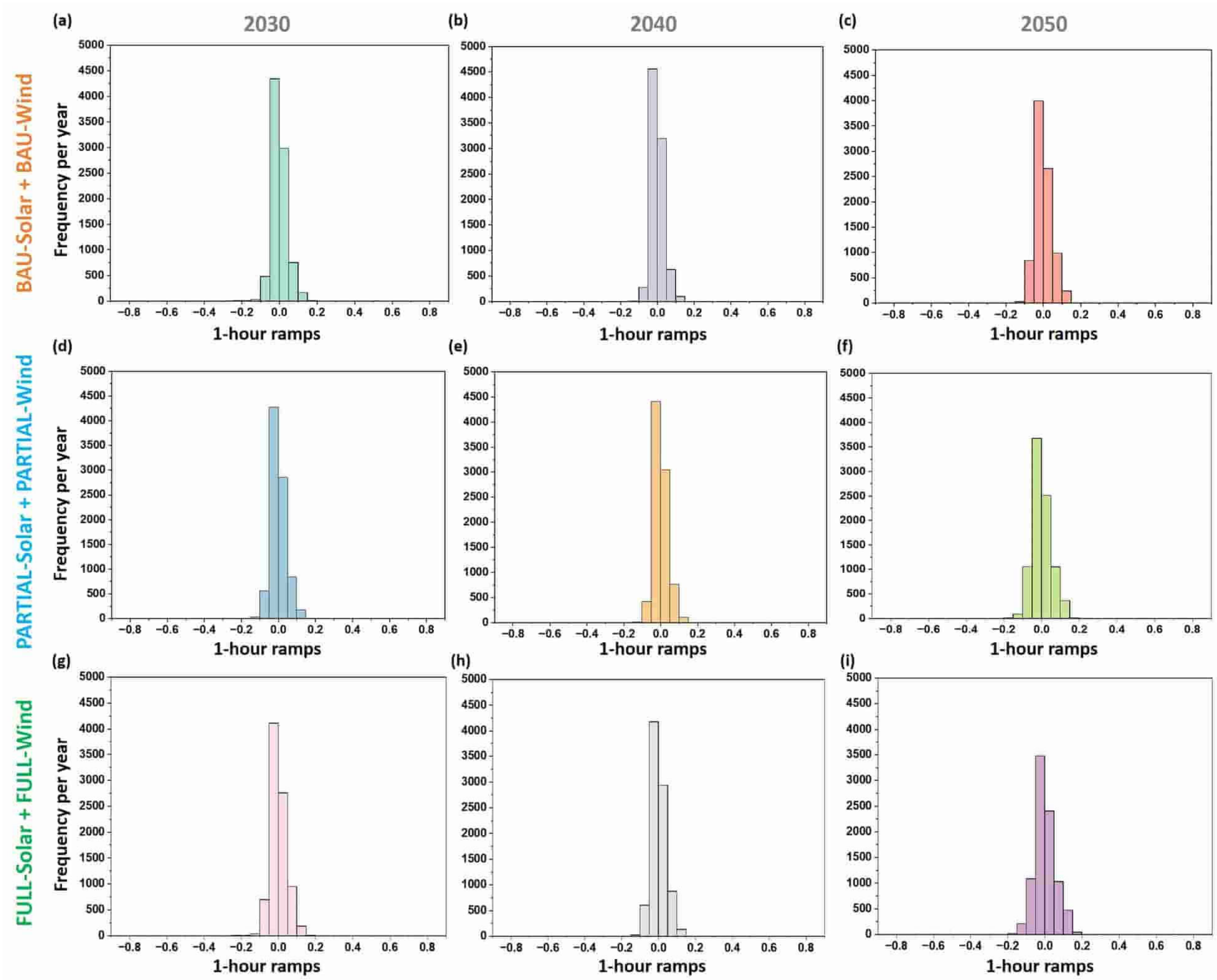

Fig. S50. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Slovenia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

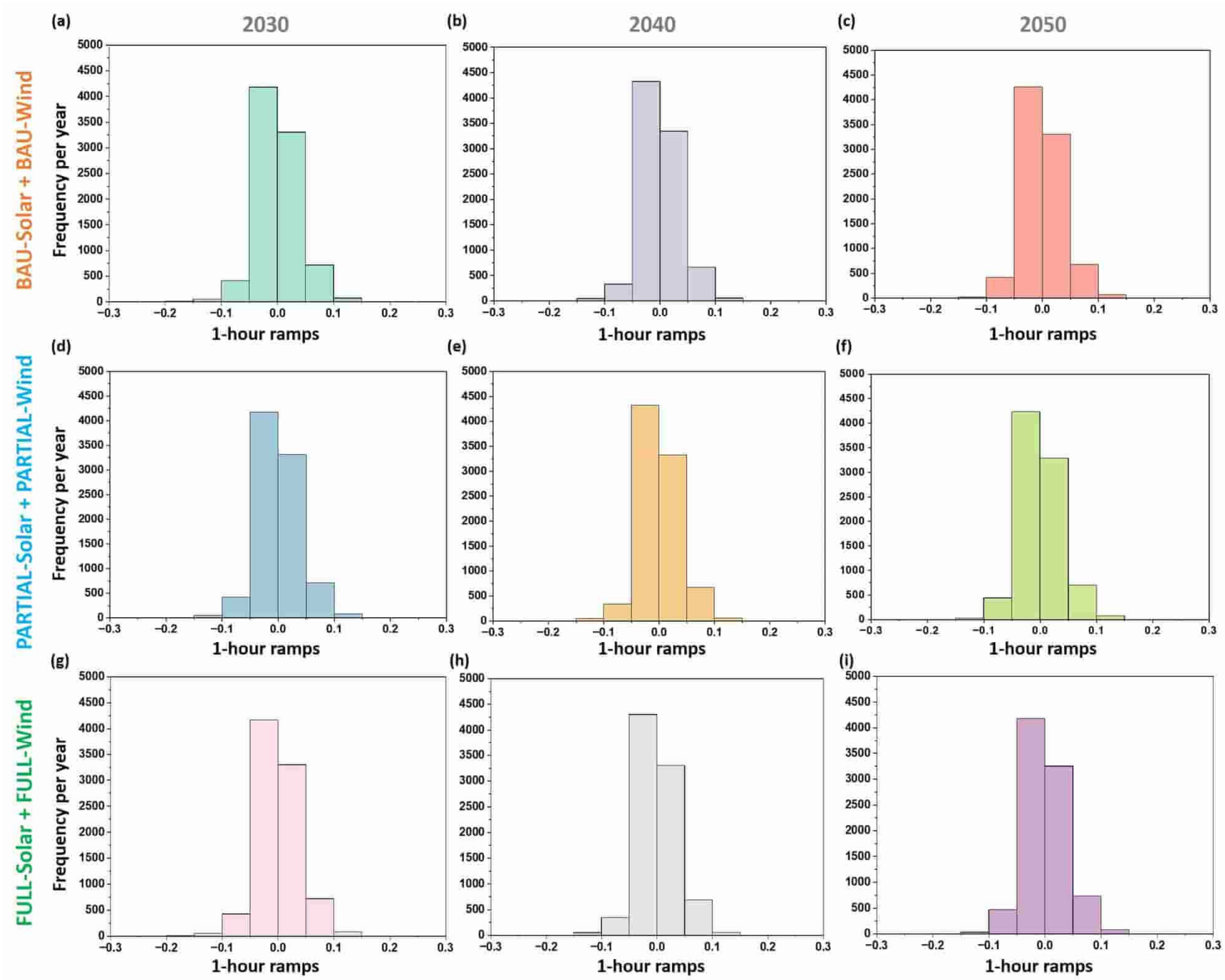

Fig. S51. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Luxembourg*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

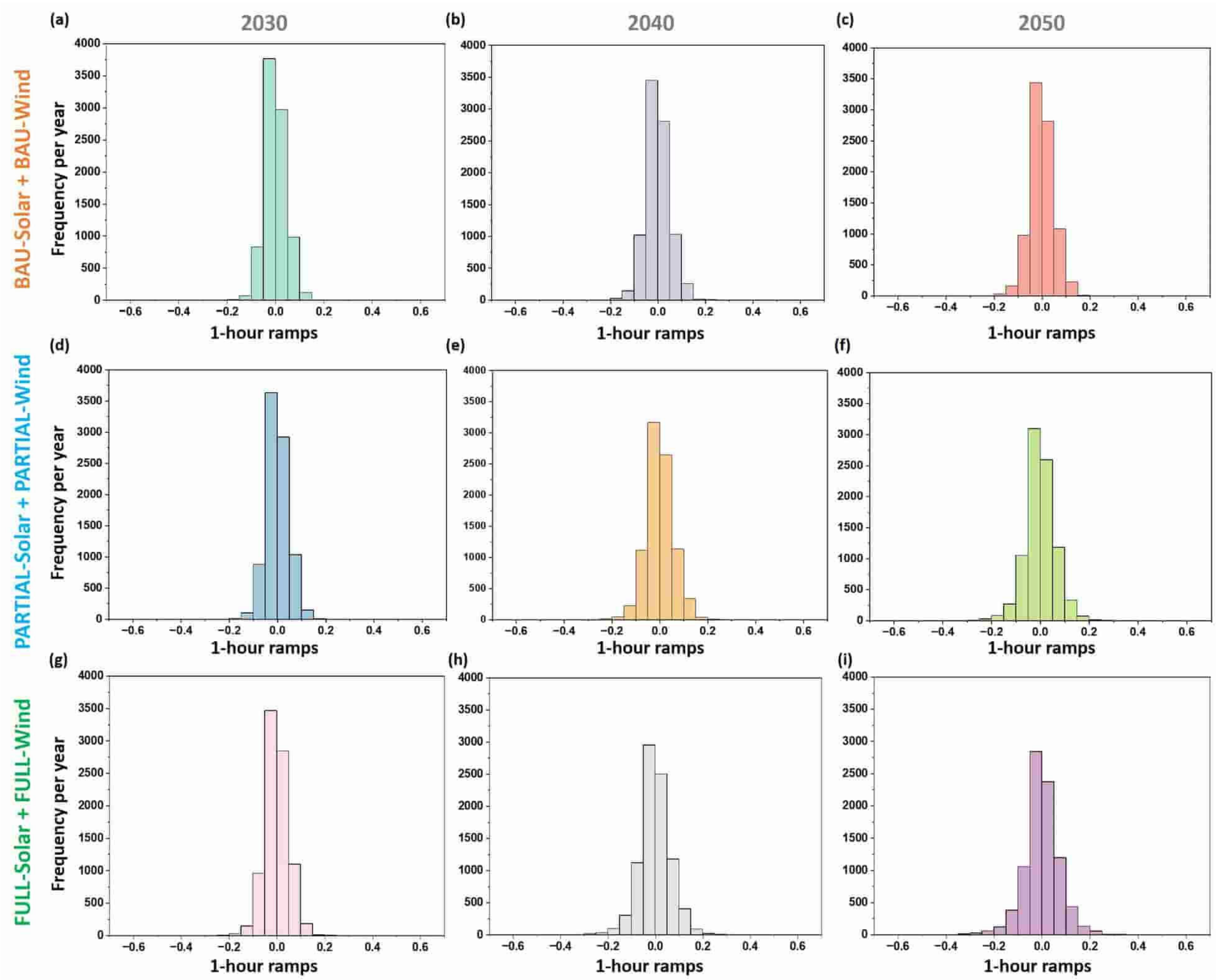

Fig. S52. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Lithuania*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

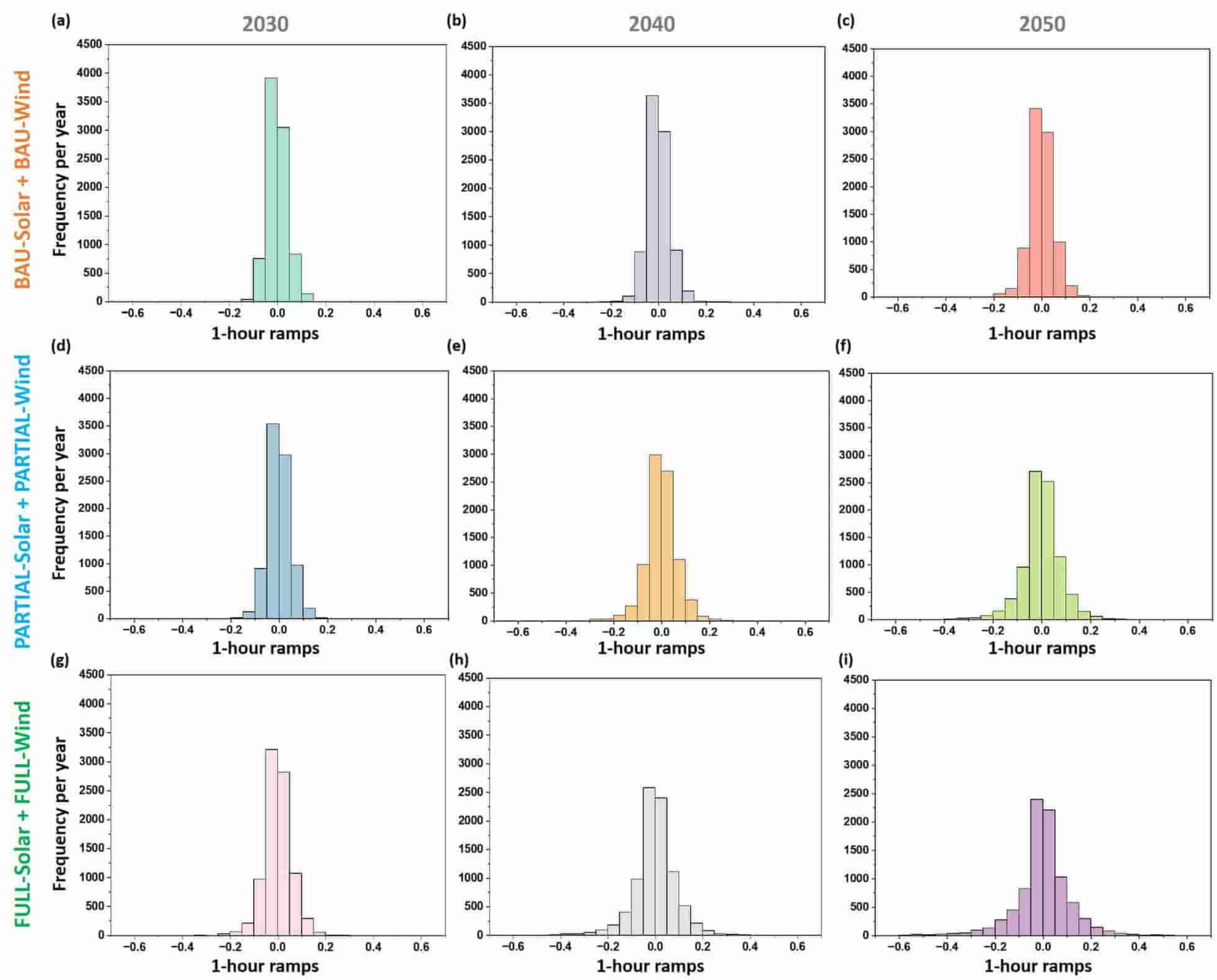

*Fig. S53. Frequency distribution for hourly net-load ramps normalized to the peak load in **Ireland** under **a.,** BAU implementation scenario in 2030. **b.,** BAU implementation scenario in 2040. **c.,** BAU implementation scenario in 2050. **d.,** PARTIAL implementation scenario in 2030. **e.,** 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.*

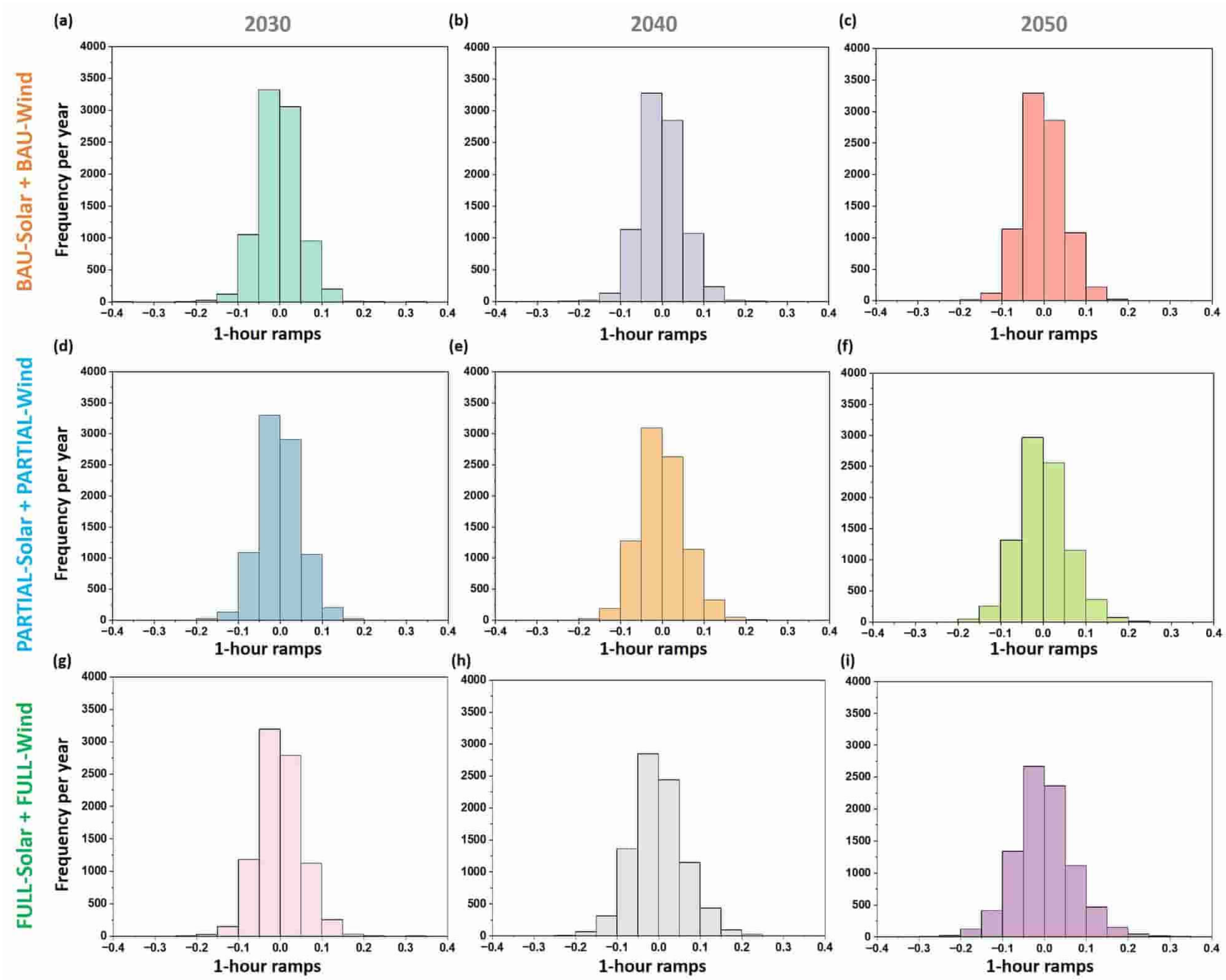

Fig. S54. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Croatia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

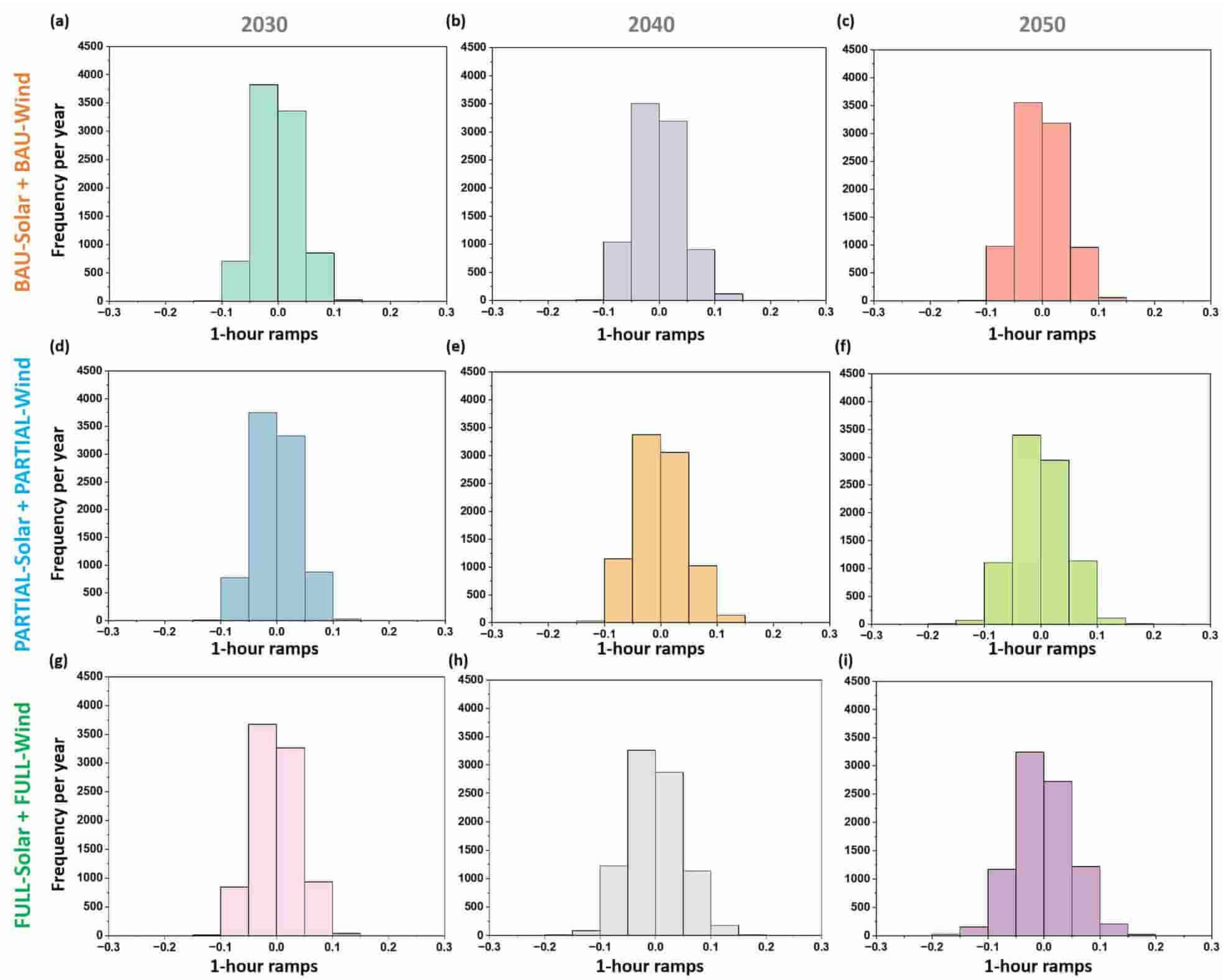

Fig. S55. *Frequency distribution for hourly net-load ramps normalized to the peak load in* ***Latvia*** *under* ***a.,*** *BAU implementation scenario in 2030.* ***b.,*** *BAU implementation scenario in 2040.* ***c.,*** *BAU implementation scenario in 2050.* ***d.,*** *PARTIAL implementation scenario 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.*

Reviewer's Comment (8)

8. Reference Energy System: Please provide details on the reference energy system implemented in the model. It would be helpful to understand how different sectors are modeled. For example: Is green hydrogen production based on dedicated projects, grid connection, or both? How is the road transport sector modeled? Are natural gas, gasoline, diesel, electricity, and hydrogen competing within each segment (passenger cars, two-wheelers, buses, trucks, etc.)?

Answer: Thanks for the comment. We have added details on the reference energy system in the SI file, including how different sectors are modeled, such as specifications on green hydrogen production and segments within the road transportation sector.

Action

- *On pages 88 to 90 of the revised SI file:*

"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, Table S3 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.*

Table S3. 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 the 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."

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Reviewer's Comment (9)

9. Regional Trade Considerations: Since this is a multi-node model, a discussion on intra-regional trade potential within the EU would be valuable. The paper briefly mentions international trade outside the EU but does not explore integration opportunities within the union.

Answer: Thanks for the comment. We agree with the reviewer's feedback to explore intra-regional trade potential. In the revised SI file, we illustrate the clean electricity and green hydrogen trade opportunities across EU member states under the investigated scenarios and varying time horizons. To further contextualize these findings, we have also revised the Discussion section of the main file to present a multi-layered framing that incorporates domestic interventions, intra-EU coordination, and selective international partnerships as complementary components of a resilient energy strategy.

Action

- *On pages 40 to 43 of the revised SI file:*

*"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 **Figs. S23-S25** illustrate a multi-layered analysis of how clean electricity and green hydrogen trade can strengthen EU-wide energy security. Specifically, **Figs. S23** and **S24** 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. **Fig. S23** 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, **Fig. S24** 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, **Fig. S25** explores the complementary role of international trade in reducing EU natural gas reliance. In this regard, **Fig. S25**a illustrates the percentage reduction in gross inland natural gas consumption under different scenarios, while **Figs. S25**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."

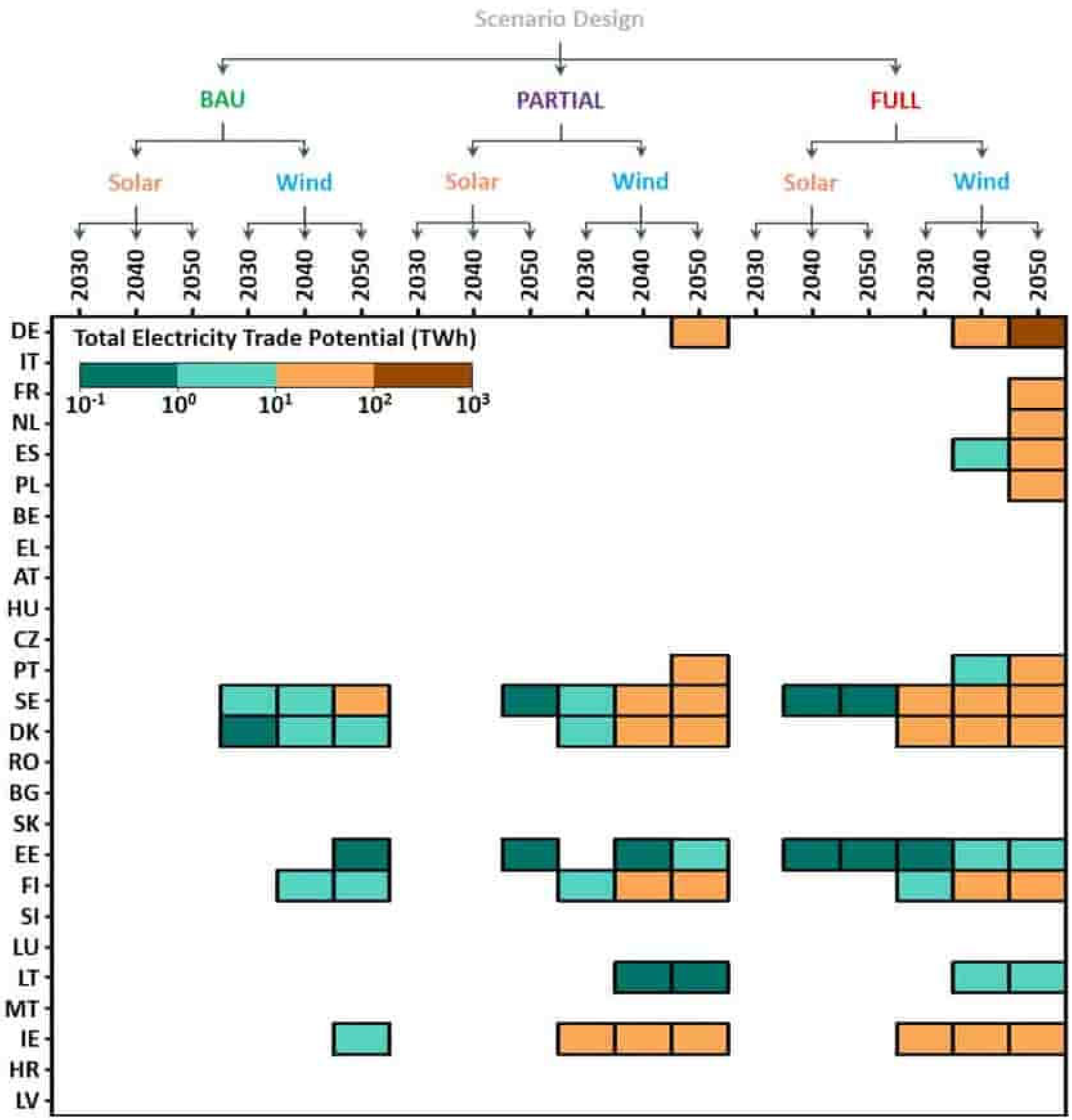

Fig. S23. *Comparative assessment of intra-regional clean electricity trade opportunities among EU countries across BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind scenarios over varying time horizons (2030, 2040, and 2050). The analysis is based on excess electricity supply 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).*

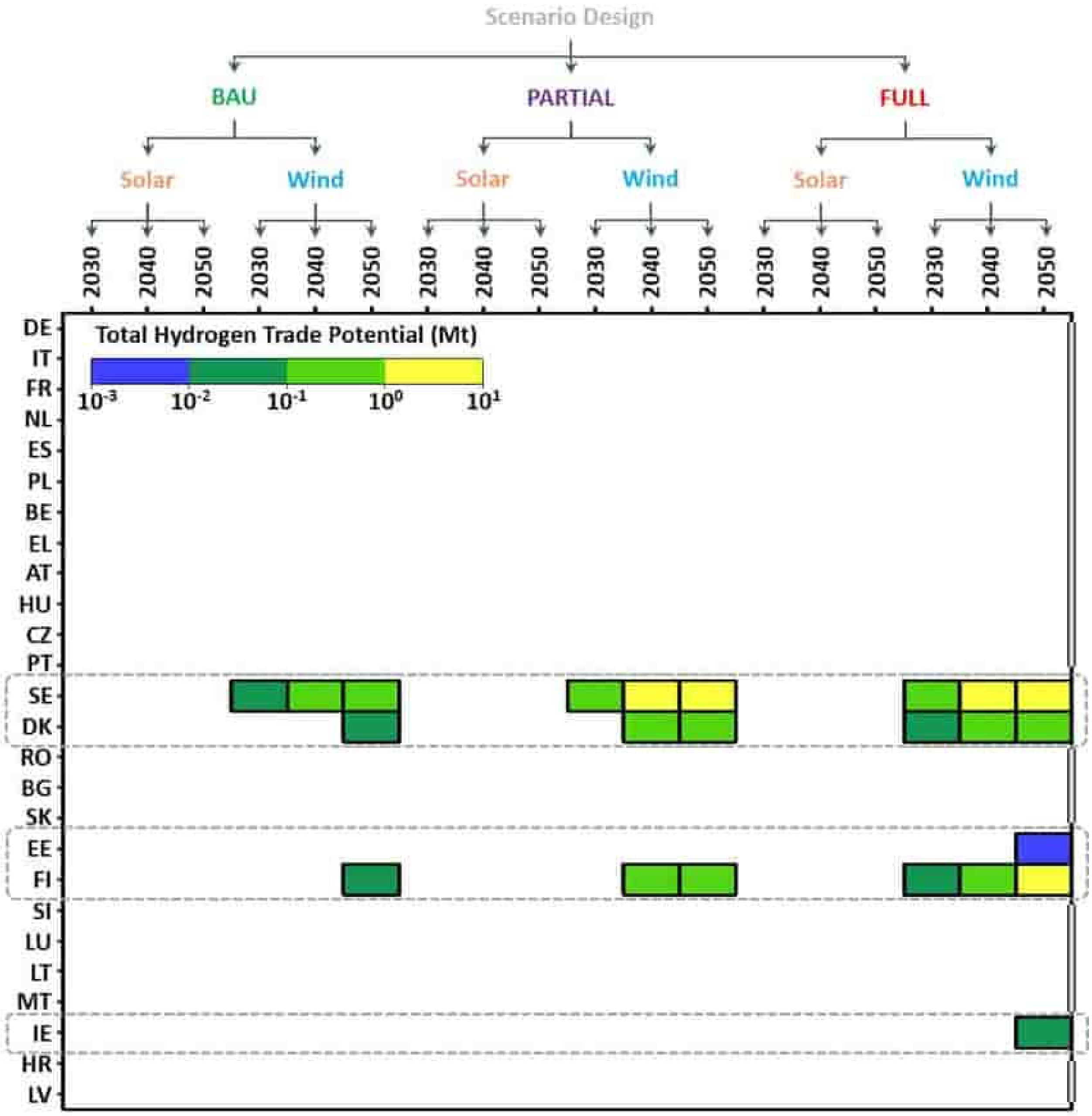

Fig. S24. *Comparative assessment of intra-regional green hydrogen trade opportunities among EU countries across BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind scenarios over varying time horizons (2030, 2040, and 2050). The analysis is* *based on excess green hydrogen supply 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).*

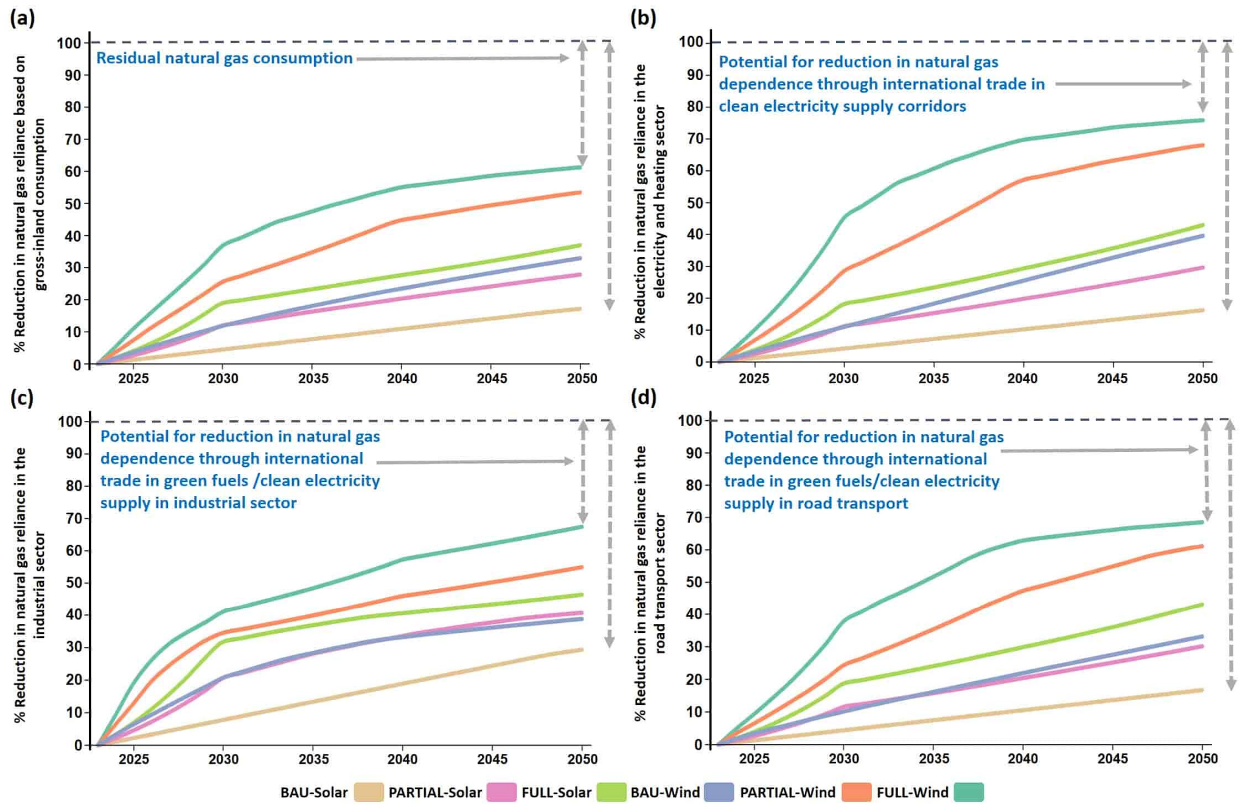

Fig. S25. a., *Percentage reduction (%) in the EU natural gas reliance based on gross inland consumption across different scenarios.* ***b.,*** *Percentage reduction (%) in natural gas reliance in the electricity and heating sector, illustrating the potential opportunity for international trade in clean 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.*

- *On page 19 of the revised main file:*

"The EU's energy landscape faces a pivotal moment due to the evolving geopolitical events of recent years. While domestic natural gas production in the EU declined by 9% in the first nine months of 2022[87] *and by 18.6% in 2023 compared to the previous year*[88]*, a defining shift occurred with the sharp reduction in imports from Russia, falling from over 40% in 2021 to around 11% by 2024*[4]*, triggered by the geopolitical fallout of the conflict. This disruption prompted an urgent reassessment of energy security strategies across member states*[89]*. For instance, the EU diversified its energy imports, notably increasing natural gas supplies from the US by 138.6% over the same period*[4]*. However, this reconfiguration introduced new strategic complexities. Recent shifts in US foreign policy discourse signal a potential inclination to frame energy exports as essential geopolitical levers*[90]*, such as in trade negotiations*[91]*, thereby highlighting strategic considerations surrounding the long-term reliability of US energy supplies*[92]*. Moreover, the evolving geopolitical landscape reveals that international alliances are increasingly fluid*[93]*, shaped by shifting strategic interests. In this context, the findings of this work underscore the need for a multi-layered strategy, combining domestic electrification and green hydrogen deployment in the investigated scenarios (**Figs. 1** and **3**) which can reduce up to 61.3% of gross inland consumption of natural gas by 2050, which can be further improved with coordinated intra-EU trade and selective international partnerships. While regional integration within the EU can unlock clean electricity and hydrogen trade opportunities by leveraging surplus capacities in specific member states (**Figs. S23** and **S24**), the extent of reliance on external suppliers must be approached pragmatically. In order to avoid substituting one dependency for another, residual sector-specific substitution needs (**Fig. S25**) should guide the design of essential future trade strategies to prevent a recurrence of past vulnerabilities. For example, in sectors such as electricity and heating, light industries, and segments of the road transportation sector, clean energy electrification through international corridors can play a significant role. In contrast, for hard-to-abate sectors like heavy industries, green hydrogen carriers represent more effective alternatives to reduce natural gas reliance."*

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Reviewer's Comment (10)

10. Supplementary Material Navigation: The supplementary material would benefit from a table of contents, table of figures, and table of tables, as it contains extensive information that is difficult to navigate.

Answer: Thanks for the comment. In the revised SI file, we have added a table of contents, table of figures, and table of tables to improve content navigation.

Action

- *On pages 2 to 8 of the revised SI file:*

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Reviewer's Comment (11)

11. Data and Code Availability: The manuscript lacks a clear statement on data availability and code availability. Including this information is essential for ensuring transparency and reproducibility, which would strengthen the study's credibility and prevent criticism related to limited accessibility.

Answer: Thanks for the comment. In the revised manuscript, we have added the statement on data and code availability at the end of the main file.

Action

- On page 30 of the main file:

"All data and code needed to evaluate the conclusions in the study have been provided in the Supplementary Information and deposited in GitHub [https://github.com/PEESEgroup/EU-Energy-Project]. Source Data are provided with this paper."

Reviewer 4

Review

Transforming the EU Energy Landscape to Align Climate Mitigation with Energy Autonomy Can Achieve Decarbonization Potential of 20.1 $GtCO_2$ through 2050

The manuscript deals with an interesting topic. It is well written and the methods chosen are common for solving such problems. However, the manuscript does not clearly explain the novelty of the analysis performed. Several publications (scientific and technical reports) have already analysed possible paths of the energy transition and also pointed out security issues and dependencies (on energy and technology imports). From this perspective, it cannot be recognised that the present study has a high degree of novelty in the scientific literature (although I personally agree with most of the results). Therefore, in my view, the study is not ready for publication in Nature Communications.

Some more detailed comments on individual points of the manuscript:

Reviewer's Comment (1)

Regarding Introduction

In general, the introduction is well written. The literature review needs to be improved, especially focussing on studies on energy security and energy dependency and the energy transition model in Europe in general. The introduction lacks the emphasis on novelty and the clear formulation of the research question and the aim of the proposed work.

Answer: Thanks for the comment. We agree with the reviewer's feedback to improve the literature review, emphasize the novelty of the study, and clearly articulate the research question and aim of the proposed work. To address this, we have implemented the following revisions in the Introduction section:

- The opening paragraph now presents a broader framing of the EU's dual challenge of energy security and climate mitigation and introduces an overarching research question focused on detailed scenario-based evaluation and sector-specific interventions.
- Subsequently, we have strengthened the review of existing literature with a particular focus on studies related to energy security, energy dependency, and energy transition models in Europe to establish the aim of this study.
- Lastly, we have added a structured list of bullet points outlining the novel contributions of the work.

Action

- *On pages 2 to 4 of the revised main file:*

"The continued dependence of EU energy demand on fossil fuel supplies underscores the pressing challenge of energy security, particularly in light of recent geopolitical tensions. The Russia-Ukraine conflict, for instance, exemplifies the concerns with surging energy prices[1, 2] and persistent disruptions in fossil fuel supply chains[3]. In this context, a targeted focus on reducing sector-specific natural gas consumption remains critical, given its continued role as a key input across electricity, heating, industrial, and transportation sectors[4], emergence as a principal vulnerability during recent geopolitical disruptions[5], and intertwined implications for the climate crisis. For instance, Russian gas imports, which previously accounted for over 40% of the EU's natural gas supply, represented around 11% in 20244, underscoring the severity of the shift caused by geopolitical tensions. While other energy imports, such as oil, also play a role in the EU's energy mix, analysis by the European Parliament indicates that the EU has numerous options for oil imports, as it is flexibly traded and transported across the world[6]. However, natural gas remains a pressing challenge due to its heavy reliance on pipelines[7], which are time-consuming to develop[8] and highly vulnerable to supply disruptions[9]. Alongside the potential risks to future energy security in the EU[10, 11], climate change persists as an impending crisis. The proximate deadlines for the climate targets, particularly those set for 2030, 2040, and 2050[12, 13], necessitate robust strategies to curtail carbon emissions across diverse sectors. Moreover, the uncertainty surrounding the economic implications of geopolitical tensions, such as higher costs[14] and economic slowdowns[15], necessitates evaluating how varying cost development trajectories affect the competitiveness of sector-specific clean energy strategies across the EU. Therefore, a critical gap persists in the systematic evaluation of strategic interventions driven by renewable capacity expansion, across spatial, sectoral, and temporal horizons in the EU, along with the associated economic implications, thereby necessitating scenario-based assessment to inform infrastructure planning and policy decisions. This analysis aims to address these questions without delving into deep geopolitical nuances.

Empirical assessments demonstrate that renewable energy deployment can act as a substitute for energy imports, with various EU countries exhibiting improved efficiency and productivity through technological innovation and convergence toward renewable energy and energy security goals[16]. Tracking the evolution of energy security indicators reveals that diversification of primary *energy sources, along with the share and diversity of energy imports, are key drivers of improvement, with regional cluster analysis highlighting transferable policy insights[17]. Complementary assessments further suggest that sufficiency measures can substantially reduce final energy demand and alleviate pressure on supply-side interventions by 2050[18]. These insights are reinforced by policy mechanisms such as REPowerEU 2030[19, 20], and the recently announced targets for 2040[21], which collectively signal a strategic pivot toward renewable energy across electricity, heating, and transportation to reduce natural gas dependence. Nonetheless, recent setbacks in global emissions reduction efforts[22, 23] and reduced accessibility to affordable energy in the EU[24] reveal the susceptibilities in pre-conflict energy and climate strategies, indicating the need for scenario-based frameworks that align energy security improvements with climate mitigation, using reductions in natural gas consumption as a central metric across diverse renewable deployment pathways.*

Previous studies also examine the European energy transition using modeling frameworks based on least-cost optimization to determine energy system configurations[25, 26, 27], or offer insights at the transmission network level[28]. These analyses outline the diversity of feasible system designs[29], foster communication across societal levels[30], generate high-level insights for multi-sector system integration[31], and investigate grid constraints[32]. Some assessments also focus on individual energy pathways[33, 34], or region-specific crisis responses[2], without directly addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions. Within this broader transition landscape, sectors that are difficult to electrify, such as heavy industries, require complementary technological pathways. Green hydrogen emerges as a promising vector for advancing energy transition and climate mitigation goals[35, 36], supported by the expansion of renewable capacity and offering a critical alternative to natural gas in heavy industries[37, 38, 39]. Recent literature highlights the importance of competitive and secure renewable hydrogen to minimize reliance on single suppliers[40]. Regional assessments further underscore the role of hydrogen infrastructure during the energy crisis[41], the feasibility of substituting carbon-intensive hydrogen production with renewable-based electrolysis[42], and the potential of hydrogen and power-to-liquid pathways to reduce energy-related import costs[43]. Additionally, studies emphasize the role of hydrogen in decarbonizing the European energy system, with projections of substantial hydrogen production by 2050[44, 45]. However, these opportunities require careful policy choices to avoid perpetuating long-standing vulnerabilities[46]. These insights reinforce the need for sector-

disaggregated analysis aimed at reducing natural gas consumption and emissions through targeted interventions, evaluated across diverse cost trajectories, to advance EU-wide energy security and decarbonization outcomes.

While previous studies provide valuable perspectives, also summarized in Table S1 for comparative reference, this work seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation in the EU energy landscape, with the following novel contributions:

- *Develops a comprehensive scenario-based assessment centered on renewable expansion pathways and incorporating targeted strategies, including electrification, green hydrogen deployment, and carbon offsetting, to align the EU's dual goals of energy security and climate sustainability amidst geopolitical disruptions.*
- *Introduces a sector-disaggregated framework targeting reductions in natural gas consumption and emissions across electricity and heating, light and heavy industries, and transportation, capturing the differentiated impacts of transition strategies across spatial and temporal horizons in the EU.*
- *Establishes a robust analytical framework to evaluate the economic feasibility of targeted interventions, incorporating a comprehensive spectrum of technology cost trajectories informed by historical learning rates under varying renewable expansion scenarios."*

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Reviewer's Comments (2) and (3)

Regarding Fig. 2:

The term "current" is somehow misleading. What is exactly analysed? Is it the current LCOE or the LCOE in 2050 under current policy? If it is the current LCOE, why values in a) and b) are different? Does this LCOE include all generation technologies or only solar PV and wind, respectively? Please explain this and improve the description of the figure.

Please explain your higher LCOE compared to other studies. For instance, you show current LCOE for solar PV in Germany of 0.17 /kWh and for 2050 a value of 0.07 $/kWh. This values are way higher than of other studies like in

- *https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html,*
- *https://www.statista.com/statistics/1110938/eu-countries-solar-power-price/,*
- *https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3659, or*
- *https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023*

Answer: Thanks for the comment. The authors are grateful for the reviewer's feedback on Fig. 2 and the supporting LCOE values. The term "current", as originally presented in Fig. 2 refers to LCOE estimates for 2024, calculated using present-day cost parameters. Correspondingly, LCOE values projected to 2050 are derived using a spectrum of cost development trajectories based on historical learning rates, as detailed in the Scenario Design section of the revised main text and SI file. The LCOE values in panels (a) and (b) reflect technology-specific assessments: (a) corresponds to solar PV systems, and (b) to wind power installations. These values are calculated individually and do not include other generation technologies. We have revised the terminology in the figure and caption to improve clarity.

We also recognize the importance of situating our estimates relative to other studies. The higher LCOE values reported in this analysis, such as \$0.17/kWh for solar PV in Germany, can be attributed to several analytical parameters, including the inclusion of battery storage (consistent with IEA specification of four-hour storage sized at 20% of renewable output capacity (IEA, 2024)), the use of country-wide solar irradiance profiles rather than site-specific locations, and the application of standardized economic assumptions such as interest rates.

Specifically, the study by Fraunhofer ISE uses site-specific irradiance profiles, focusing on locations in Germany with solar irradiation between 950 and 1300 kWh/(m^2·a), and applies a 3% interest rate (Fraunhofer ISE, 2024), resulting in LCOE estimates of approximately €0.06-

0.11/kWh (around \$0.065-\$0.12/kWh) for PV-battery systems. In contrast, this work uses country-wide output profiles to align with the scenario-based framework, which evaluates renewable deployment pathways across all EU member states in response to policy targets. Additionally, an interest rate of 10% is adopted in this study, consistent with assumptions used in previous IEA assessments (IEA, 2012; IEA, 2015; IEA, 2010; IEA, 2014) and related literature (Hernández-Moro & Martínez-Duart, 2013; Tran & Smith, 2018). The analysis by IRENA, which reports lower LCOE values than those presented in this study, illustrates the country-level weighted average LCOE for solar PV plants and does not include battery storage (IRENA, 2024). Breyer et al. present LCOE projections with investments distributed across multiple technologies, without isolating values for solar PV systems (Breyer et al., 2023). Similarly, Statista (Statista, 2020), which cites LCOE data from Carbon Tracker (Carbon Tracker, 2020), reports country-level solar PV prices; however, it does not provide sufficient details or indicate the inclusion of storage or the applied parameters, making direct comparisons challenging.

However, following the reviewer's feedback and to contextualize the LCOE estimates presented in this work, we conducted an additional analysis comparing values under different storage configurations (with and without battery storage) and applied interest rates (3% and 10%). To illustrate the influence of solar radiation profiles on LCOE outcomes, this analysis is performed both at the EU-wide level and for disaggregated NUTS-2 regions within Germany. The extended results are presented in **Fig. S27-S30** of the revised SI file.

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Action:

- *On pages 45 to 50 of the revised SI file:*

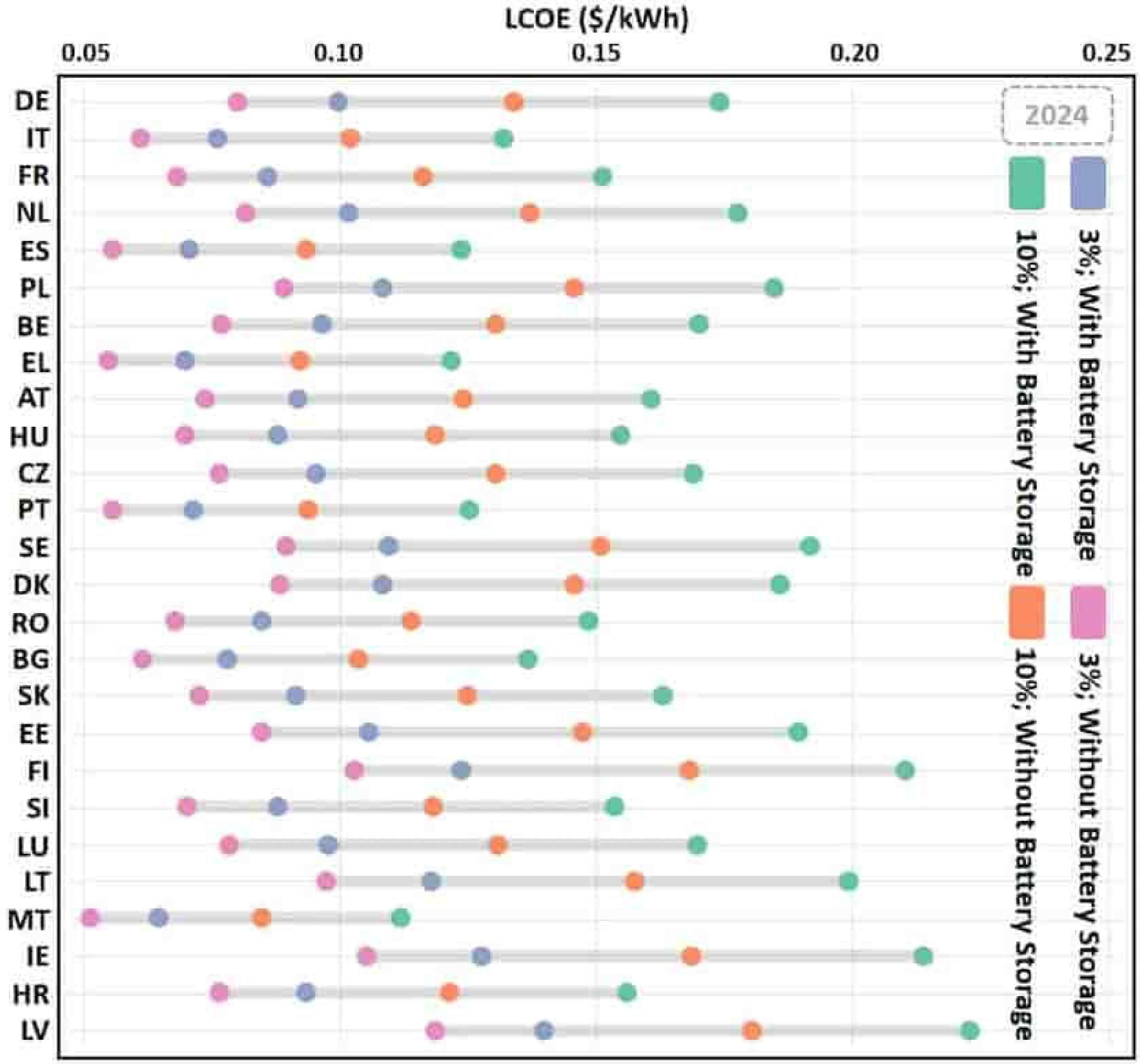

Fig. S27. *Comparative assessment of solar PV LCOE for EU countries in 2024 under different assumptions for battery storage inclusion and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. 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).*

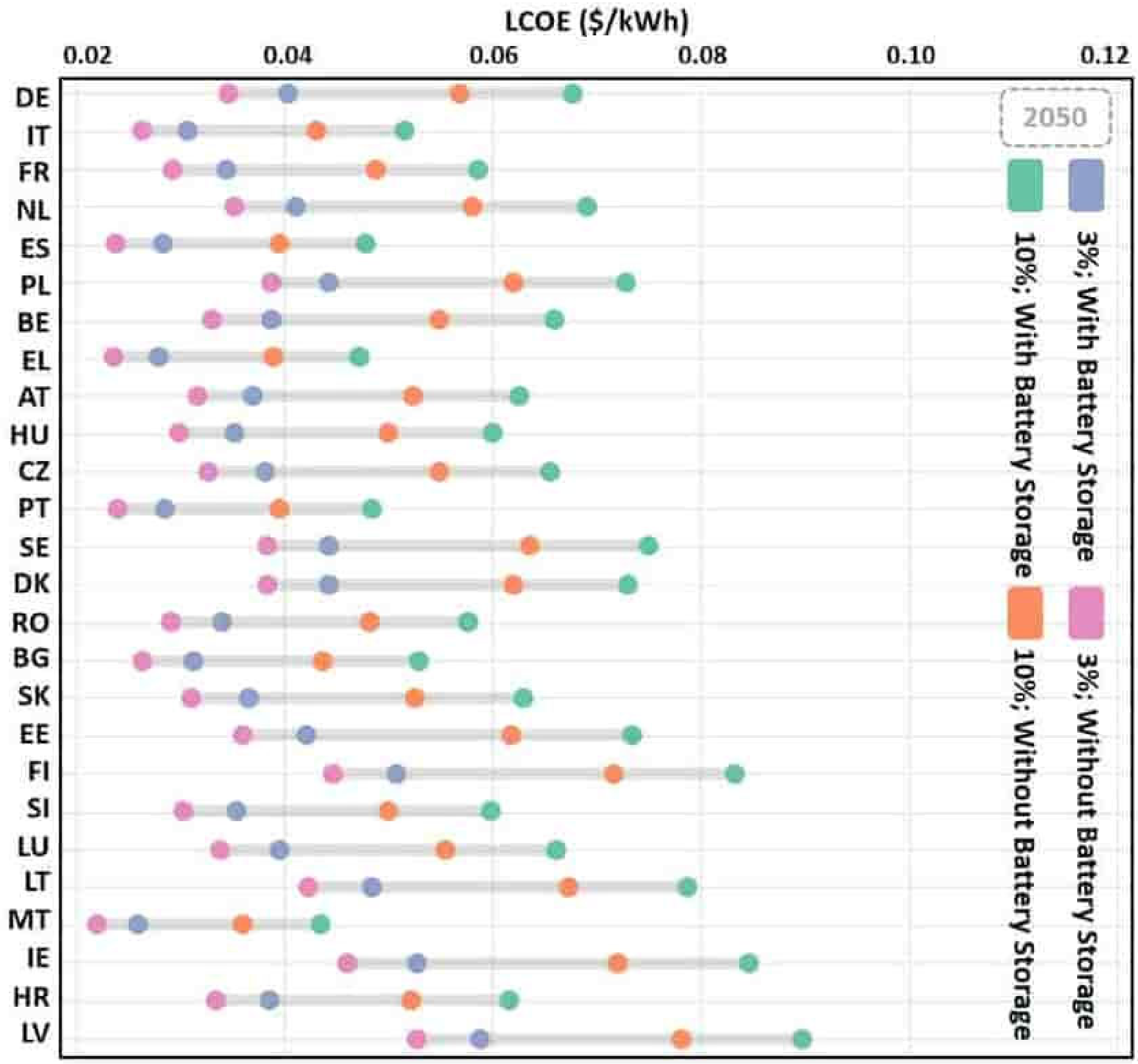

Fig. S28. *Comparative assessment of solar PV LCOE for EU countries in 2050 under different assumptions for battery storage inclusion and interest rates. The analysis includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without battery storage. 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).*

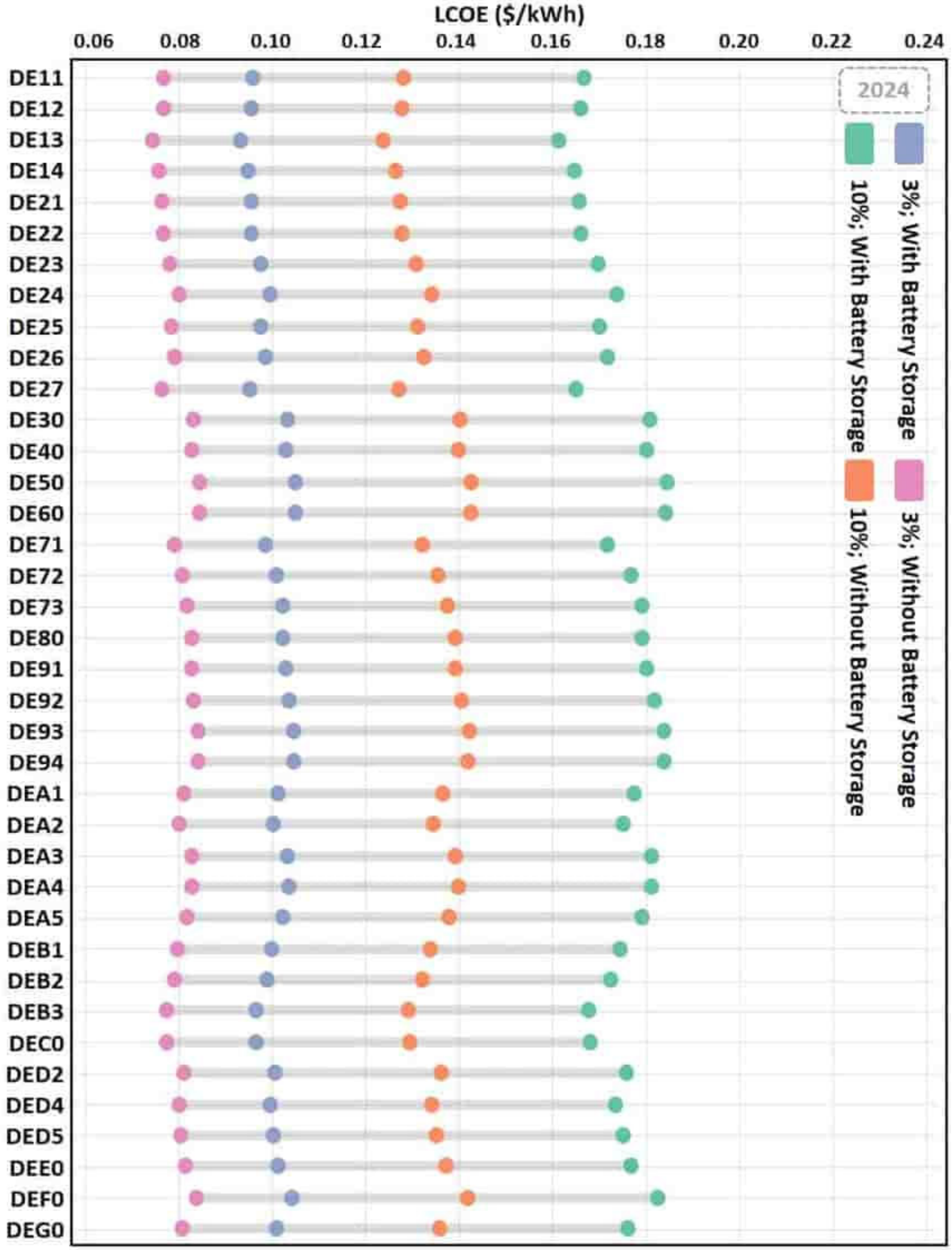

Fig. S29. *Comparative assessment of solar PV LCOE across NUTS-2 regions in Germany for 2024 under different assumptions for battery storage inclusion and interest rates. The analysis* *includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without 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).*

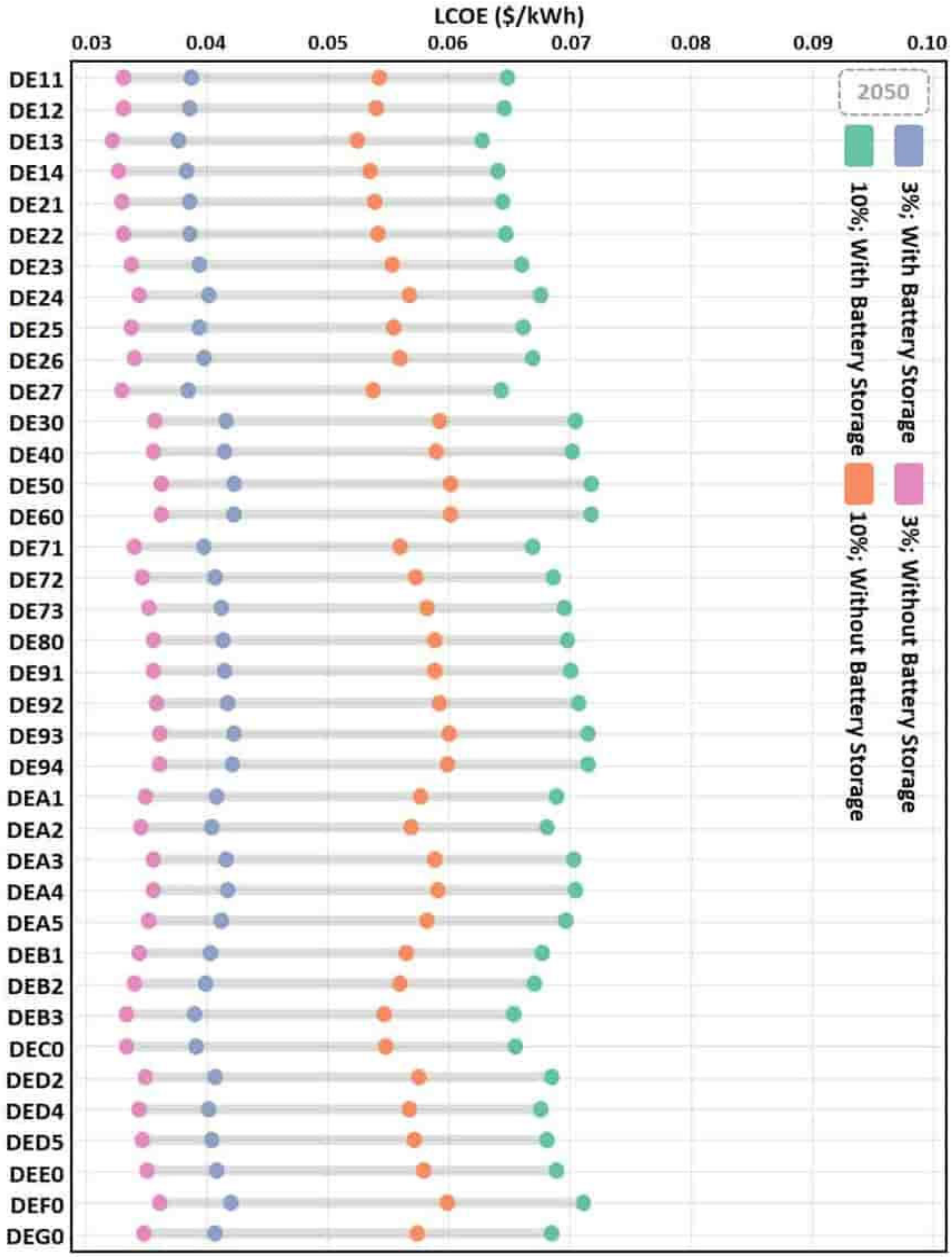

Fig. S30. *Comparative assessment of solar PV LCOE across NUTS-2 regions in Germany for 2024 under different assumptions for battery storage inclusion and interest rates. The analysis* *includes four configurations: 10% interest rate with and without battery storage, and 3% interest rate with and without 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).*

- *On pages 10-11 of the revised main file:*

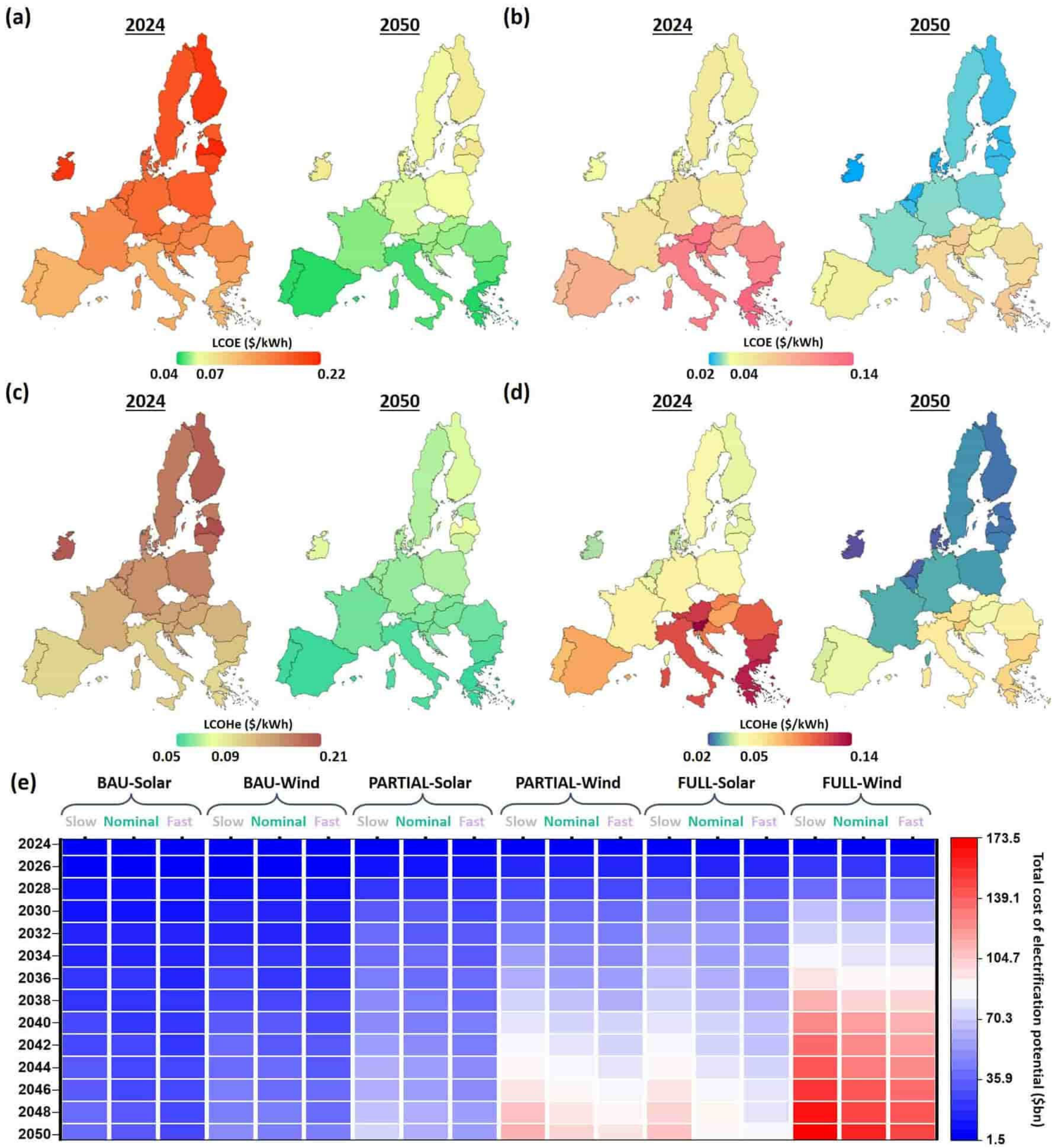

Fig 2. a., *Levelized cost of electricity ($/kWh) from solar power expansion with battery storage in 2024 and under a fast cost-reduction trajectory by 2050.* ***b.,*** *Levelized cost of electricity ($/kWh) from wind power expansion with battery storage in 2024 and under a fast cost-reduction trajectory by 2050.* ***c.,*** *Levelized cost of heat ($/kWh) from solar power expansion in 2024 and under a fast cost-reduction trajectory by 2050.* ***d.,*** *Levelized cost of heat ($/kWh) from wind power expansion in 2024 and under a fast cost-reduction trajectory by 2050.* ***e.,***

Total annual cost of electrification potential ($bn) under renewable capacity scenarios (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind) and varying cost trajectories (Slow, Nominal, and Fast) through 2050.

"In order to evaluate the economic implications of strategic scenarios, this work assesses the levelized cost of electricity (LCOE), levelized cost of heat (LCOHe), and the total cost of electrification potential under three cost development trajectories categorized as slow, nominal, and fast. These trajectories reflect varying learning rates informed by historical trends[59], capturing uncertainties in future cost competitiveness. ***Figs. 2****a and b illustrate the spatial variation in LCOE in 2024 and under a fast trajectory in 2050 for solar and wind power expansion, incorporating battery storage. The average LCOE across EU countries is $0.16/kWh for solar and $0.08/kWh for wind, based on country-level estimates, which drops by 60.9% and 46.0% in 2050, respectively.* ***Figs. 2****c and d present the corresponding spatial variation in LCOHe driven by solar and wind power installations.* ***Fig. 2****e presents the total cost of electrification potential across different scenarios (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind) under varying cost trajectories through 2050. In the FULL-wind scenario, the total cost reaches $173.2 bn under the slow trajectory but declines by 13.7% under the fast trajectory. The comparison highlights the role of accelerated cost reductions, potentially driven by policy support and investment incentives, in enhancing economic feasibility. Similarly, under the PARTIAL-solar and PARTIAL-wind scenarios, total electrification costs reach $62.7 bn and $102.3 bn, respectively, by 2050 under the nominal trajectory. These intermediate pathways illustrate a cost-effective middle ground between ambitious deployment targets and economic feasibility across the EU. Moreover, the results show that in pathways with dominant wind capacity (e.g., FULL-wind), the incremental cost of solar expansion becomes marginal, offering flexibility in deployment strategy. To contextualize the cost estimates presented in* ***Fig. 2****, an additional analysis is conducted across the EU and disaggregated NUTS-2 regions within Germany (****Figs. S27-S30****), comparing LCOE outcomes across different configurations based on economic parameters and the inclusion of battery storage."*

Reviewer's Comment (4)

Regarding Fig. S56:

The analysed pathways are highly simplified. Indeed, in the industries summarised under "heavy industries" various technological pathways for direct electrification exist or are under development (and thus maybe available until 2050) (see e.g. doi.org/10.1016/j.energy.2016.07.110).In the categorisation, also a more distinguished categorisation could be helpful. For instance: steel processing industry may have currently a high natural gas consumption due to furnaces, but these could be electrified via resistance heating (fully or partly). Same should be discussed also for other sectors. Besides technological pathways, also efficiency gains, changing production chains and markets as well as flexibility options in production should be mentioned and discussed as these drivers will change the energy demand for natural gas and hydrogen, respectively.

Answer: Thanks for the comment. The authors are grateful for the study suggested by the reviewer which explores the potential for renewable electricity in the basic materials industry using a what-if thought experiment (Lechtenböhmer et al., 2016). We also agree with the reviewer's feedback that electrification pathways are under development and may be available until 2050. Recognizing the need for sector-specific decarbonization pathways driven by renewable capacity expansion, the schematic in Fig. S56 (Fig. 61 in the revised manuscript) represents the strategies modeled in this work, following the IEA's assessments which indicate that in the industrial sector, the highest potential for electrification lies in low-temperature heat processes (IEA, 2023a), along with its identification of light industrial applications as having lower temperature requirements (IEA, 2023b). We acknowledge that this categorization is structured to align with the modeling scope and decarbonization strategies assessed in this work, without encompassing the full diversity of emerging industrial pathways or adopting a what-if analytical construct. Accordingly, following the reviewer's suggestion, we have included a discussion of technological pathways and broader structural and operational shifts in industrial energy demand that may influence the long-term evolution of decarbonization strategies.

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Action

- *On page 90 of the revised SI file:*

*"The categorization in **Fig. S61** 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."*

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Reviewer's Comment (5)

Regarding "Energy Security"

It is well noticed that the manuscript aims to focus on this important issue. However, it is not seen that any common or novel measurement for "dependency" and "security" rather than demand and costs are considered. Here, the manuscript needs to be improved to cover a broader understanding of these terms.

Answer: Thanks for the comment. We agree with the reviewer's feedback that energy security and dependency are multifaceted concepts, and a broader understanding extends beyond demand trends or cost metrics. In the revised manuscript, we adopt a multi-layered evaluation strategy to reflect this complexity. Specifically, we first evaluate the reduction in gross inland natural gas consumption as a primary indicator of overall natural gas reliance (**Figs. 1** and **3**), consistent with the metric used in Eurostat's reporting (Eurostat, 2023). This indicator captures the structural shift in natural gas use and its alignment with long-term energy security and climate mitigation objectives.

While indices are often used to evaluate the diversity of an energy mix (Ranjan & Hughes, 2014; Servín-Campuzano et al., 2024), it has been noted that even with a stable evolution of the diversity and low market concentration, high import dependency can still hamper energy security (De Rosa et al., 2022). Accordingly, we also evaluate the reduction in natural gas import dependency rate (in percentage points) across scenarios, as depicted in **Fig. S26**, which also aligns with Eurostat's prior reporting (Eurostat, 2022).

Moreover, the recent reconfiguration in the EU's natural gas supplier shares, particularly following reduced flows from Russia (European Council, 2024), alongside shifts in foreign policy orientations of key exporting countries (Reuters, 2025; Forbes, 2025), further highlights the risks of substituting one form of dependency for another. In this context, we extend the scope of the manuscript to examine intra-regional trade potential within the EU. The revised SI file illustrates the clean electricity and green hydrogen trade opportunities across EU member states under the investigated scenarios and varying time horizons (**Figs. S23** and **S24**).

Building on this intra-EU dimension, we also examine the complementary role of international trade in reducing residual sector-specific natural gas reliance (**Fig. S25**). This framing supports the design of future trade strategies aimed at lowering external supply concentration and mitigating the recurrence of past vulnerabilities.

To contextualize the findings, we have also revised the Discussion section of the main file to present a multi-layered framing that incorporates domestic interventions, intra-EU coordination, and selective international partnerships as complementary components of a resilient energy strategy.

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Action

- *We have presented the analysis on reductions in gross inland natural gas consumption in response to Comment 10 from Reviewer 1. To reduce the length of this file, please refer to pages 44 to 47 for the complete revision.*
- *We have presented the analysis of the natural gas import dependency rate in response to Comment 6 from Reviewer 3. To reduce the length of this file, please refer to pages 114 to 115 for the complete revision.*
- *We have presented the analysis of intra-EU trade opportunities and the potential role of selective international partnerships in response to Comment 9 from Reviewer 3. To reduce the length of this file, please refer to pages 147 to 150 for the complete revision.*
- *We have presented the revised text in the Discussion section outlining the complementary components of a resilient energy strategy in response to Comment 2 from Reviewer 2. To reduce the length of this file, please refer to pages 96 to 97 for the complete revision.*

Reviewer's Comment (6)

Regarding Discussion

The discussion is generally well written. In-line with the comments on other parts: Novelty of the findings is not well explained. In some cases, comparison with existing literature is done but this should be improved and extended. Some statements are general and findings in the result sections should be involved more. Also, limitations of the examined study need to be pointed out and discussed here.

Answer: Thanks for the comment. In the revised manuscript, we have improved the Discussion section to better illustrate the novelty of the findings by referencing relevant outcomes from the Results section and expanding the comparison with existing literature and selected elements of the EU action plan related to energy supply diversification. We have also included a discussion on the limitations of the proposed methodology and outlined recommendations for future improvements.

Action

- *On pages 17 to 22 of the revised main file:*

"In light of the recent geopolitical tensions and the pressing need for robust policy measures, this work offers a novel strategic perspective by targeting sector-specific reductions in natural gas consumption as a central metric to align energy security with climate goals. The proposed scenario framework demonstrates how strategic interventions, such as electrification and green hydrogen utilization, can be tailored to natural gas consumption profiles across EU member states, enabling a more targeted approach to prevent conflict-induced energy crises that lead to heightened consumer prices[60] and increased public expenditure to protect vulnerable populations from the resulting impact[61]. Achieving the REPowerEU 2030 policy targets[19, 20] is a critical step in this direction, supported by recent progress in expediting renewable energy permitting[62] and the establishment of industrial alliances[63]. In this context, the results from the FULL scenarios for solar and wind power expansion, aligned with these targets, indicate the potential to reduce gross inland natural gas consumption through electrification by up to 32.8% in 2030 and 50.9% by 2050. This reduction translates to sector-specific declines of 75.9%, 67.4%, and 68.6% in the electricity and heating, industrial, and road transportation sectors, respectively, by 2050. These insights suggest that renewable energy incentives should be designed as sector-informed mechanisms that account for differences in deployment needs, such as grid integration support[64] and dedicated schemes for clean industrial clusters[65], aligning with the EU strategy for energy

system integration which emphasizes greater electrification of end-use sectors[66]*. Similarly, green hydrogen can play a critical role in reducing natural gas reliance in hard-to-abate sectors such as heavy industries. Results from the FULL capacity expansion scenarios indicate that green hydrogen deployment can avoid up to 10.3% of gross inland natural gas consumption and yield cumulative emissions reductions exceeding 947.5 $MtCO_2$ by 2050. By evaluating this potential at a spatial and sectoral level, this analysis underscores the strategic relevance of EU hydrogen initiatives*[67] *which support the development of electrolyzer capacity, and distribution infrastructure and facilitate industrial uptake of green hydrogen across member states*[68]*. Moreover, given the differentiated and essential role of green hydrogen revealed through scenario-based analysis, sector-specific Contracts for Difference*[69, 70] *can serve as targeted policy instruments to ensure deployment certainty and alignment with energy security and decarbonization objectives.*

Over the years, technological advancements have improved the cost-effectiveness of renewable power generation[71, 72] *and green hydrogen production*[73, 74]*, which play a pivotal role in reducing fossil fuel use*[75, 76]*. The analysis demonstrates that under the FULL implementation scenario, targeted to reduce sectoral natural gas consumption across the EU, the annual total cost of electrification in 2050 can be reduced by up to 19.9% and 13.7% for solar and wind power installations, respectively, when comparing fast and slow cost-reduction trajectories. This finding underscores the importance of continued learning in lowering the total cost of transition. Furthermore, the LCOE shows a projected decline of up to 61.5% and 46.2%, and the LCOH by up to 60.2% and 41.3%, for solar and wind power respectively by 2050 across EU member states, with pronounced regional variation, highlighting that uniform incentive schemes may lead to misallocated support and reinforcing the need for regionally differentiated policy measures. Similarly, the annual total hydrogen production costs vary from $7.3 bn to $49.5 bn across the investigated scenarios in 2050, providing an indicative cost range that can inform strategic planning for industrial stakeholders in hard-to-abate sectors. As such, the economic implications of this transition offer scenario-based insights across stakeholder groups, enabling policymakers to align support instruments with sectoral and temporal differences in natural gas substitution potential across regions, while allowing industrial actors to evaluate the competitiveness of electrification and hydrogen deployment under varying cost trajectories. However, the realization of these cost benefits also hinges on policy measures that ensure infrastructure and supply chain* *readiness, such as mitigating potential bottlenecks in the availability of key solar and wind power components. Thus, further government incentives focusing on research and development*[77] *and advanced manufacturing and installation processes that reduce "soft costs"*[78] *may be necessary to ensure adequate supply and accelerate cost reductions in wind and solar power expansion.*

While natural gas is often viewed as a transition fuel used to maintain energy systems as renewables are brought online[79]*, recent geopolitical disruptions highlight the need for the EU to align its energy security priorities with long-term climate objectives. Robust climate policies, such as carbon credit systems, can help reduce the EU's reliance on natural gas while advancing toward aggressive climate goals*[80]*. Specifically, avoided emissions driven by sector-specific targeted strategies can serve as the basis for credit issuance, with implementation benchmarked against reduction thresholds set under the EU Emissions Trading System (ETS). In this regard, the analysis presented in* ***Fig. S22*** *illustrates how scenario-driven reductions in carbon emissions from electrification, hydrogen production, and carbon offsetting can be benchmarked against ETS-defined reduction targets, offering a foundation for the design and implementation of performance-based carbon credit systems. This impetus behind carbon credit mechanisms can be leveraged to help close climate finance gaps*[81]*, a role emphasized by decision-making bodies such as COP28, which frame it as a critical enabler of climate action*[82]*, particularly in supporting the affordability of clean energy transitions. Accordingly, in addition to bolstering decarbonization efforts, the proposed strategies align with equity objectives through the progressive reduction of exposure to volatile fossil fuel markets, which led to sharp increases in energy costs*[83, 84]*, especially for households*[1]*, during recent geopolitical disruptions. The implementation of emergency fiscal measures, such as energy price caps*[85] *and one-off subsidies*[86]*, underscores these energy cost pressures, further highlighting how the proposed strategies target a primary root cause, reducing natural gas consumption, instead of relying on reactive compensatory mechanisms to ensure affordable energy access.*

The EU's energy landscape faces a pivotal moment due to the evolving geopolitical events of recent years. While domestic natural gas production in the EU declined by 9% in the first nine months of 2022[87] *and by 18.6% in 2023 compared to the previous year*[88]*, a defining shift occurred with the sharp reduction in imports from Russia, falling from over 40% in 2021 to around 11% by 2024*[4]*, triggered by the geopolitical fallout of the conflict. This disruption prompted an urgent* *reassessment of energy security strategies across member states[89]. For instance, the EU diversified its energy imports, notably increasing natural gas supplies from the US by 138.6% over the same period[4]. However, this reconfiguration introduced new strategic complexities. Recent shifts in US foreign policy discourse signal a potential inclination to frame energy exports as essential geopolitical levers[90], such as in trade negotiations[91], thereby highlighting strategic considerations surrounding the long-term reliability of US energy supplies[92]. Moreover, the evolving geopolitical landscape reveals that international alliances are increasingly fluid[93], shaped by shifting strategic interests. In this context, the findings of this work underscore the need for a multi-layered strategy, combining domestic electrification and green hydrogen deployment in the investigated scenarios (**Figs. 1** and **3**) which can reduce up to 61.3% of gross inland consumption of natural gas by 2050, which can be further improved with coordinated intra-EU trade and selective international partnerships. While regional integration within the EU can unlock clean electricity and hydrogen trade opportunities by leveraging surplus capacities in specific member states (**Figs. S23** and **S24**), the extent of reliance on external suppliers must be approached pragmatically. In order to avoid substituting one dependency for another, residual sector-specific substitution needs (**Fig. S25**) should guide the design of essential future trade strategies to prevent a recurrence of past vulnerabilities. For example, in sectors such as electricity and heating, light industries, and segments of the road transportation sector, clean energy electrification through international corridors can play a significant role. In contrast, for hard-to-abate sectors like heavy industries, green hydrogen carriers represent more effective alternatives to reduce natural gas reliance.*

While previous studies have also explored alternate energy pathways for Europe, providing valuable insights through a focused examination of renewable investments[33], hydrogen infrastructure[34], or region-specific crisis response to recent geopolitical tensions[2], this work presents a comprehensive evaluation of strategic scenarios incorporating electrification, green hydrogen, and carbon offsetting strategies. For instance, Ruhnau et al.[2] highlight the maximum reductions in natural gas consumption during the 2022 energy crisis, estimating savings of 10.6 TWh in industry and 5.9 TWh in the power sector in Germany. These reductions reflect an immediate crisis response during specific months in 2022; however, this study's analysis of the FULL scenarios for solar and wind capacity expansions with green hydrogen deployment indicates that up to 31.0 TWh and 101.0 TWh of industrial natural gas consumption in Germany can be reduced by 2050, respectively. Similarly, reductions in the electricity and heating sector *can reach 220.8 TWh and 433.0 TWh under the same scenarios and time horizon, underscoring the strategic value of sustained and tailored renewable deployment strategies that account for region-specific sectoral demand profiles. Shirizadeh et al.*[94] *estimate that clean hydrogen (produced from low-carbon electricity via electrolysis or natural gas with abated* CO_2*) can potentially meet nearly a quarter of Europe's final energy demand by 2050. van der Zwaan et al.*[95] *indicate that hydrogen can constitute approximately 6% of final energy consumption in Europe by mid-century under a deep decarbonization scenario. While these studies offer pertinent estimates of hydrogen's role in final energy demand, this analysis illustrates the contribution of green hydrogen, produced solely from renewable electricity, to reducing gross inland natural gas consumption across the EU. Under the BAU, PARTIAL, and FULL scenarios for solar and wind power expansion, green hydrogen alone accounts for a 1.7% to 10.3% reduction in natural gas use by 2050, providing sector-specific insights for energy security planning. van Ouwerkerk et al.*[33] *evaluate the economic and environmental benefits of residential renewable investments for single-family homes in Germany, identifying solar PV systems as a no-regret strategy during and beyond the energy crisis. Complementing this perspective and reinforcing the strategic role of solar power installations, the policy-driven scenarios evaluated in this analysis, when combined with targeted interventions, can reduce gross inland natural gas consumption in Germany and the EU by 21.6% to 42.9% and 17.2% to 37.0%, respectively, by 2050, translating into climate benefits of 0.6* $GtCO_2$ *to 1.5* $GtCO_2$ *and 2.0* $GtCO_2$ *to 5.4* $GtCO_2$ *in emissions reductions. Moreover, the EU action plan to address the energy crisis also outlines the role of diversifying natural gas sources*[89]*. This pathway focuses on establishing agreements with alternative suppliers and infrastructure upgrades such as investment in terminals and gas interconnectors. These measures can alleviate energy security concerns, at least in the near term, by expanding supply routes; however, they do not inherently contribute to long-term climate mitigation. In contrast, the proposed strategies in this analysis center on reducing sector-specific natural gas consumption across the EU as a structural metric, thereby aligning energy security planning with the EU's climate objectives.*

This work investigates various scenarios for renewable capacity growth, incorporating the role of electrification potential, green hydrogen utilization, and carbon offsetting measures, thereby providing relevant insights for EU energy security and decarbonization goals. However, some limitations provide opportunities for future improvements. While the proposed framework *adopts a sectoral classification to evaluate natural gas displacement through renewable-driven strategies (**Fig. S62**), it can be strengthened by incorporating more granular representations that capture the evolution of emerging industrial pathways and the growing feasibility of electrification in heavy industries[96]. Additionally, the framework can benefit from accounting for extreme weather events and interannual variability, which may influence the long-term resilience of the energy system. Although this study does not utilize the value-adjusted LCOE (VALCOE) approach[97], the findings by the IEA indicate that the adjustments required to the LCOE in the case of solar PV and wind power with storage are relatively modest[98]. This finding suggests that the current methodology provides relevant insights into the affordability of the investigated energy pathways. Nevertheless, future work incorporating the VALCOE approach can further refine the analysis, especially as new technologies and market dynamics evolve."*

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Reviewer's Comment (7)

Regarding Methods

All methods are briefly described in the main text. Additional information is given in supplementary material. The chosen approach is well suitable for the problem addressed and commonly used in scientific and technical reports on energy transition. It could be beneficial to add additional figures in the main text on important issues like the overall modelling framework and the analysed scenarios. Also here: The choice of e.g. the optimisation framework should be explained in more detail. It should be explained why this approach instead of widely used modelling frameworks (e.g. PyPSA Europe) is taken. Also, novel aspects of the chosen approach should be highlighted.

Answer: Thanks for the comment. We agree with the reviewer's feedback to add a figure in the main file illustrating the overall modelling framework and analyzed scenarios, and to explain the use of this approach instead of previously used frameworks. In the revised Systems Analysis Framework section, we have added Fig. 5 as a schematic representation of the methodological framework used in the study and expanded the discussion to highlight its components and contributions relative to existing modeling approaches. Additionally, the revised Introduction section establishes the knowledge gap addressed in this work compared to existing assessments and outline the novel contributions through a set of bullet points.

Action

- *We have presented the revised text in the Introduction section and the Systems Analysis Framework section in response to Comment 1 from Reviewer 1. To reduce the length of this file, please refer to pages 1 to 9 for the complete revision.*

Aligning EU Energy Security and Climate Mitigation through Targeted Transition Strategies

Apoorv Lal, Massimo Tavoni, Nathan Preuss, Fengqi You

Response to reviewers and actions taken

Reviewer 2

The revised version addressed my comments adequately.

The paper now focuses more on its valuable contribution - a new model trying to explore and evaluate the feasibility of pathways to reducing natural gas imports through accelerated deployment of renewables and electrification (and the implications on DAC). The framing is also more believable. We assume that reduction in natural gas imports represents a policy objective of the EU (because of the recent shocks resulting from geopolitical evolutions) and we assume reductions in CO2 emissions are also desirable. As such, the relevance of the question and of the implications are guaranteed, so we proceed to demonstrating possible pathways using the data and the model.

I still have a few observations to make.

Reviewer's Comment (1) and (2)

At page 4: 'Previous studies also examine the European energy transition using modeling frameworks (...) without directly addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions'

This does not sound like a credible justification of the novelty. If this were true, you could simply use their results and argue they are relevant for the 'strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions'. In my view, the novelty of your work consists of the new model, new data that yield new results. The results are relevant because reducing imports and consumption of natural gas in the EU are an explicit policy goal due to the recent geopolitical experience and the imperative of mitigating climate change. This is already strong enough.

At page 5: 'seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation'

Again, that does not sound like what this paper is doing. Indeed, the results of your study can be relevant for this matter, but the matter itself is much more complex than that. It is absolutely fine for the paper not to go into all the complexities of the energy security - climate change nexus, so it does not have to make bold claims about it. For example, the issue of dependency on critical minerals, dominance of China in batteries and PV modules, and many other issues need to be addressed for an adequate treatment of energy security - climate mitigation.

Answer: Thanks for the comment. In the revised manuscript, the literature review in the Introduction section has been refined to remove the justification around previous studies "not addressing the strategic urgency of EU-wide natural gas dependence amidst geopolitical disruptions." Instead, following the reviewer's feedback, the novelty is now presented in terms of a new scenario-based analytical framework that supports the assessment of natural gas reduction strategies across the EU, an explicit policy goal reinforced by recent geopolitical developments and the broader imperative of mitigating climate change. We have also removed the phrasing "seeks to offer comprehensive insights by aligning energy security with the long-term imperative of climate change mitigation" to avoid overclaiming in the presentation of the study's contributions.

Action

- *On pages 3-4 of the revised main file:*

"Previous studies also examine the European energy transition using modeling frameworks based on least-cost optimization to determine energy system configurations[25, 26, 27], or offer insights at the transmission network level[28]. These analyses outline the diversity of feasible system designs[29], foster communication across societal levels[30], generate high-level insights for multi-sector system integration[31], and investigate grid constraints[32]. Some assessments also focus on individual energy pathways[33, 34] or region-specific crisis responses[2]. Within this broader transition landscape, sectors that are difficult to electrify, such as heavy industries, require complementary technological pathways. Green hydrogen emerges as a promising vector for advancing energy transition and climate mitigation goals[35, 36], supported by the expansion of renewable capacity and offering a critical alternative to natural gas in heavy industries[37, 38, 39]. Recent literature highlights the importance of competitive and secure renewable hydrogen to minimize reliance on single suppliers[40]. Regional assessments further underscore the role of hydrogen infrastructure during the energy crisis[41], the feasibility of substituting carbon-intensive hydrogen production with

renewable-based electrolysis[42], and the potential of hydrogen and power-to-liquid pathways to reduce energy-related import costs[43]. Additionally, studies emphasize the role of hydrogen in decarbonizing the European energy system, with projections of substantial hydrogen production by 2050[44, 45]. However, these opportunities require careful policy choices to avoid perpetuating long-standing vulnerabilities[46].

While previous studies provide valuable perspectives, also summarized in Supplementary Table 1 for comparative reference, this work advances the existing literature by developing a scenario-based assessment centered on renewable expansion pathways and incorporating targeted strategies, including electrification, green hydrogen deployment, and carbon offsetting, to evaluate pathways for reducing natural gas dependence and associated emissions across the EU, an explicit policy goal reinforced by recent geopolitical developments and the imperative of mitigating climate change. The analysis introduces a sector-disaggregated framework that captures the differentiated impacts of transition strategies across electricity and heating, light and heavy industries, and transportation, spanning spatial and temporal dimensions within the EU. Furthermore, the study establishes an analytical foundation for assessing the economic feasibility of these targeted interventions through a comprehensive spectrum of technology cost trajectories informed by historical learning rates under varying renewable expansion scenarios."

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Reviewer's Comment (3)

At page 26:

- The discussion of carbon credits is a bit superficial. It is not clear what type of credits they are, who would be the buyers, it makes it seem like this has no cost implications for anyone, which is obviously impossible. This should either be elaborated or eliminated.

- The implied message that fossil fuel consumption is the primary root cause of expensive energy and that reducing fossil fuel consumption ensures affordable energy access is weak. This depends on many other factors including the actual price of fossil fuel (which may become lower as demand is reduced), the cost of capital (highly relevant for renewables), the market for clean technologies, the cost of transmission and distribution, etc. The hyper-simplified message is more fitting for a political statement than a research article. I suggest qualifying it or eliminating it.

The required changes are just nuances, but relevant nuances for the overall quality and robustness of this valuable piece.

Answer: Thanks for the comment. Following the reviewer's feedback, we have eliminated the discussion of carbon credits and the associated framing of fossil fuel consumption as the primary root cause from the revised manuscript. We have also briefly noted in the Discussion section that the evaluation of carbon credit mechanisms lies beyond the scope of this study, which focuses on scenario-based assessments of renewable expansion pathways and targeted strategies for reducing natural gas dependence and associated emissions.

Action

- *On page 22 of the revised main file:*

"Furthermore, carbon credit mechanisms were not included in the analysis, as their evaluation lies beyond the scope of this study, which centers on a scenario-based assessment of renewable expansion pathways and targeted strategies for reducing natural gas dependence and associated emissions."

Reviewer 4

Dear Authors,

thank you for your revised manuscript and the detailed responses. In my opinion, the revised literature review is well done. It sets the frame for the submitted manuscript. However, it also shows that many exisiting reports deal with similar topics and thus the novelty is not very high but still ok.

Reviewer's Comment (1)

With regard to the economic parameters - such as used for calculating LCOE - the response and the revised SI file clarify some assumptions. However, there are several further uncertainties that are not reflected and the presentation of results could have been done with regard to uncertainties, i.e. representing ranges instead of absolut values.

Answer: Thanks for the comment. We agree with the reviewer's concern to represent the range of LCOE instead of absolute values. The authors are also grateful for the references suggested by the reviewer in the earlier feedback (IRENA, 2024; Fraunhofer ISE, 2024; Breyer et al., 2023; Statista, 2020), which helped us identify the key sources of variation, including the applied interest rate, technology cost trajectories, storage assumptions, and resource heterogeneity. Accordingly, in the revised manuscript we incorporated these factors to construct LCOE ranges based on the cost development trajectories for solar and wind technologies (represented here as slow, nominal, and fast pathways), variation in solar irradiation and wind power output at NUTS2-level within EU countries to capture resource heterogeneity, interest rates, and the inclusion or exclusion of battery storage. The resulting ranges represent the envelope of outcomes derived from these combined parameter variations. By combining these dimensions, we present LCOE results as a range of values for both 2024 and 2050, as shown in the revised Figure 2.

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Action

- *On page 10 of the revised main file:*

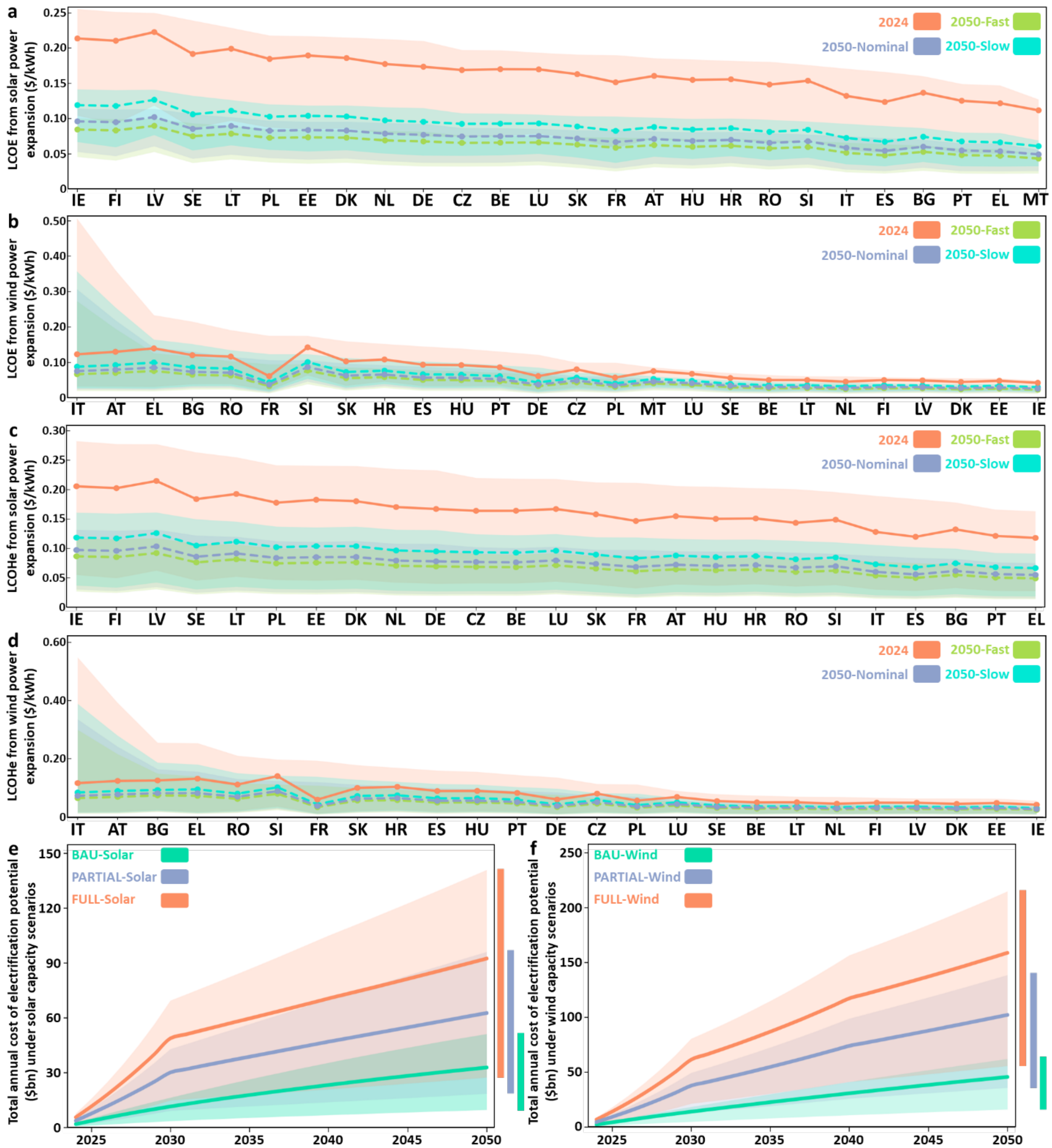

Fig 2. a-d., *Range of levelized cost of electricity (LCOE, $/kWh) and levelized cost of heat (LCOHe, $/kWh) from solar and wind power expansion in 2024 and under slow, nominal, and fast cost-reduction trajectories by 2050.* ***e-f.,*** *Total annual cost of electrification potential ($bn) under renewable-capacity scenarios (BAU-solar, BAU-wind, PARTIAL-solar, PARTIAL-wind, FULL-solar, and FULL-wind) through 2050. The shaded ranges in panels a-f represent the envelope of outcomes derived from variations in interest rate, battery-storage inclusion,*

NUTS2-level solar irradiation and wind power output profiles across EU countries, and technology cost trajectories. 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).