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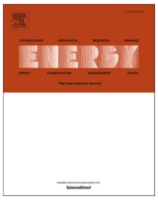

Three different directions in which the European Union could replace Russian natural gas

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ABSTRACT

Russia's invasion of Ukraine fuelled an energy crisis, which considerably impacted Europe given its heavy reliance on Russian natural gas imports. This study uses an ensemble of four global integrated assessment models, which are further soft-linked to two sectoral models, and explores the synergies and trade-offs among three approaches to living without Russian gas in Europe: (a) replacing with other gas imports, (b) boosting domestic energy production, and (c) reducing demand and accelerating energy efficiency. We find that substituting Russian gas from other trade partners would miss an opportunity to accelerate decarbonisation in end-use sectors while risking further fossil-fuel lock-ins, despite featuring the lowest gas price spikes and potentially reducing heating costs for end-users in the near term. Boosting domestic, primarily renewable, energy production on the other hand would instead require considerable investments, potentially burdening consumers. Energy demand reductions, however, could offer considerable space for further emissions cuts at the lowest power-sector investment costs; nonetheless, an energy efficiency-driven strategy would also risk relocation of energy-intensive industries, an aspect of increasing relevance to EU policymakers.

1. Introduction

Russia's war against Ukraine has exacerbated an ongoing energy and resource crisis [1], disproportionately affecting the European Union [2] (EU) and highlighting its considerable dependence on Russian natural gas. This has put energy sustainability and affordability at risk and reduced Europe's geopolitical room for manoeuvre [3,4]. Unless sufficiently resolved, these overlapping challenges [5] could eventually impact global financial markets [6] as well as possibly delay or reverse progress to climate goals [7], sustainable development [8], and future resilience [9]. On the climate front, despite the ever-closing window of delivering on the Paris Agreement temperature goals [10,11] and clear

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signs of insufficient acceleration of global mitigation efforts [12–14], the 27th UNFCCC Conference of Parties (COP27) was marked by lack of ambition to phase out fossil fuels; this was largely a continuation of the climate negotiation status-quo but also owing to the ongoing energy crisis [15].

In response, the EU released its REPowerEU strategy shortly after the invasion, aiming to rapidly attenuate its ties to Russian fossil fuels and become fully energy-independent from Russia by 2027 [16], along with a mandate on gas storage obligations [17] and efforts to accelerate the uptake of renewable energy and energy efficiency. Many EU countries also prioritised decoupling their economies from Russian fossil fuels at the national level, adopting a range of energy [18] and fiscal [19] measures towards mitigating the impact of higher costs on consumers and businesses, stabilising wholesale prices, and securing their energy supply. Although the coordinated European response entails measures to reduce energy vulnerability [20], entirely replacing Russian gas imports will be challenging in the near-term [21,22], with non-pipeline Russian gas still finding its way to Europe [23,24]. Ongoing and planned liquefied natural gas (LNG) infrastructures are projected to increase today's EU terminal capacity by 48 % until 2030, with risks of possibly becoming stranded assets due to a mismatch with reductions in gas demand to meet climate objectives [25]. Meanwhile, Russia has continued to further reduce its gas supplies to the EU, essentially escalating its strategy of "weaponising" energy [26].

Pre-war Russian pipeline exports to the EU were 1463 TWh in 2021, i.e., 41 % of the bloc's total gas consumption (3630 TWh). At the beginning of 2023, Russia still exported some 5 TWh per week via Turkstream and Ukraine (15 % of pre-war volumes) as well as some 3.5 TWh as LNG—which would over the year sum up to around 440 TWh. Assuming that the EU eventually loses the entire amount of about 1500 TWh of annual imports [22] relative to pre-war levels and that this reduction is permanent, the Union must seek ways in which it can optimally replace this loss. However, the impacts of gas market disruptions on the European energy system and overall economy and, in turn, the effects of EU responses on its transition pathway and 2030 climate targets remain uncertain [27–29].

A growing number of studies have set out to analyse the impacts and trade-offs of a temporary [30,31] and/or prolonged [21,32,33] Russian gas cut-off, with some discussing the evolution of the European gas market [20] and electricity system [34], assessing supply and demand policy options to mitigate adverse effects [18,35], or shedding light on potential spillover effects to biodiversity [35], climate risks [36], and stranded assets [37]. Owing to significant uncertainties as well as related resource requirements, modelling research has been sparing in assessing the implications of the Russia-Ukraine conflict and the impacts of a fast Russian gas phaseout in the EU [38]. Among the few studies available to date, all have been single-model efforts, while most have focussed on offering a very short-term outlook with limited possibilities of adjusting investment, production, and consumption patterns [32,34,39]. Few studies investigated longer-term impacts of a modelled European response to the conflict-fuelled energy crisis, including on emissions, by assuming different levels of and parties involved in an embargo [40–42], while aiming for the cost-optimal course of action. Building on but straying from these efforts, our research contributes to both literature and the heated policy discourse, by exploring *explicit directions* of how Russian gas could be phased out in the bloc as well as their implications *benchmarked against actual climate targets for 2030 and 2050*, enabling to identify insights into the trade-offs and synergies between the different considered approaches to replacing Russian gas. We also employ a *diverse ensemble of models* of different structure and theory, thereby enhancing the robustness of resulting policy prescriptions [43] and our understanding of the future uncertainty space [44] based on four established Integrated Assessment Models (IAMs), as well as allowing to extract finer sectoral insights via interlinkages with two sectoral modelling tools.

2. Methods

In this study we use an ensemble of four established integrated assessment models (IAMs), a bottom-up technology-rich electricity system optimisation model, and an Input-Output model to explore the energy-system implications—including macroeconomic impacts in the energy sector—of a complete and rapid phaseout of Russian gas imports in the EU by the end of 2023. Drawing from the directions explicitly discussed in the REPowerEU policy document [16], we consider three 'corner' options for replacing Russian natural gas, representing entirely different directions and reflecting the core options embedded in the policy debate: (a) increasing natural gas imports from other regions to make up for the lost Russian supply ('*Gas Imports*'), (b) boosting energy production within the EU to make up for the lost gas imports ('*Domestic Production*'), and (c) accelerating the deployment of energy efficiency measures across sectors to reduce energy consumption accordingly ('*Energy Efficiency*')—see **Section 2.2**. The idea behind selecting these 'corner' scenarios lies in the motivation to explore the trade-offs between these completely different strategies rather than prescribing specific policy portfolios; in essence, while either route would only cover part of the spectrum of policy choices to respond to the gas crisis, the selected approach reflects the boundaries of this spectrum rather than concrete instances within it, offering policy-friendly insights into what is lost and/or gained by following one strategy against another. Our modelling approach represents each 'corner' strategy as an individual scenario, benchmarked against a baseline that reflects mitigation efforts implied by Nationally Determined Contributions (NDC) for 2030 and long-term net-zero pledges for 2050 but disregards the energy-supply crisis ('*Baseline*'). Although our aim is not to calculate a cost-optimal course of action but rather to understand what each of these three markedly different directions could imply for the European energy system, we additionally calculate a *'Model-optimal'* scenario that does not prescribe a directed response but allows models to calculate their cost-optimal pathways to the EU's 2030 and 2050 climate targets without Russian gas imports.

2.1. Model ensemble

Four global integrated assessment models are inter-compared in this research: GCAM, TIAM, MUSE, and PROMETHEUS. These are selected to reflect the broad diversity of modelling theories, spanning a range from least-cost energy system optimisation to partial equilibrium and to agent-based modelling. Diversity of modelling structure, theory, and solution is typically sought in multi-model studies, allowing to reflect the broad range of structural uncertainties.

GCAM [45] (Global Change Analysis Model) is a partial equilibrium technology-rich IAM, achieving equilibrium between energy supply and demand in each represented sector, accounting for the changes in energy prices resulting from changes in fuels and technologies used to satisfy energy-service demands in these sectors. The model operates on a recursive dynamic ('myopic'—i.e., each time step is solved without full knowledge of what comes after), cost-minimisation (i.e., 'optimisation' rather than 'simulation') basis and solves for the least-cost energy system (constrained by observed technological preferences) in a given period before moving onto the next period and performing the same process. GCAM features trade for natural gas in each region using an Armington approach, with regions allowed to choose between domestically produced or globally traded gas when making a consumption decision [46]. For the purposes of this study, we use a version of GCAM explicitly that distinguishes between pipeline gas and LNG trade, with the latter represented following the Heckscher-Ohlin approach, as separate trade pathways [47]. In particular, LNG is traded in a single, global market, while pipeline gas is traded in six regional pipeline networks (Europe, Russia+, Africa and Middle East, Asia-Pacific, North America, and Latin America). The pipeline networks that a given GCAM region may import from are dependent on historical country-level bilateral trade flows. It should be noted that this version of GCAM disaggregates EU regions as follows:

- EU_Central (Austria, Czech Republic, Hungary, Slovakia, Slovenia, Croatia, Poland)
- EU_Southwest (Italy, Malta, Portugal, Spain, Andorra, Gibraltar, San Marino, Vatican)
- EU_Southeast (Romania, Bulgaria, Cyprus, Greece)
- EU_Northwest (Belgium, Germany, France, Monaco, Netherlands, Luxembourg, Denmark)
- EU_Northeast (Finland, Sweden, Estonia, Latvia, Lithuania)
- EU_UK+ (United Kingdom, Ireland, Channel Island, Faroe Island, Guernsey, Greenland, Jersey, Saint Helena)

TIAM [48] (Times Integrated Assessment Model) is also a partial equilibrium IAM and achieves similar equilibrium between energy supply and demand in each sector. However, TIAM operates on an intertemporal (‘perfect foresight’—i.e., the model’s agent knows with full certainty what is available and required in the future), welfare cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction, and energy price changes over the entire time horizon are considered when minimising the cost of the energy system to provide energy-service demands within specified emissions constraints.

MUSE [49] (ModUlar energy systems Simulation Environment) is an agent-based system model providing a detailed account of the energy sector to calculate least-cost GHG emissions reduction pathways—or the costs of alternative climate policies. It is bottom-up, in that it assumes short-term microeconomic equilibrium on the energy system by iterating market clearance across all sector modules and interchanging price and quantity of each energy commodity within each region, but it is also agent-based, in that it tries to determine a mitigation pathway by providing an as-realistic-as-possible description of the investment and operational decision-making in each geographical region within a sector.

PROMETHEUS [50] is a global energy system model covering in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level, allowing to assess mitigation pathways and low-emissions development strategies, analyse the energy system, economic, and emissions implications of a wide spectrum of policy instrument differentiated by region and sector, and explore the economics of fossil-fuel production to quantify the impacts of climate policies on the evolution of global energy prices. It notably features world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements. Much like GCAM and MUSE, it operates ’myopically’, meaning each time step is solved without full knowledge of the future.

All four IAMs differ in the way technologies are chosen across sectors: GCAM and PROMETHEUS employ a logit technology choice mechanism (i.e., gradually decreasing returns as a technology is further diffused); TIAM uses a winner-takes-all optimisation mechanism (i.e., the cheapest technology can dominate all new deployment until maximum potential capacity expansion is reached); and MUSE follows an agent-based approach (i.e., agent decision goals and strategies determine technology choices in each time step).

Furthermore, these global IAMs are then interlinked with two sectoral models, to provide additional insights with regard to electricity (EXPANSE) and employment (MARIO) impacts of the modelled pathways per model and scenario.

EXPANSE [51] is a spatially explicit, bottom-up, technology-rich, single-year optimisation model of the European electricity system that covers 33 countries (EU minus Cyprus and Malta, and plus Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, and the UK). The model accounts for operation and capacity planning of electricity generation, storage, and transmission until 2035. The model represents electricity generation at the level of 296 NUTS-2 regions and electricity demand, storage, and transmission at the level of 128 transmission grid nodes, ensuring that electricity generation, storage, and transmission balance inelastic electricity demand at each transmission grid node and time step.

MARIO [52] (Multi-functional Analysis of Regions through Input-Output) is an open suite for input-output analysis based on the DynERIO [53] (Dynamic Extraction and Recycling Input-Output) framework, a comparative-static simulation model able to assess the impacts of implemented macroscopic trends and scenarios from an economic and environmental perspective—here with respect employment implications of the IAM-modelled pathways. With respect to typical input-output models, DynERIO allows to quantitatively assess the extraction of raw materials for selected technologies driven by regional production of commodities provided by the Leontief Production Model.

Gas prices, electricity demand, power-sector CO$_2$ emissions, and gas availability from the four IAMs are then used as inputs into EXPANSE, which also uses GDP growth as a proxy of households’ consumption growth, regionally adjusted according to population growth projections.

MARIO, on the other hand, requires gas import patterns that are implemented into the Exiobase database as an economic perturbation, electricity production mixes that are used to model the gradual regional shifts from fossil to renewable power generation, and industrial electrification rates (fraction of electricity over total energy consumed).

Table 1 summarises key features of all six models, including references to detailed online documentation in the I^{2}AM PARIS platform, while Fig. 1 illustrates the information flow among the six models.

2.2. Scenario design

We consider three strategies (scenarios) prescribing different ‘corner’ options for replacing the lost Russian gas. As the goal is to understand the implications of these three strategies in Europe (EU27 + UK), not only from an energy security and socioeconomic perspective in

Table 1
Key characteristics of all six models, including references to detailed online documentation.

Model Name	Model Type	Solution Horizon	Tech choice	Detailed documentation in I^{2}AM PARIS
GCAM	Partial equilibrium	Recursive dynamic (myopic)	Logit choice	https://www.i2am-paris.eu/detailed_model_doc/gcamv2022
PROMETHEUS	Partial equilibrium	Recursive dynamic (myopic)	Logit choice	https://www.i2am-paris.eu/detailed_model_doc/prometheus
TIAM	Partial equilibrium	Intertemporal optimisation (perfect foresight)	Winner takes all	https://www.i2am-paris.eu/detailed_model_doc/tiam
MUSE	Partial equilibrium – Agent based	Recursive dynamic (myopic)	Agent decision goals and strategies	https://www.i2am-paris.eu/detailed_model_doc/muse
EXPANSE	Electricity system	Intertemporal optimisation (perfect foresight)	Winner takes all	https://www.i2am-paris.eu/detailed_model_doc/expanse
MARIO	Input – Output	Comparative-static simulation	Input from IAMs	https://www.i2am-paris.eu/detailed_model_doc/dynerio

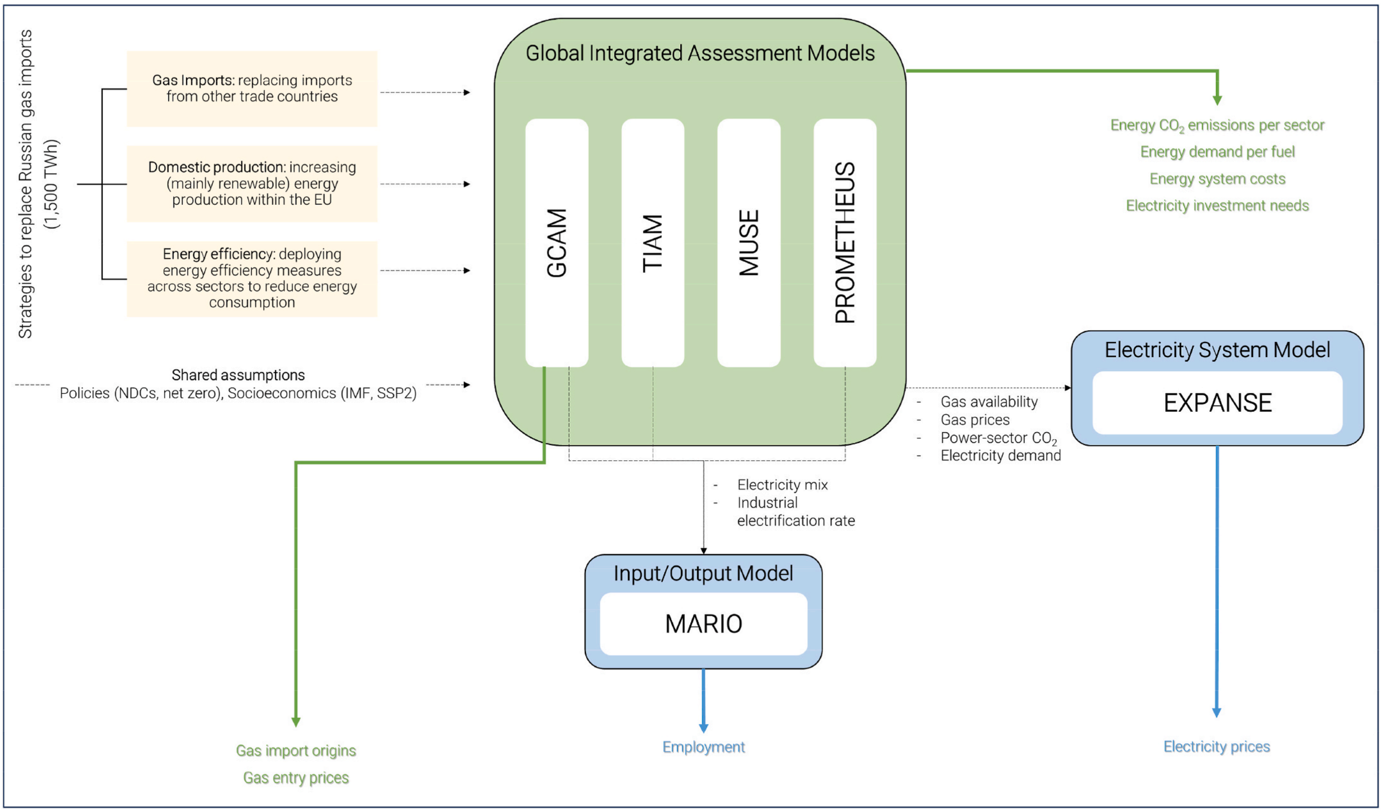

Fig. 1. Methodological framework and information flow, including scenario design, model ensemble, and inputs and outputs of each model.

the near term, but also from a climate policy perspective in the longer term, we use 2050 as our time horizon, with the aim to comprehend any impacts on the EU's path to net zero.

The *Baseline* scenario, against which all other scenarios are benchmarked, reflects mitigation efforts implied by NDCs and long-term strategies on top of current policies. It is assumed to describe the climate policy context before Russia's invasion of Ukraine: we draw from the current climate targets and NDCs of all regions until 2030, and LTSs post-2030 and until 2050 (see Ref. [11] for more details). All pledges announced until COP26 in Glasgow are considered, including the revised NDC target of the EU, for which the *Baseline* scenario assumes that the bloc achieves its NDC target of at least 55 % GHG emission reductions in 2030, relative to 1990 levels, as well as climate neutrality by 2050. Socioeconomic assumptions are drawn from the EUROPOP2019 database [54] and latest short-term socioeconomic outlook of the IMF WEO of October 2022 [55] until 2027 (extrapolated to 2050 according to the commonly used SSP2 socioeconomic pathway reflecting historic trends, see Ref. [56]) to account for the recent implications of the COVID-19 shock and recovery as well as the onset of the energy crisis—i.e., without describing Russia's invasion of Ukraine and associated policy responses. Furthermore, regarding technoeconomic assumptions, the harmonisation protocol described in Giarola et al. [57] was updated (e.g., to reflect observed 2020 values for electricity generation costs) and implemented. All scenarios prescribing ways to replace the lost Russian gas are benchmarked on top of this *Baseline* scenario.

The *Model-optimal* scenario allows the four IAMs to identify their own cost-optimal way[1] of replacing these gas imports while still meeting the EU's climate targets for 2030 and 2050. To implement this scenario, Russian pipeline gas into Europe is completely switched off in 2023, but current policies, NDC targets for 2030, and net-zero targets for 2050 are retained.

The *Gas Imports* scenario assumes that the EU replaces Russian gas imports with energy—and primarily gas (both pipelines and LNG)—imports from other trading partners. This scenario explores the expectedly increasing pressure emerging in LNG and pipeline gas markets, to cover for the loss of Russian gas. Policy decisions to encourage this strategy include gas infrastructure developments and gas supply deals. It is noteworthy that many European countries have taken both approaches since the beginning of the energy crisis.

The *Domestic Production* scenario assumes that the EU replaces Russian gas imports with increased domestic energy production—notably via accelerated electrification, increased gas/hydrogen production, new infrastructure in domestic renewable/nuclear power options, etc.—without increasing imports from non-EU regions. Energy trade from other regions is assumed identical to *Baseline*. The EU could encourage this approach by providing additional funding for clean electricity and electrification of heat, transport, and industry, or through establishing higher and legally binding renewable energy targets—the European Parliament, European Commission and European member states

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[1] In MUSE, an agent-based simulation model, cost-optimality applies to each single agent (investor-consumer) operating in each sector. In fact, each agent chooses an investment minimising its own costs, leading to a solution that may diverge from the typical comprehensive perspective of a "social planner". Therefore, differently from the other three IAMs, the optimisation approach in MUSE offers the diverging, yet additional, 'narrower' focus of a limited, sequential perspective.

reached a political agreement on 30 March 2023 on a target of 42.5 % of the share of renewable energy in the EU's overall energy consumption by 2030.

The *Energy Efficiency* scenario assumes that the EU replaces Russian gas imports, essentially reducing gas demand with enhanced energy efficiency—including renovation, relocation of emissions-intensive trade-exposed (EITE) industries outside the EU, demand-side response, and behavioural changes. Stronger energy efficiency targets, improved building standards, and funding for retrofitting could spur energy efficiency improvements, for example.

A detailed account of policy representation in the *Baseline* scenario is available in van de Ven et al. [11], which is closely followed in this study. For the detailed protocol and assumptions underlying all other scenarios introduced and implemented across the four IAMs in our study, see Table S1 in Supplementary Material.

3. Results

This section presents and discusses the resulting changes in energy supply and demand, including critical trade-offs, energy system costs, and diversification of import sources, documented in the modelling suite upon running each of the scenarios described in Section 2.

3.1. Clear trade-offs between supply- and demand-side energy CO_2 emissions

Overall EU fossil energy CO_2 emissions do not vary across scenarios (1.4–2.3 $GtCO_2$ in 2030 and -0.4 to −0.03 $GtCO_2$ in 2050—i.e., an average decline of 8 % per year over 2020–2050), since aggregated emissions in the EU are largely driven by the 2030 (−55 %) and 2050 (net zero) targets rather than impacted by any response to the energy crisis. There are, however, observed differences in emissions in different sectors, most notably between residential/commercial and industry sectors, depending on how Russian gas is substituted in each strategy (Fig. 2a).

Results show greatest emissions cuts in the *Energy Efficiency* scenario on top of the *Baseline* in all energy end-use sectors, due to reduced overall energy use with energy savings and efficiency measures deployed sooner and deeper, alongside relocation of EITE industries outside the bloc. Moderate emissions cuts are also observed in the *Domestic Production* scenario, where GCAM and PROMETHEUS agree that these cuts mainly happen in the residential and commercial sectors, critically as in this scenario gas is being displaced by electricity (which can be easier produced within the EU). The building sector is the most sensitive to such a switch, as enhanced competitiveness of heat pumps notably enables their increased uptake. In contrast, the *Gas Imports* strategy would achieve negligible emissions deviations from the *Baseline*—from very low emissions cuts to increases even, across model range—as Russian gas would be substituted by other forms and sources of imported pipeline or liquefied gas, at best slightly changing demand levels caused by higher gas import costs. In this case, a small uptick in industrial emissions can be expected as coal and/or oil would replace part of the more expensive gas; instead, residential and commercial emissions would slightly drop.

Overall, across most IAMs and strategies, there is consensus that supply-side energy-related CO_2 emissions would increase within any response to the energy supply crisis, as the EU quickly stood poised to enable all readily available fossil-fuel levers (e.g., decommissioned coal plants) to make up for the critical amounts of gas that was until recently imported from Russia. That contrasts with projected CO_2 emissions reductions in the end-use sectors, where residential and commercial emissions would drop due to the gas-to-electrification shift, especially since coal and oil use in the EU are in long-term decline in these sectors and there exist limited prospects for EU consumers to return to coal and oil use in buildings. This observed trade-off between demand- and supply-side CO_2 emissions when substituting Russian gas, to be in line with the 2030 and 2050 targets, hints at the need to reconsider the EU's sectoral pathways to carbon neutrality in the light of the Russia-Ukraine conflict.

Model variance points to the diverse representation of certain technologies in each model. Technology-richer models cover a wider set of energy efficiency measures and technologies, thereby better exploring the potential of energy efficiency in the building and industrial sectors; notably, in PROMETHEUS, emissions cuts are projected to continue until 2050 since technology push is assumed to continue post-2030, reducing total gas consumption and the need for gas imports in the EU.

3.2. Consistently decreased energy demand in any response to the Russian gas import ban

Energy demand reduction requirements are primarily subject to the 2018 recast of the Energy Efficiency Directive, which entails a target of 846 Mtoe of final energy demand across the EU-27 by 2030 [58]. Critically, though, demand reduction played a critical role as a first-level response to the energy crisis [38]: the European Council introduced a voluntary 15 % gas demand reduction target (compared to the average of the previous five years) in August 2022, which was extended in March 2023 to last for an additional year [59]. An emergency regulation was also introduced in October 2022 that inter alia set electricity demand reduction targets between December 2022 and March 2023 [60].

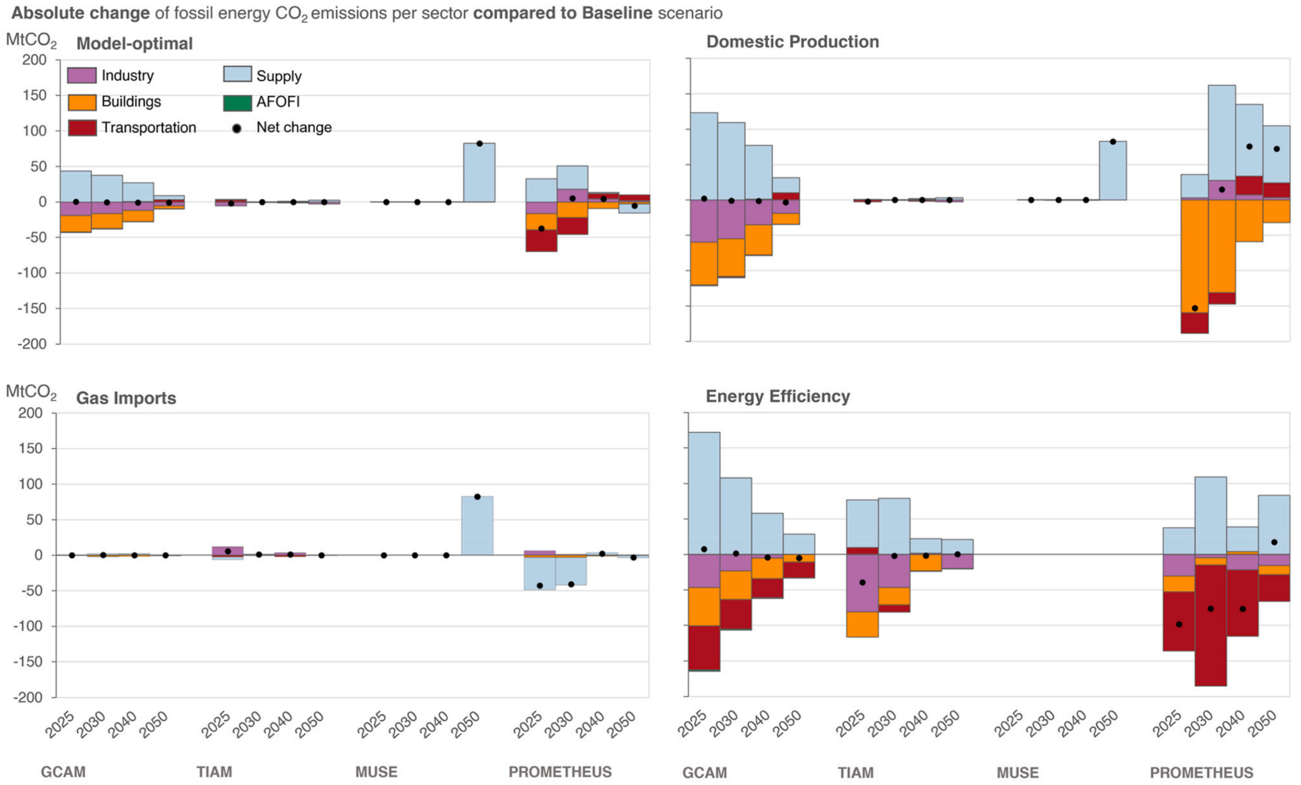
In our study, the calculated 2025–2050 final energy evolution varies, but we mostly project a decrease in final energy demand compared to the *Baseline* scenario (Fig. 2b). The highest demand reductions are observed in the *Energy Efficiency* scenario, ranging in 2030 from −11 % to −4% and in 2050 from −5% to −2% compared to the *Baseline*, mainly driven by reductions of demand for electricity, gases, and liquids.

To a lesser extent, this is also the case for the *Domestic Production* scenario, where reductions range from −5% to −1% in 2030, and from −2% to −1% in 2050, compared to the *Baseline* scenario. Finally, the *Gas Imports* scenario overall displays only a minor effect in end-use demand, as Russian gas is almost entirely substituted by liquefied and pipeline gas from trade partners outside Russia; nonetheless, even in this case, the PROMETHEUS model—which is richer in terms of efficiency technology representation—foresees demand cuts due to slight increases in gas import costs, implying there exists high potential for demand-side reductions as well as potential benefits through learning-by-doing and learning-by-research, which is endogenously available only in this model among the ensemble.

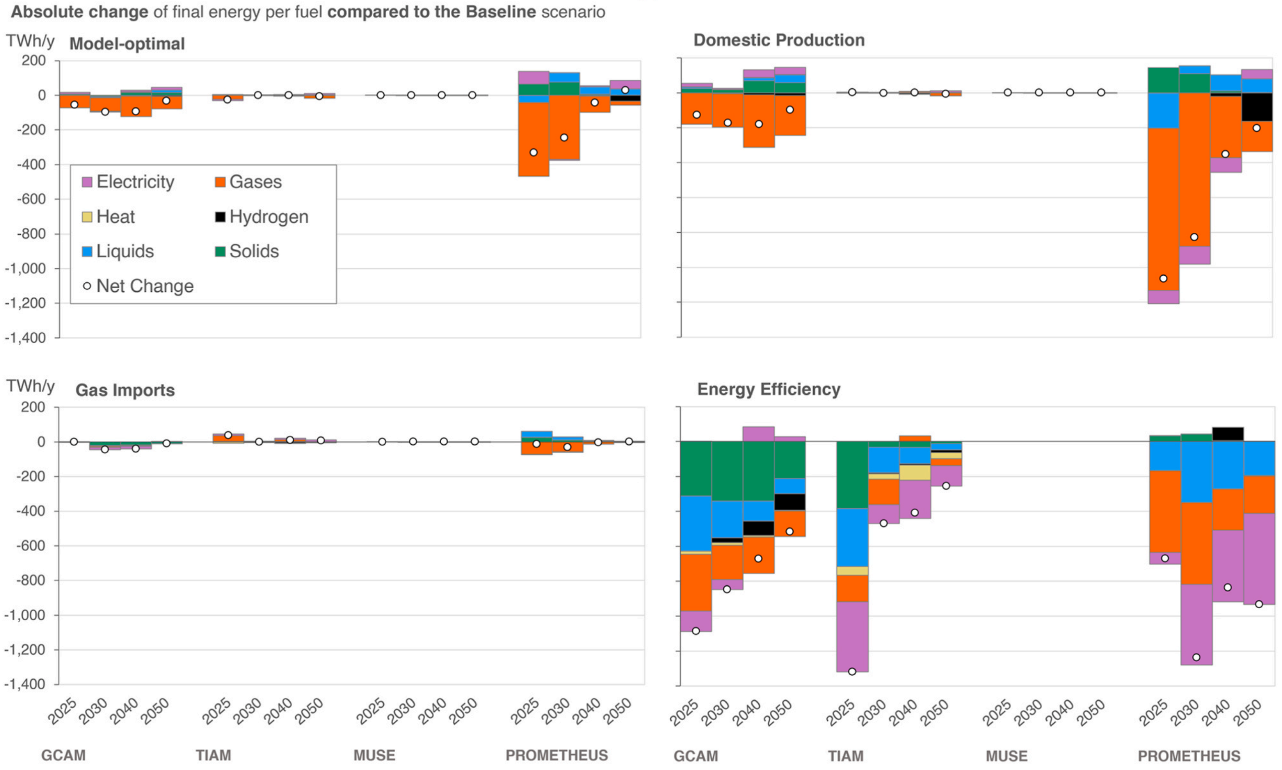
3.3. Higher energy-system costs, unevenly distributed electricity price changes across the EU, but positive implications for electricity-sector employment

When it comes to energy-system costs, which can only be directly extracted from two models in the ensemble, expectedly the *Model-optimal* pathway is cheaper than all other 'corner' options, as it is by definition calculated to minimise system costs (Fig. 3a). We also see that the costs of the *Domestic Production* pathway are consistently moderate; in TIAM costs are higher in the *Energy Efficiency* scenario in the short term but become the lowest in the long run, while in PROMETHEUS costs are consistently higher in the *Gas Imports* scenario due to higher cost of imported fuels from regions outside Russia. This traces to model dynamics and the role that the two models envisage for natural gas in their *Baseline* scenarios: in TIAM, gas would more radically phase out post-2030, meaning there is considerable need to invest in energy efficient technologies to offset the loss of Russian gas imports until then. Nonetheless, both IAMs agree that the *Energy Efficiency* strategy eventually becomes the cheapest among the three 'corner' options after 2030 (i.e., excluding *Baseline*), while also pushing carbon prices lower in both models.

As industry, transport, and heating are increasingly electrified, the electricity system will become the backbone of Europe's decarbonised



(a)



(b)

Fig. 2. Absolute changes across the four IAMs and across scenarios compared to *Baseline* (2025–2050), in terms of (a) fossil energy CO_2 emissions, and (b) final energy per fuel. AFOFI includes emissions from fossil fuel combustion in the agriculture, fisheries, and forestry sectors. MUSE cannot implement the 'Energy Efficiency' scenario protocol, as final energy consumption cannot be constrained in the model.

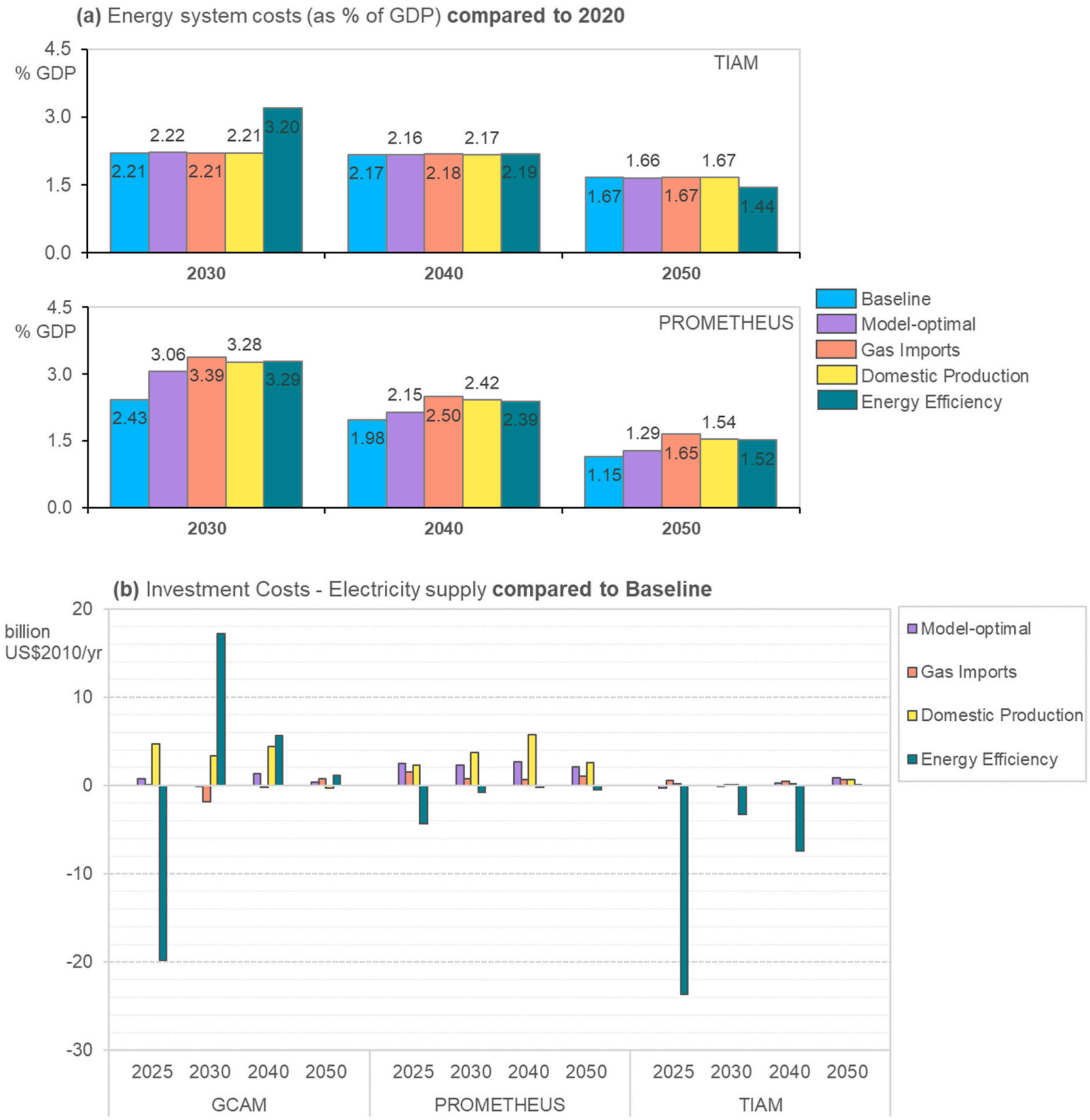


Fig. 3. Energy system and electricity investment costs. (a) Energy system costs (as % of EU GDP), as a % change compared to 2020 in TIAM and PROMETHEUS (data not available for GCAM and MUSE). (b) EU electricity supply annual investment costs (in billion US$/2010) compared to *Baseline* (2025–2050) in GCAM, PROMETHEUS, and TIAM (data not available from MUSE).

energy system. The electricity-sector investments necessary (Fig. 3b) to simultaneously decarbonise and meet increasing electricity demand are thus considerable, while renewable energy capacity and the associated clean technology infrastructure needed to complement it must be deployed at significant scale. Our analysis consistently points to high annual investment costs for electricity supply in the *Domestic Production* case, due to the investments required for ramping up domestic energy supply to make up for lost Russian pipeline gas (e.g., renewable electricity used for heat pumps and electric vehicles accompanied by storage)—although this effect is less pronounced in TIAM. It also points to lower electricity supply investments in the *Energy Efficiency* strategy, due to overall decreased demands, although one model (GCAM) projects a trend reversal towards the end of this decade, owing to increased electrification to satisfy end-use demands with reduced energy quantity; in particular, GCAM reduces electricity supply in 2025 because the large final energy demand constraint-related “shock” causes a strong decline in final demand for energy services (similar to TIAM’s response) that also comes down to less electricity use but, in subsequent periods, the persistent constraint to final energy supply stimulates electrification of final demand sectors, increasing electricity demand to above baseline levels. These increased costs could potentially be lowered, by improving sector coupling and integration [61], for example with the use of district energy that could considerably boost energy efficiency in the European energy system [62].

These investment cost changes are also reflected in the projected electricity prices (Fig. 4 for 2035), obtained from the EXPANSE electricity system model, soft-linked with the scenario results of the four IAMs (see **Section 2.1**). Average electricity prices in the middle of the next decade are projected to be lowest in the *Energy Efficiency* scenario, as improving efficiency leads to the lowest electricity demand, investment costs, and hence electricity prices (as low as 20–30 EUR/MWh in Scandinavian countries and Ireland). Conversely, increasing domestic production and importing gas from elsewhere can both lead to high electricity prices (as high as 60–120 EUR/MWh in the east, in 2035). Again, GCAM shows opposite, albeit more moderate, trends due to increased electricity demand.

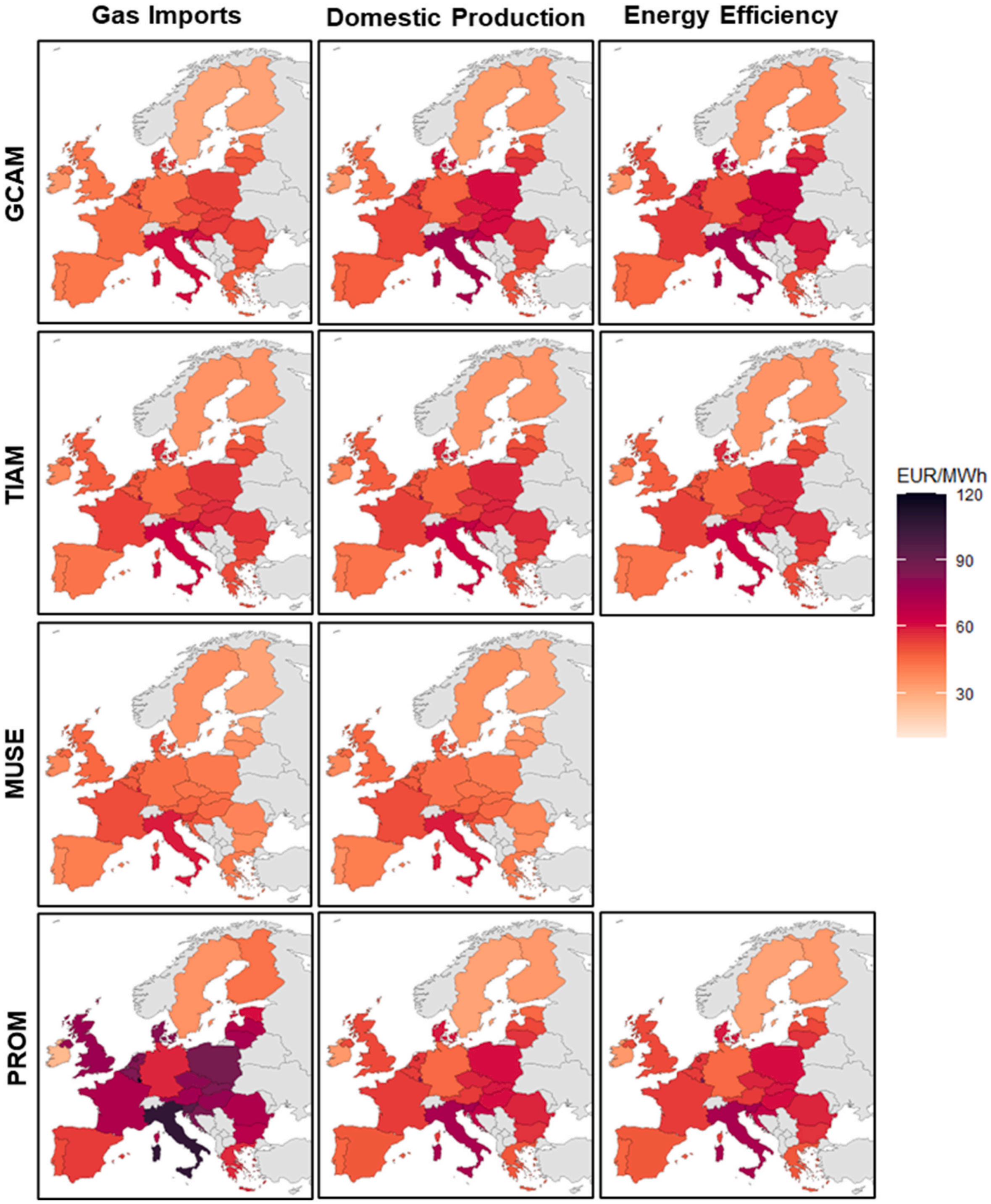


Fig. 4. Average electricity prices across European countries, across scenarios, and across IAMs, for the year 2035. Source: EXPANSE, using inputs from the global IAMs. MUSE cannot implement the 'Energy Efficiency' scenario protocol, as final energy consumption cannot be constrained in the model.

Critically, southern Europe seems to be the most vulnerable to electricity price spikes: Italy appears to be the country facing the highest electricity price spikes, due to its relatively higher reliance on gas imports, followed by eastern countries. We also perform a deeper dive into the electricity system across our model ensemble. A snapshot for the same year (2035), illustrated in Fig. S1 (in Supplementary Material), shows PROMETHEUS seeing the highest renewable electricity generation in the *Gas Imports* scenario, along with increased (hydrogen) storage capacity, grid expansion, intermittent renewable energy capacity, and prices (as opposed to *Energy Efficiency*). Conversely, GCAM sees maximum RES electricity generation, grid expansion, and battery storage capacity in the *Energy Efficiency* Scenario. In TIAM and MUSE, there is less variation in electricity-system configuration across scenarios, with TIAM however projecting the highest (battery) storage capacity, grid expansion, and RES capacity in the *Domestic Production* strategy. These trends are also evident in electricity-system costs (see Table S2 in Supplementary Material) since, in the case Russian gas is substituted by gas imports from other sources, the low electricity demand in TIAM and PROMETHEUS also implies less capital and operational expenditure compared to a strategy promoting energy efficiency uptake—as opposed to GCAM that shows reverse cost trends, with the *Energy Efficiency* strategy requiring the highest capital electricity system costs.

We finally provide insights into employment impacts by sector, using MARIO (Fig. 5), soft-linked with the scenario results of the four IAMs (see Section 2.1). Mining and quarrying essentially constitute the only sector experiencing employment losses—naturally as they encompass fossil fuel extraction activities. The electricity-sector structural differences (see Fig. S1 in Supplementary Material) lead to diverging insights into power-sector employment between GCAM on the one hand and TIAM and PROMETHEUS on the other, driven also by different labour intensity for each technology. Power-sector employment shows more than a 1.5-fold increase in the *Energy Efficiency* scenario by 2050 in GCAM, while PROMETHEUS and TIAM showcase a mid-term employment decrease across all scenarios, in fact with a steeper decline (followed by a post-2040 increase) in the *Energy Efficiency* scenario owing to the high decrease in investments in the sector as a short-term response. Nonetheless, we project an overall positive impact on electricity-sector employment in the long term, also considering the decrease in fossil-dominated sectors and the relative higher labour intensity of renewable energy technologies compared to fossil fuels [63–65]. It should be noted that sectors outside power are not considered in this analysis, despite expected implications (e.g., in the construction sector).

3.4. *Diversifying import sources reduces gas prices but fosters a new gas trade landscape in Europe*

The envisaged role of gas in Europe's energy system in the transition to net zero has been fundamentally changed in response to the recent energy crisis. Here, we focus on the *Gas Imports* scenario and the GCAM model, as it features increased granularity for the bloc's gas pipelines and routes (see Section 2.1 for regional disaggregation). Despite direct substitution of gas from other sources, the EU is on track to reducing its net gas imports by almost 40 % in 2030, compared to 2020. In most regions, the remaining gas imports may be provided either by European pipeline gas (predominantly from Norway) or LNG, up by 28.5 % and 33.3 % EU-wide in 2030 compared to 2020, respectively. An exception here would be southwestern Europe, where pipeline gas from Africa (Algeria and Libya) covers 30 % of gas imports, resulting in EU-wide imports from those regions doubling by 2030. Demand for LNG would also increase in all regions, with considerably higher imports in the central and eastern member states (see Fig. 6).

Average natural gas (entry) prices across scenarios are shown in Fig. 7, alongside the % change compared to the *Baseline*: the *Domestic Production* strategy would lead to the highest gas prices until 2050, owing to reduced supply based on the cap on imports and reflecting the stronger burden to replace Russian gas with domestic energy production; the *Model-optimal* and *Energy Efficiency* scenarios would arrive at similar mid-range prices; whereas the *Gas Imports* scenario would instead lead to the lowest prices through diversification of import sources, notably even lower than the *Baseline*. The regional disaggregation of price difference for the mid-range *Model-optimal* scenario is also shown in Fig. 7: in general, regions with the highest Russian gas imports in 2020/2021, low LNG capacity, and insufficient storage capacity are the most vulnerable to higher gas price spikes [66]. Modelling results suggest that the highest gas price differences in 2030 compared to the *Baseline* are observed in Finland, Sweden, and Baltic countries, followed by Central Europe, Poland, then Northwest and Southeast EU, and finally Southwest EU.

4. Discussion and conclusions

Our results suggest that entirely replacing Russian pipeline gas with gas imports from other sources, such as LNG from the USA or pipeline gas from North Africa and Norway, misses an opportunity to accelerate decarbonisation of the European economy, especially in energy end-use sectors. In contrast, increasing the use of domestic resources (outside gas) and—especially—investing in energy efficiency would mitigate demand and enable reinforcing emissions reductions in certain sectors. Unlike other studies [41], the projected overall EU's emissions pathway is mainly driven by 2030 and 2050 climate targets and thus relatively unimpacted by any response [42]. Positive environmental implications of any of the three 'corner' options would thus be observed on the demand side, as low-carbon energy outcompetes fossil fuels in end-use sectors, with supply-side energy-related CO_2 emissions instead growing to make up for the lost Russia-imported supply. This diversity in sectoral emissions responses is partly reflected in the different ways member states addressed the energy supply crisis in the short term. For example, much like the EU overall [67], Germany and Poland both saw lower GHG emissions in 2022, with Germany achieving greater industrial and household energy demand cuts than coal use spikes and Poland boosting renewable power generation to a record while cutting both gas and coal consumption; Spain, on the other hand, saw its gas and coal use for electricity radically increase, leading to a ~7 % increase in GHG emissions compared to 2021 [68]. As a long-term strategy, substituting

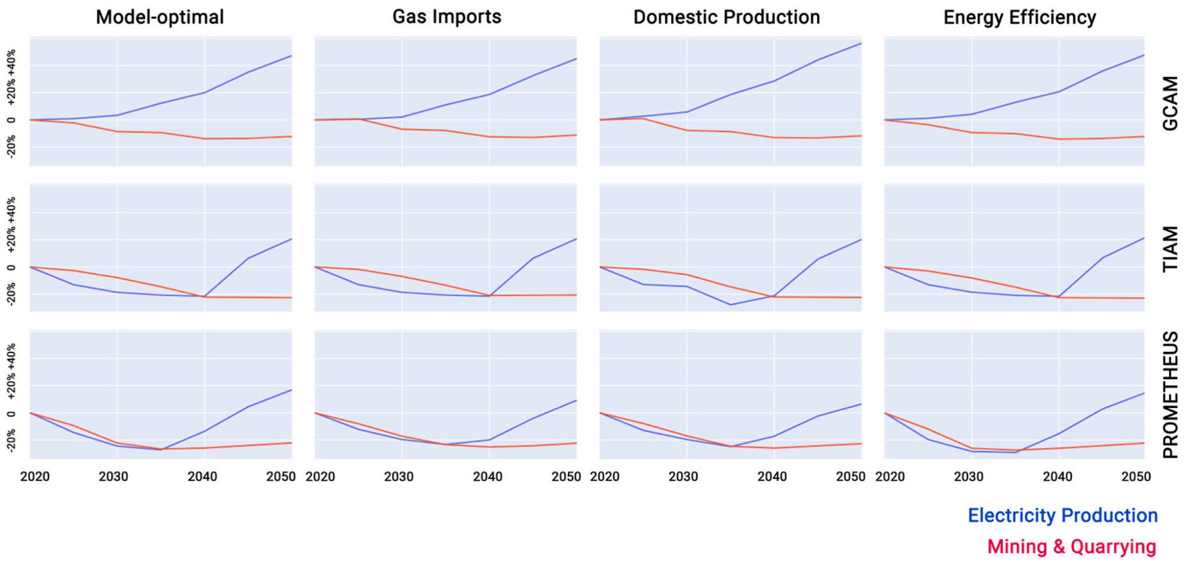


Fig. 5. Employment by sector and region (variation from Baseline). Employed population in electricity production and mining & quarrying sectors compared to *Baseline* in the EU (2020–2050) in GCAM, TIAM, and PROMETHEUS. Source: MARIO, using inputs from the global IAMs.

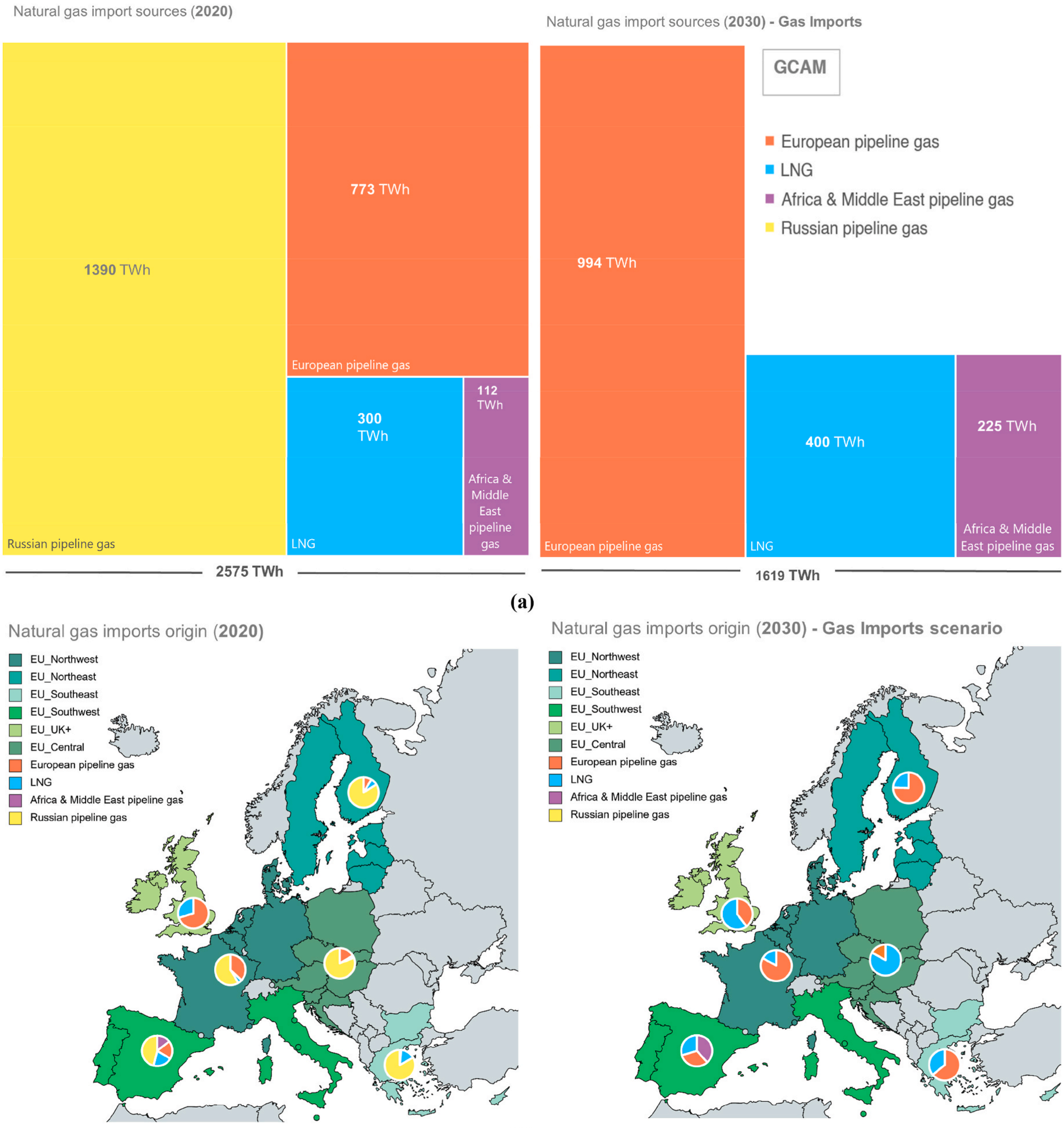
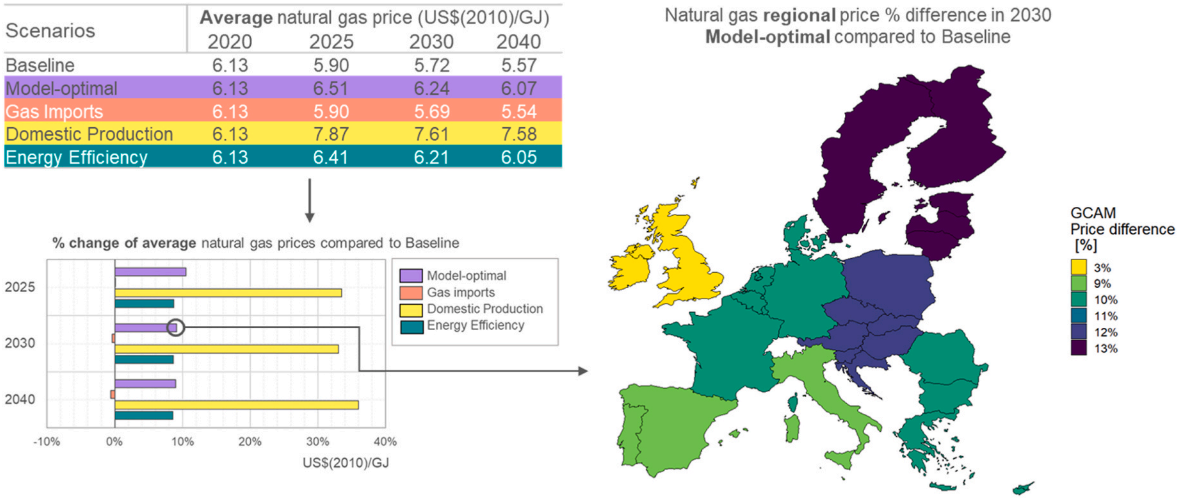


Fig. 6. Natural gas imports in 2020/2030 for the *Gas Imports* scenario. (a) Gas import sources, (b) regional disaggregation. Only GCAM results are available. See Section 2.1 for regional disaggregation in the GCAM model.

Russian gas by gas of different origin (‘Gas Imports’) critically risks locking Europe into fossil-fuel dependency and carbon-intensive infrastructure (e.g., LNG import terminals), when alternative approaches are feasible. It would also see minimal reductions in demand for energy carriers, compared to all other options.

The challenge of balancing the need to resolve the short-term energy supply-demand mismatch with the long-term aims of a cost-optimal and just energy transition are highlighted in our results, which point to similar-to-higher energy-system costs should Russian gas imports be replaced by gas trade with other countries. Insistence on gas, alongside higher costs of imported fuels as well as reduced security of supply—and increased vulnerability to international price changes—could also plausibly affect electricity-system costs and, correspondingly, prices for end-users. Given these potentially higher system costs, also driven by short-term fossil-fuel infrastructure needs [21], there is evident conflict with the long-term goals of decarbonisation and energy security, risking creating sizeable, stranded assets in the fossil-fuel sector—e.g., in LNG infrastructure, as much as half of which may be obsolete by the end of this decade [25]. Nonetheless, it would also entail the lowest gas price uptick in the near term among all ‘corner’ options, due to the relatively increased availability of gas, making it perhaps an attractive proposition from a political perspective as end-use heating costs for consumers might be lower; besides, along the transition by 2050, gas prices may affect not only heating costs for end users but also the overall evolution of the heating sector [69].

On the other hand, despite displaying moderate energy-system costs, increasing energy production within the EU using all domestically available levers to make up for the 1500 TWh of lost Russian gas, is projected to require the costliest investments (especially in electricity supply and storage) and thus feature high annual costs for power supply, in turn pushing electricity prices up, as the costs of meeting the higher demand for electricity must be ultimately recovered from consumers.



Scenarios	**Average** natural gas price (US$(2010)/GJ) 2020	2025	2030	2040
Baseline	6.13	5.90	5.72	5.57
Model-optimal	6.13	6.51	6.24	6.07
Gas Imports	6.13	5.90	5.69	5.54
Domestic Production	6.13	7.87	7.61	7.58
Energy Efficiency	6.13	6.41	6.21	6.05

Fig. 7. Natural gas prices. Average natural gas entry price (USD_{2010}/GJ) in the years 2020, 2025, 2030, and 2040, across all scenarios (top left), as well as % change of average gas prices compared to Baseline (bottom left); regional price increase in the *Model-optimal* scenario for 2030 (right). Only GCAM results are available. See Section 2.1 for regional disaggregation in the GCAM model.

Our results imply that whichever approach Europe takes to respond to the crisis may mostly not (according to TIAM), or even negatively (according to PROMETHEUS), impact total energy-system costs: results from the model showing the most pronounced effects (PROMETHEUS) suggest an increase in costs of 26–40 % in 2030 and 12–32 % in 2050, across scenarios. A study by Pedersen et al. [40] showed similar findings in the near-term and more pronounced impacts by mid-century: about +30 % and +5 % in 2030 and 2050, respectively, for a 2°C-aligned pathway, whereas zero impacts in a 1.5°C-consistent trajectory. It should be noted, however, that our pathways are calculated on top of actual policies and pledges rather than regional carbon budgets consistent with global temperature goals. Increased sector-coupling—including electricity for heating in district energy and thermal storage—could help mitigate these effects of increased system costs by providing alternatives to expensive electricity supply and storage. We acknowledge that such opportunities are not considered in detail in our study, although we note that European energy system transition pathways considering extensive sector coupling and synergetic effects across energy grids have been explored in the recent literature (e.g., Ref. [61]).

Responding to a structural loss in gas supply by reducing demand for energy would yield the highest cuts in energy use and emissions on top of the *Baseline* (notably among the technology-richer models with a diverse range of energy efficiency options) and the lowest energy-system costs in the long term. The International Energy Agency had, early in the crisis, released a report outlining several such instruments that could enable such a strategy [70], featuring both technological solutions and lifestyle changes. From this technological perspective, although the IAMs used in our study can explore policy packages related to decarbonisation and/or energy efficiency, a detailed assessment of specific efficiency measures would be beyond the core scope of their use in this research. However, considering the specifications of our *Energy Efficiency* scenario and based on the analysis of our modelling results, we can identify some broad viable strategies targeted at reducing energy consumption that are implied in the resulting trajectories, in tandem with energy demand reductions (as in lifestyle changes) and as reflected in the relatively high energy system costs early in the time horizon (Fig. 3). These would include increased thermal insulation in buildings, renovations, and overall adoption of highly efficient technologies (e.g., more efficient appliances, heat pumps alongside electrification, and strong phaseout of fossil fuel boilers in the built environment, electric and/or plug-in hybrid electric vehicles in transport, energy management systems and heat recovery in industry, etc.). Consistently across all models, this strategy would also see the lowest electricity-sector investment costs, on the order of tens of millions of euros per year, as well as the lowest electricity price spikes in the long term in most models, emphasising that policy measures incentivising energy efficiency can mitigate the costs of the energy transition, increase EU system resilience and security of energy supply, and enable positive impacts on overall energy-sector employment. Despite its numerous advantages, however, this 'corner' option also comes with notable risks. For example, emissions reductions in the models were achieved in part through the relocation of energy-intensive industries, which is of paramount concern to European policymakers. There is also the issue of potential rebound effects in the longer run, in relation to both emissions and investment needs [71]. As energy efficiency measures are deployed and delivering the same energy services with less energy becomes possible, the demand for those services may increase, wiping out the gains from efficiency and in fact negating the return on associated investments.

Focussing on the bloc's most pressing concern [72] of addressing gas price spikes and reducing natural gas demand, a strategy replacing lost Russian gas with domestic, predominantly renewable energy resources would lead to the fastest decline of natural gas in the European economy, while even diversifying gas import sources is in line with a 40 % reduction of gas imports by 2030. In the latter case, although LNG demand would increase across the EU, the bloc would benefit more from additional European pipeline gas (primarily from Norway, acknowledging however the challenges Norway faced in ramping up production to make up for lost Russian gas in 2022) as well as pipeline imports from North Africa and Turkey, than it would from additional LNG imports (a moderate +100 TWh by the end of the decade); this adds to the existing body of literature, which points to higher LNG needs [1], considering however that the focus of such studies had been on mitigating gas shortage in the short term while leveraging all possible options, rather than 'corner' long-term equilibrium solutions sought in our research. In 2021, EU's natural gas import dependency rate was 83 % (estimated as the ratio of imported natural gas to gas primary energy); in 2030 and across scenarios, this rate is projected to decrease to 58–69 % (averaged values across models), compared to 73 % in the *Baseline* scenario (see Fig. S2 in Supplementary Material).[2] Our study also suggests that gas consumption is bound to decrease overall (up to −11 % in 2030) compared to the *Baseline*, although this effect is not as pronounced as a previous study—comparing against a similar baseline, albeit based on a single model of different economic theory—where gas consumption could drop by up to 25 % [42]. As far as natural gas prices are concerned, we find notable discrepancies across the EU and critically across scenarios, with the highest prices observed for a strategy prioritising domestic energy production to replace the lost gas rather than trading with other countries. Even the models' cost-optimal approach—i.e., without prescribing a 'corner' response to the crisis—finds such regional discrepancies, with the southern and Atlantic regions seeing lower gas prices than the northern regions by 2030, as countries previously dependent on Russian gas imports but with low LNG capacity are susceptible to gas price volatility going forward. Understanding such distributional effects of the new energy landscape in Europe is critical if EU energy and climate policymaking is to obtain sufficient buy-in from member states to achieve the Union's decarbonisation ambitions together with enhanced energy security and resilience.

To summarise our findings in concrete policy terms, the EU's original strategic plan to address the Russian gas supply crisis ('REPowerEU') appears to be broadly on the right path. However, while we have mostly seen efforts in the 'diversification' pillar of this plan (with a particular focus on LNG expansion), we find that the bloc has more to gain from stronger prioritisation of energy efficiency measures to reinforce its efforts towards net zero, as this strategy displays multiple co-benefits beyond helping to manage the short-term supply and demand mismatch: quicker decarbonisation in end-use sectors, lower investment costs through diminished demand, and lighter burden on households. However, these benefits must be interpreted with caution, as they could entail negative macroeconomic and societal impacts if driven by industrial demand destruction. Importing gas from international partners, while necessary to balance supply and demand of energy in the aftermath of the crisis, on the other hand, runs the risk of contradicting decarbonisation visions if implemented as a long-term strategy, while producing more domestic energy may prove costly from an investment perspective but avoid competitiveness risks of domestic energy demand reduction. It is evident that all examined approaches have their pros and cons, and EU policymakers should consider their trade-offs to decide the right balance and prioritisation. It should be noted that, as with any study, our research comes with its limitations, and that resulting policy prescriptions must be considered alongside important caveats. Among these, the *Baseline* scenario—which is a decisive factor in any modelling study—has been based on a top-down implementation of the EU's 'Fit for 55' target for 2030, without breaking it down into the individual components that are being finalised (e.g., the EU-ETS and ESR targets) and which may prove critical from a sectoral perspective. In fact, even the 'Fit for 55' target may entail model-specific assumptions with regard to non-CO_2 gases (see Ref. [73]). Moreover, despite harmonisation of modelling inputs to reduce unwanted model response heterogeneity due to parametric uncertainty, the four employed IAMs differ in terms of technological representation, which in turn increases results heterogeneity due to structural uncertainty—for example, the models do not represent behavioural change measures and energy efficiency technologies with the same granularity, with relevant divergences especially in the context of the *Energy Efficiency* scenario. Along the same lines, not all models could implement each scenario in the same manner (creating cross-model dependencies—e.g., relocation of EITE industries drew from the GCAM model's *Baseline*), nor necessarily all scenarios (in particular, *Energy Efficiency* was not implemented in MUSE)—see more information on scenario implementation across models in Table S1 in Supplementary Material. Especially regarding uncertainty, we acknowledge that using model ensembles such as ours is only one way to increase confidence in modelling outcomes; future research directions could include employing sensitivity analysis to further enhance the robustness of model-derived insights.

CRediT authorship contribution statement

Alexandros Nikas: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing - original draft, Writing - review & editing, Funding acquisition, Visualization. **Natasha Frilingou:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing, Supervision, Validation. **Conall Heussaff:** Conceptualization, Writing - original draft. **Panagiotis Fragkos:** Conceptualization, Data curation, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **Shivika Mittal:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Jon Sampedro:** Formal analysis, Investigation, Validation, Writing - original draft. **Sara Giarola:** Data curation, Formal analysis, Investigation, Validation, Writing - original draft. **Jan-Philipp Sasse:** Data curation, Formal analysis, Investigation, Visualization. **Lorenzo Rinaldi:** Data curation, Formal analysis, Investigation, Validation, Visualization. **Haris Doukas:** Conceptualization, Funding acquisition, Project administration, Validation. **Ajay Gambhir:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. **Anastasis Giannousakis:** Data curation, Formal analysis, Investigation, Validation. **Nicolò Golinucci:** Data curation, Formal analysis, Investigation, Validation, Visualization. **Konstantinos Koasidis:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Matteo Vincenzo Rocco:** Data curation, Formal analysis, Investigation, Validation. **Evelina Trutnevyte:** Data curation, Formal analysis, Investigation, Validation. **Georgios Xexakis:** Data curation, Formal analysis, Visualization, Writing - review & editing. **Georg Zachmann:** Conceptualization, Supervision, Writing - original draft. **Eleftheria Zisarou:** Data curation, Formal analysis, Investigation. **Emanuela Colombo:** Data curation, Formal analysis, Methodology, Validation. **Adam Hawkes:** Formal analysis, Investigation, Methodology, Validation. **Brinda Yarlagadda:** Formal analysis, Software, Writing - original draft. **Matthew Binsted:** Formal analysis, Investigation, Software. **Gokul Iyer:** Methodology, Software, Validation. **Rasmus Magni Johannsen:** Conceptualization, Validation, Writing - review & editing. **Jakob Zinck Thellufsen:** Conceptualization, Validation, Writing - review & editing. **Henrik Lund:** Conceptualization, Validation, Writing - review & editing. **Dirk-Jan Van de Ven:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ajay Gambhir reports a relationship with UN Foundation's Accelerator for Systemic Risk Assessment (ASRA) that includes: employment.

Data availability

Data will be made available on request.

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[2] Gas import (and price) deviations from the baseline are affected by technoeconomic assumptions on costs and resource availability (partly harmonised across models), as opposed to increasing imports. However, some overall trends can be extracted across IAMs, while a reduction in natural gas imports over time can be observed as an effect of the fossil fuel phase-out, justified by decarbonisation efforts.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.130254.

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