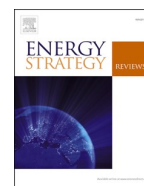




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## A multi-model assessment of technological constraints on Europe's energy transition

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### ABSTRACT

Europe's pursuit of net-zero emissions by 2050 is driven by the urgent need to contribute to global climate efforts and enhance its energy security, reducing its reliance on imported fossil fuels. The path to net zero entails a significant, economy-wide uptake of clean energy technologies. However, geopolitical tensions impeding trade, resource unavailability, or sociopolitical factors may give rise to considerable constraints to the uptake of such technologies. Using a diverse model ensemble, we explore the implications of limitations in terms of availability of critical low-carbon technologies such as renewables and batteries, biomass, and carbon capture and storage. Our findings suggest that such constraints could impact mitigation efforts as costlier alternatives become essential, compromise energy security while increasing reliance on fossil fuel imports, and drive cumulative emissions upwards, essentially jeopardising the EU's mid-century climate targets. We underscore the need for resilient energy-system transformations capable of withstanding geopolitical and technological disruptions, including policies prioritising the acceleration of energy efficiency and renewable energy diffusion.

### 1. Introduction

Consistent with its initiatives at the forefront of international climate efforts [1], the European Union (EU) has set ambitious targets to reduce greenhouse gas (GHG) emissions and achieve climate neutrality by 2050, a legally binding target under the European Climate Law (Regulation (EU) 2021/1119). This framework enshrines both the long-term net-zero target and a 2030 milestone of reducing GHG emissions by at least 55% compared to 1990 levels. Operationalising these targets has produced a dense architecture of measures such as the 'Fit For 55' package [2] at the EU level or the National Energy and Climate Plans (NECPs) [3] at the Member State level. Those policies have outlined comprehensive efforts to achieve the bloc's climate targets, including a broad range of measures, from energy efficiency improvements and grid modernisation investments to green hydrogen and circularity performance.

While the EU has established one of the world's most comprehensive climate policy frameworks, the success of these targets ultimately depends on the timely and large-scale deployment of a limited set of critical technologies. Renewable energy systems and storage underpin power-sector decarbonisation and widespread electrification. Those are pivotal technologies for achieving the bulk of the near-term emission reductions required under the 2030 target. Sustainable biomass has a dual role as a versatile energy carrier and as a feedstock for carbon-negative solutions when combined with carbon capture and storage (CCS), thereby contributing to emissions reductions across energy, industrial, and land-use sectors. CCS is essential for decarbonising hard-to-abate industries such as cement, steel, and chemicals, while bioenergy with CCS (BECCS) is a key lever for offsetting residual emissions in the long term, supporting the climate neutrality goal by 2050. Therefore, the EU's ability to achieve these near- and long-term climate objectives hinges not only on robust policy frameworks but also on the capacity to scale these technologies quickly and effectively under conditions of

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**List of abbreviations**

BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
EJ	Exajoule = $10^{18}$ Joule
EU	European Union
EV	Electric Vehicle
GCAM	Global Change Analysis Model
IAM	Integrated Assessment Model
IEA	International Energy Agency
LTT	Long- Term Target
MtCO <sub>2</sub>	Million tons of carbon dioxide
NDC	Nationally Determined Contributions
RES	Renewable Energy Sources
TIAM	TIMES Integrated Assessment Model

uncertain global supply chains and geopolitical risks that may impede access to critical materials, infrastructure development, and technology deployment.

The EU faces considerable challenges in securing stable access to critical raw materials essential for clean technologies such as lithium, cobalt, nickel and rare earth elements [4]. These resources are vital for several low-carbon technologies, such as wind turbines and batteries, but are heavily concentrated in few regions outside the EU, exposing the EU to price volatility and geopolitical risks. China dominates the value chain of such elements [5], while Europe's lithium and cobalt imports are sourced from Australia, Chile [6] and the Democratic Republic of Congo [7]. This dependence leaves the bloc vulnerable to supply disruptions caused by geopolitical tensions, trade restrictions, or market volatility. Past disruptions, such as China's 2010 export quota reductions [8], have already shown how such dependencies can slow European industry and clean technology deployment [9]. More recently, the Russia-Ukraine conflict has underscored Europe's vulnerability to energy system shocks. Beyond supply risks, technology diffusion is also constrained by grid limitations, intermittency, storage bottlenecks, land-use conflicts, and societal opposition to large-scale infrastructure, including wind, solar, and CCS projects [10,11]. While the EU has enacted the Critical Raw Materials Act (CRMA) to boost domestic extraction, processing, and recycling while diversifying imports and fostering international partnerships, meeting ambitious targets for 2030 will require coordinated investments and policy alignment across member states.

Integrated assessment models (IAMs) are the primary quantitative tools used to map out long-term mitigation pathways because they integrate energy, economic, land-use and environmental systems within a single analytical framework. This holistic approach makes IAMs uniquely suited to assessing the interactions, trade-offs, and synergies across critical sectors, such as power, transport, industry and agriculture that must transform simultaneously to meet the EU's climate goals. Previous research has demonstrated that model structure and assumptions significantly influence mitigation outcomes, with families of models differing in optimisation approaches, foresight, decision-making behavior, and technological detail yielding varying responses to policy and technological shocks. This amplification of structural uncertainty underlines the importance of employing a multi-model ensemble, harmonised under consistent scenario assumptions, to robustly characterise uncertainties and isolate model-driven variability. Such ensemble approaches have been championed by leading efforts such as the IPCC working Group III and recent multi-model comparison studies, which show that ensemble analyses provide stronger, policy relevant insights by revealing commonalities and divergence across models. For the EU context, where complex geopolitical, technical and economic constraints could shape technology diffusion trajectories, a harmonised

multi-IAM approach is critical to credibly quantify the risks to climate targets and thus inform resilient and adaptive policy design.

While much of the existing modelling literature in support of energy and climate policy has focused on identifying what must be done to achieve climate targets or how far current policies may take us [12–15], insufficient attention has been paid to technical and sociopolitical constraints that could hinder progress and the associated vulnerability to such constraints. Recent literature has highlighted key areas of concern, including the speed of renewable and CCS technology diffusion [16,17], storage capacity potentials [18], availability of bioenergy resources [19], societal acceptance of large-scale infrastructure projects [20], and geopolitical risks associated with critical materials [21]. Despite these concerns, IAMs and other analytical frameworks have been slow to keep up in examining the broader implications of these constraints. A handful of studies (e.g., Refs. [22–24]) have explored specific technological limitations to RES, CCS, and carbon dioxide removal; however, these have had an international angle, while taking aim at individual technological solutions.

The aim of this study is to assess how Europe's pathway to climate neutrality by 2050 could be disrupted if access to three critical technologies—namely renewable energy and batteries, biomass, and CCS—is constrained by geopolitical tensions, supply disruptions, or societal oppositions. We explicitly focus on the EU context, where climate ambition is high but reliance on imported critical raw materials and technologies creates significant vulnerabilities.

This study directly addresses this literature gap in three ways that increase significance. First, it provides an EU-focused assessment that combines the bloc's legal and institutional context (European Climate Law, Fit-for-55, NECPs) with EU-specific import-dependence and sectoral structure, producing outputs that are immediately relevant for European policy. We examine risks posed by technological constraints on achieving climate targets particularly for renewables, battery storage, CCS, and biomass, through a lens that incorporates a range of influential factors. Such factors include but are not limited to geopolitical tensions, trade wars, or industrial production protectionism, all of which could disrupt supply chains and critical material imports, as well as societal opposition to and political backtracking on large-scale infrastructure projects, or unavailability of relevant resources or storage sites. Second, it uses a harmonised multi-model ensemble to capture structural model diversity and to distinguish robust from model-specific responses. Third and crucially, to tackle structural uncertainties, we integrate an Input-Output model that quantifies the impacts of geopolitical and economic disruptions on clean technology costs, which is then soft-linked to the IAM ensemble (see Methodology). To expand the action space from diverse theoretical viewpoints, we also harmonise key assumptions to minimise response heterogeneity across models, towards attributing divergences to model structures themselves rather than unaligned model inputs. Additionally, particular emphasis is placed on economically integrating adjustments to technological costs because of adverse geopolitical developments, aiming to capture the disruptive effects of the shocks introduced to framework conditions. Together, these features allow us to quantify not only emissions impact, but also fuel-import exposure and sectoral vulnerabilities under constrained technological futures, delivering actionable, uncertainty-aware evidence that current studies do not currently provide. In short, this study delivers EU-focused, multi-model, traceable, and policy-ready evidence on the risks of constrained technological futures, that clarifies their implications on Europe's energy transition.

The remainder of this paper is structured as follows. Section 2 presents the modelling framework, including a description of the IAMs and the scenarios developed. Section 3 reports the results. Section 4 discusses the implications for policy and resilience, while Section 5 concludes with key messages and recommendations for Europe's energy transition.

## 2. Methodology

The main research question of this paper is how constraints on specific clean energy technologies (CCS, RES and storage, biomass) could alter the EU's short- and medium-climate targets. To answer this, we require models that i) represent the wide-economy landscape in sufficient and technological detail, ii) capture the substitution dynamics of fuels and technologies under different cost or availability conditions, and iii) have structural diversity to provide robust insights across modelling paradigms, so that results are not artefact of a single model structure.

For these reasons, this study uses three well-established IAMs (GCAM, PROMETHEUS, TIAM) that have been widely used to assess the environmental, economic, and technology impacts of climate policies. These IAMs have a distinguished record of robust application in exploring climate mitigation pathways, technology deployment challenges, and socio-economic-energy interactions, making them ideal for analysing technological constraints on Europe's energy transition.

GCAM, has been employed in numerous studies to explore the interactions between energy, water, land, climate, and economic systems, providing insights into the implications of different policy scenarios on global and regional scales [25,26]. PROMETHEUS has analysed energy system dynamics, including the assessment of mitigation pathways and low-emission development strategies, by quantifying the energy-system, economic, and emission implications of energy and climate policy measures [27,28]. TIAM has assessed the feasibility of large-scale CCS deployment [29] and sectoral decarbonisation strategies across multiple regions [30].

To explore the impacts of geopolitical constraints, we use projections from the multi-sectoral MARIO model [31] which quantifies the impacts of two contrasting scenarios regarding the availability of critical materials and trade dynamics on the costs of clean energy technologies. These projections are then integrated into the three IAMs, which in turn quantify the energy-system, technology uptake, and emissions impacts of said geopolitical disruptions and supply-chain constraints. This section provides a brief description of the four models—detailed descriptions are available at the IAM PARIS platform [32].

### 2.1. Models

GCAM [33] is a global IAM representing human and Earth-system dynamics. It explores the behaviour of and interactions between the energy system, agriculture and land use, the economy, and climate. Its components provide a reliable representation of the best current scientific understanding of the different systems and their dynamics/interlinkages. GCAM allows users to explore what-if scenarios, quantifying the implications of possible future conditions. It uses assumptions about population, economic activity, technology, policies, and other key drivers, to assess their implications for decision-relevant energy-climate-economy outcomes—e.g., commodity prices, energy, land, and water use, and GHG emissions.

PROMETHEUS [34] is a global energy-system model covering in detail the complex interactions between energy demand, supply, and prices at the regional and global level. Its main objectives are to assess mitigation pathways and low-emission development strategies, and quantify the energy-system, economic, and emission implications of energy and climate policy measures, differentiated by region and sector. It can support impact assessments of strategies/measures applied at regional and global level, including price signals—such as taxation, subsidies, technology standards, renewables and energy efficiency promoting policies, etc.

TIAM is the multi-region, global version of TIMES that combines a technology-rich, energy-system representation of fifteen different regions with options to mitigate CO<sub>2</sub> as well as non-CO<sub>2</sub> greenhouse gases and non-energy CO<sub>2</sub> mitigation options (e.g., afforestation) over a long-term, multiple-period time horizon [35]. Like GCAM, it uses emissions

from these sources to calculate temperature changes and can be used to address a diversity of research questions on how to mitigate climate change through energy-system transformations, including in terms of reductions in non-energy CO<sub>2</sub> emissions and non-CO<sub>2</sub> emissions. Energy-system operations include the extraction of primary energy, its conversion into useful forms, and the use of the latter in a range of energy service applications and sectors.

Finally, MARIO [31] is a versatile Python-based framework designed for Input-Output modelling. It facilitates the development and manipulation of Input-Output and Supply-Use models, allowing parsing major databases like EXIOBASE, EORA, and FIGARO, or customised datasets. One of its key features is its ability to handle both monetary and physical units while providing extensive functionality for database aggregation and extension (including the possibility to extend tables via hybrid life-cycle assessment techniques) [36], scenario analysis, and environmental assessments. MARIO allows users to model economic interactions between sectors and track both direct and indirect environmental impacts and model the ripple effects of supply-chain disruptions, decarbonisation measures, or technological advancements.

Table 1 provides an overview of key elements underpinning each model, including references to detailed documentation, while Fig. 1 offers a high-level visualization of the modelling framework in the case of geopolitical tensions affecting the deployment of RES and energy storage technologies: MARIO is soft-linked to the three IAMs, by providing them with technological costs adjusted over time according to scenario assumptions. In particular, relying on the EXIOBASE hybrid-units database [37], the model outputs future material demand for green technology manufacturing; each material's resource depletion rate is used as a proxy to estimate price increases, influencing technology costs, while accounting for decreasing cost trends via learning rates from region-specific historical data.

The three IAMs then run in parallel, based on the same set of assumptions, with the aim to output comparable pathways that enhance confidence in model results.

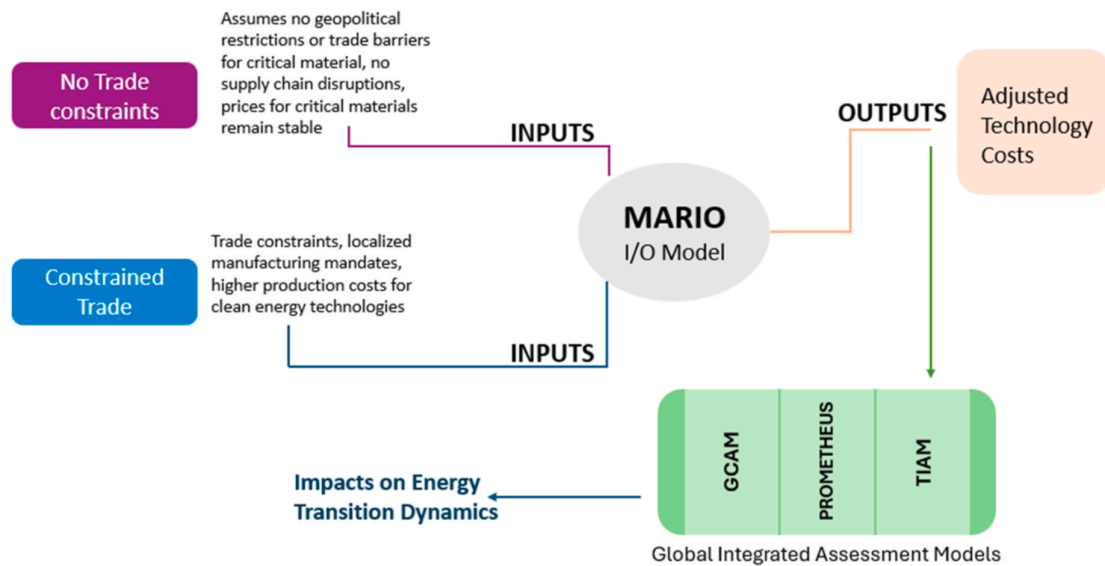
### 2.2. Iteration procedure

The models are integrated into a soft-linked, scenario-based modeling framework (Fig. 1) that integrates the MARIO input-output model with the three IAMs. The framework is designed as a computational procedure that propagates the effects of material availability, supply-chain disruption, and trade dynamics through energy-system projections, capturing both direct and indirect consequences on technology adoption and emissions trajectories.

In the first step of this procedure, MARIO is used to generate projections of material demand and corresponding technology cost

**Table 1**  
Key characteristics of the four models comprising the study ensemble.

Model Name	Model Type	Solution Horizon	Tech choice	Documentation in I <sup>2</sup> AM PARIS
GCAM	Partial equilibrium	Recursive-dynamic (myopic)	Logit choice	<a href="https://www.i2am-paris.eu/detailed_model_doc/gcamv2022">https://www.i2am-paris.eu/detailed_model_doc/gcamv2022</a>
PROMETHEUS	Energy-system	Recursive-dynamic (myopic)	Logit choice	<a href="https://www.i2am-paris.eu/detailed_model_doc/prometheus">https://www.i2am-paris.eu/detailed_model_doc/prometheus</a>
TIAM	Partial equilibrium	Intertemporal optimisation (perfect foresight)	Winner takes all	<a href="https://www.i2am-paris.eu/detailed_model_doc/tiam">https://www.i2am-paris.eu/detailed_model_doc/tiam</a>
MARIO	Input – Output	Comparative-static simulation	-	<a href="https://www.i2am-paris.eu/detailed_model_doc/dynerio">https://www.i2am-paris.eu/detailed_model_doc/dynerio</a>



**Fig. 1.** Methodological framework for examining the effect of geopolitical factors impeding the diffusion of RES and energy storage in the EU: integration of MARIO projections with the global IAMs to quantify geopolitical and supply-chain impacts on the energy transition.

adjustments under two contrasting scenarios: i) constrained supply and trade, and ii) unconstrained, globalised trade. The unconstrained trade scenario represents an idealised baseline, in which global supply chains operate without limitations, critical materials are freely traded, and prices remain stable over time. In this scenario, technology costs evolve primarily according to historical learning curves, reflecting cost reductions achieved through technological progress and economies of scale. In contrast, the constrained trade scenario embodies the effects of geopolitical and supply-chain disruptions. Here, manufacturing is localised in certain regions, trade barriers restrict the global flow of critical materials, and supply-chain bottlenecks result in higher production costs for renewable energy technologies, battery storage systems, CCS infrastructure, and biomass-based energy. The logic of this scenario is to capture the systemic pressures that arise when material scarcity, regionalisation of production, and trade restrictions limit the availability of key inputs, which in turn constrains technology deployment and raises costs.

For each scenario, MARIO produces a time series of technology cost projections that reflect both the direct effects of material scarcity and the indirect effects of supply-chain interdependencies across sectors. Resource depletion rates are translated into cost increases for each technology, while learning-by-doing effects, derived from historical regional data [36], are applied to account for gradual cost reductions. For this analysis, the MARIO model incorporated historical cost trajectories for key renewable technologies—solar photovoltaics (PV), onshore wind, and battery storage. This approach allows MARIO to quantify the net impact of geopolitical constraints on technology costs over time, providing a dynamic and scenario-specific input to IAMs (see Section 2.3).

The adjusted technology costs from MARIO are then fed into the three IAMs which independently simulate the evolution of the energy system under the same scenario assumptions (see Section 2.3).

### 2.3. Scenarios

We design three scenarios reflecting limitations on different low-carbon technologies in response to one or several constraints (e.g., geopolitical tensions, supply-side disruptions, resource unavailability, environmental sustainability trade-offs etc.), which we quantify with the model ensemble and compare against a baseline scenario. This baseline

scenario assumes countries achieve the targets outlined in their Nationally Determined Contributions (NDCs) by 2030 and their longer-term emission targets (*NDC-LTT* scenario), whereby the full range of clean energy technologies—including CCS, bioenergy, renewables, and advanced storage systems—are available and scalable over time, without being disrupted/capped due to socio-economic, technical, trade, or other constraints. Our three scenarios reflect different technologically challenging developments for renewable energy, power storage, CCS and biomass on top of the same level/intensity of climate policies (including carbon prices and/or other climate policy instruments) as in *NDC-LTT*.

First, the limited RES scenario (*NDC-LTT-LimRES*) envisions a world where scarcity of critical materials hinders the widespread deployment of RES, batteries, and EVs. Using MARIO, which couples a self-consistent macro-economic framework with a tool capturing the linkages of clean energy technologies with the supply, demand, and trade of critical materials, we produce two scenarios in the context of *NDC-LTT* climate targets: (i) one without restrictions in material supply/trade (in this case, e.g., the EU continues to import large PV quantities from China, if cost-optimal); and (ii) one where trade constraints are imposed among regions so that each region should manufacture the required technologies domestically. In the latter, the costs of critical materials and, in turn, of associated clean energy technologies (solar PV, wind turbines, batteries, and EVs) increase due to import constraints—reflecting geopolitical tensions, protectionist policies, etc. These adjusted costs, calculated in MARIO, are then imposed on top of the cost assumptions of the baseline *NDC-LTT* scenario in the three IAMs, increasing cleantech costs and thus reducing the speed of technology uptake.

Second, the limited biomass scenario (*NDC-LTT-LimBIO*) assumes the availability of biomass for the EU's energy transition is capped at 5–6 EJ by 2050 in line with potentials outlined in literature [38], reflecting environmental sustainability considerations, resource unavailability, and concerns about competition with food supply.

Third, the limited CCS scenario (*NDC-LTT-LimCCS*) assumes that the deployment of CCS technologies in the EU is constrained to 10–20 MtCO<sub>2</sub>—i.e., only current pilot CCS projects materialise—due to limited development, high costs, and lack of social/political support.

Table 2 summarises the baseline scenario as well as the three technologically constrained scenarios examined in our research.

In all policy scenarios, the models use harmonised assumptions about

**Table 2**  
Descriptions of the alternative scenarios.

Scenario	Short description
NDC-LTT	Implementation of the NDC targets for 2030 and long-term targets for 2050 (e.g., net zero by 2050 in the EU)
NDC-LTT-LimRES	Limited expansion and growth of RES and energy storage technologies, including batteries, due to material unavailability and geopolitical tensions: cleantech costs increase due to import constraints in materials and clean energy technologies, as quantified in MARIO, and act as moderating factors on projected growth for RES and battery technologies.
NDC-LTT-LimBIO	Restricted use of biomass for energy purposes in the EU, with a cap set at 5-6 EJ by 2050.
NDC-LTT-LimCCS	Restricted deployment of CCS in the EU, with a cap set at 10-20 Mt CO <sub>2</sub> by 2050.

the future development of main socioeconomic drivers, namely population and GDP by region, based on widely used established databases such as Eurostat [39], UN Population projections [40], Shared Socio-economic Pathways - SSP2 [41], and IMF [42]. In addition, the technoeconomic assumptions (e.g., costs and efficiencies of technologies) and fossil fuel prices used in the models are also harmonised based on the latest EC Reference scenario [43] and the IEA, World Energy Outlook projections [44].

### 3. Results

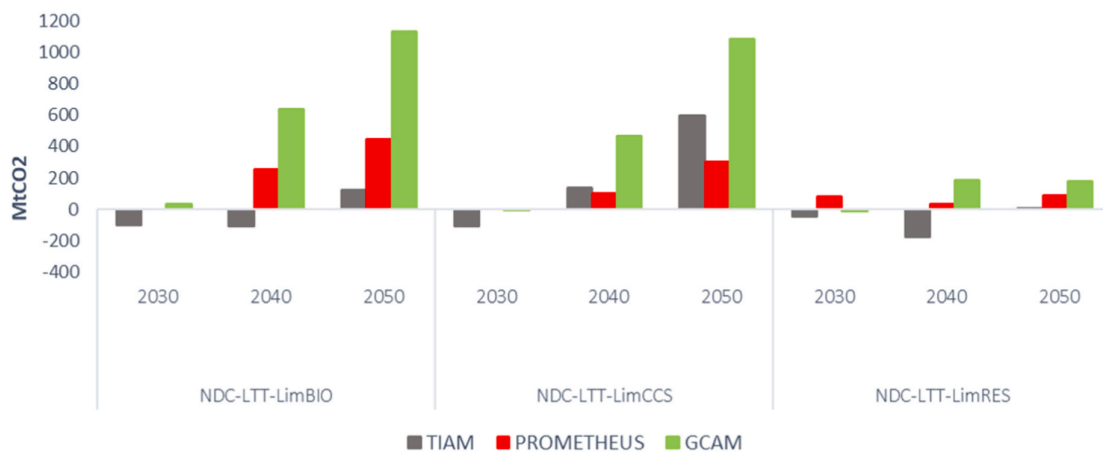
#### 3.1. Attainability of net zero by 2050 in light of technology constraints

Models show that limiting the growth of key clean energy technologies (Fig. 2) would impede progress towards the EU's climate targets. Since renewables and batteries play a crucial role in any plausible decarbonisation pathway, any increase in their costs and/or constraint on their upscale would yield higher reliance on conventional, carbon-intensive energy sources. Although this is not as evident in the near-term, with cost-competitiveness and policies in place (including ETS strengthening and transport emission standards) being the main drivers of the projected RES growth and EV uptake by 2030, this scenario shows increasingly pronounced impacts on CO<sub>2</sub> emissions post-2030. In 2040, PROMETHEUS and GCAM project an increase in CO<sub>2</sub> emissions, over the baseline, by 40-190 MtCO<sub>2</sub>, primarily due to the limited uptake of electrification in transport. The slower uptake of RES and batteries in the longer term would lead to a moderate increase in CO<sub>2</sub> emissions over the baseline of about 90-180 MtCO<sub>2</sub>, as the system struggles to fully

substitute these technologies.

Limited availability of biomass use for energy purposes, on the other hand, would render the EU more reliant on fossil fuels, significantly increasing its CO<sub>2</sub> emissions. In 2030, EU CO<sub>2</sub> emissions would increase by 10-100 MtCO<sub>2</sub> across all three IAMs, indicating higher reliance on more carbon-intensive energy sources especially in transport and industry, where biomass is an important mitigation lever. A decade later, CO<sub>2</sub> emissions would see a larger spike compared to the baseline of about 260-640 MtCO<sub>2</sub> as this overreliance would couple with slow upscale of other low-carbon options such as hydrogen and electrification, according to PROMETHEUS and GCAM. Due to its perfect foresight, which dictates early investments, TIAM projects a decrease in CO<sub>2</sub> emissions by 103 Mt CO<sub>2</sub> in 2040, due to earlier implementation of alternative mitigation technologies, to replace lost biomass, alongside energy efficiency measures. The increasing emissions trend would continue to 2050, in both PROMETHEUS (+450 MtCO<sub>2</sub>) and GCAM (+1130 MtCO<sub>2</sub>), reflecting the long-term challenges in decarbonising specific transport segments and industrial sub-sectors as well as in generating net-negative emissions from energy supply (via BECCS) without sufficient biomass. This highlights the crucial role of biomass in the route to climate neutrality, as an option to both cut emissions (when replacing fossil fuel use) and generate net-negative emissions when combined with CCS to produce electricity and/or hydrogen.

CCS technologies are also crucial in mitigating emissions, in industry and power generation alike. In the near-term, in line with current considerations and uptake challenges, the model ensemble already projects limited deployment of CCS technologies in the baseline scenario, meaning that any additional limitations on CCS availability would have minimal implications for the EU's emissions. However, as the transition picks up pace post-2035, CCS emerges as a decarbonisation option in the baseline scenario and across all IAMs. A cap on CCS uptake would thus significantly increase CO<sub>2</sub> emissions in all three models, both in 2040 (100-470 MtCO<sub>2</sub>) and in 2050 (305-1100 MtCO<sub>2</sub>). The emissions impacts are higher in GCAM, as this model *de facto* relies heavily on strong CCS uptake in both power and industry to meet the EU's climate neutrality goal by 2050. This attests to findings in the literature, including the International Energy Agency (IEA) [45,46] and the Intergovernmental Panel on Climate Change (IPCC) [36], that achieving net zero becomes extremely challenging in the absence of CCS and options to produce net-negative emissions. Therefore, if the upscale of CCS technologies is constrained for whichever reason [47], the EU risks missing its net zero goal by 2050, unless more expensive mitigation options (e.g., green hydrogen, carbon use in synthetic fuels or materials,



**Fig. 2.** Differences in EU CO<sub>2</sub> emissions between alternative scenarios and the baseline scenario for the period 2030–2050. The figure illustrates the emissions impact of constrained deployment of key clean energy technologies—including renewables, batteries, biomass, and CCS—across three Integrated Assessment Models (GCAM, PROMETHEUS, and TIAM). The results highlight the increasing divergence from the baseline over time, particularly post-2030, with the most pronounced effects observed under biomass and CCS constraints, Source: GCAM, PROMETHEUS, and TIAM model simulations.

other forms of CDR, restructured industrial processes) and policies (e.g., higher carbon prices, more ambitious standards) are considered.

Overall, our model-based analysis shows that any constraint on the upscale (and/or any increase in the cost) of clean energy technologies would increase CO<sub>2</sub> emissions in the EU. The extent of this increase crucially depends on the potential of other low-carbon options to replace those constrained. In the case of constraints in biomass and CCS deployment, there are limited mitigation options to replace them, so the emission impacts are large; on the other hand, there are domestic substitutes (albeit more expensive, like domestically produced PV, biomass, or nuclear power) to replace variable RES, meaning that the emission impacts of the LimRES scenario are smaller.

### 3.2. Reliance on (imported) fossil fuels

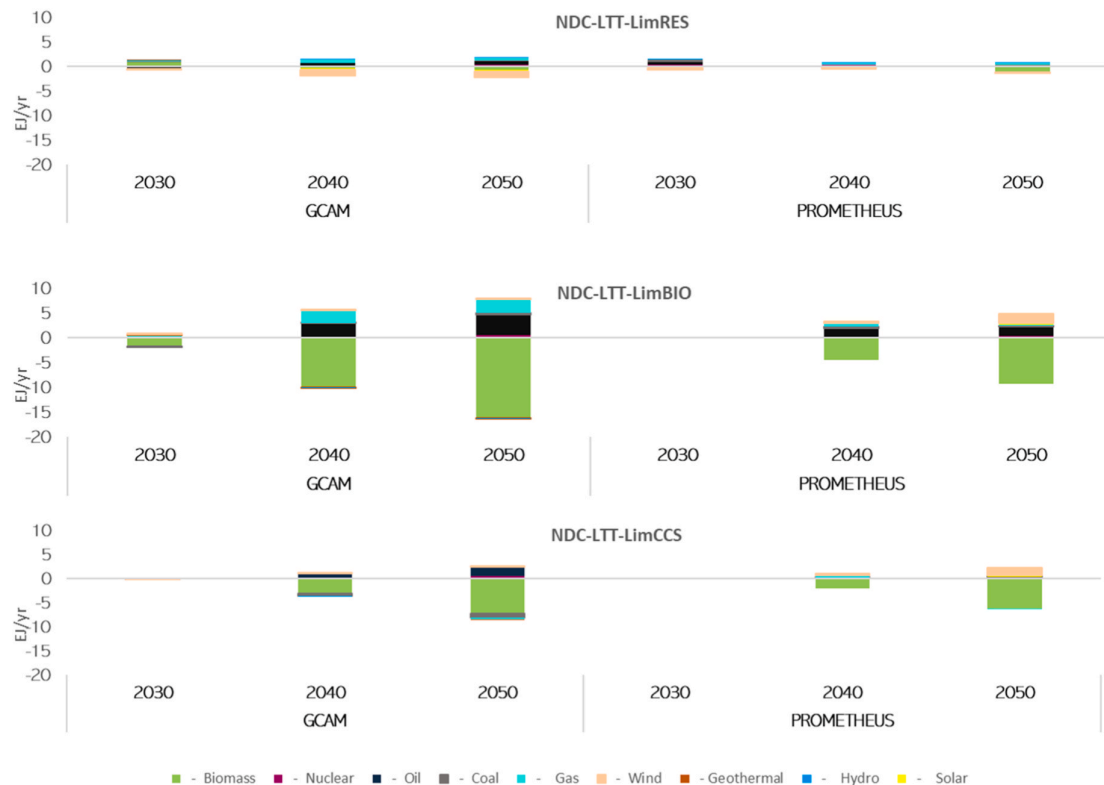
By 2050, the path to net zero by default showcases a shift of the EU's primary energy mix towards low-carbon sources: consumption of coal, oil, and fossil gas is projected to decline over time, giving its place to renewables (particularly in wind, solar, and biomass), enabled through rapid electrification of the final energy mix.

Constraints to the uptake of renewables and batteries would slightly increase biomass primary energy consumption in 2030, particularly in GCAM. Later, however, the constraints in battery supply in this scenario would result in increased oil consumption in both GCAM and PROMETHEUS, as the replacement of internal combustion engines by EVs decelerates, compared to the baseline (Fig. 3). The slower uptake of RES and electrification would keep driving an increase in the use of fossil

fuels, particularly oil and natural gas, until 2050—in line with the emissions implications discussed in Section 3.1.

A blow to biomass availability would have negligible implications for primary energy in the context of the EU's current NDC, with supply-chain constraints for biomass feedstock emerging more prominently in the longer term [11], with projected reductions in biomass use by 4-10 EJ in 2040 and 9-16 EJ across models, compared to NDC-LTT, in 2050. This would inevitably lead to increased reliance on (mostly imported) fossil fuels, already by 2040, an effect that is more pronounced by mid-century, with oil use projected to increase by 1.7-2.8 EJ in 2050 to compensate for the reduction in biofuel consumption, especially in transport—oil imports could increase by 4.2 EJ (according to GCAM) compared to the baseline, thereby challenging the EU's strategic objectives. Gas is also projected to act as a bridge fuel in this scenario, showcasing an uptick in 2040.

Finally, without scalable CCS, biomass would no longer offer a robust lever for negative emissions, as indicated by strong decreases of about 6-7 EJ in 2050 compared to the baseline scenario. Despite mitigation policies, both the electricity sector and industry would face challenges in further accelerating the deployment of other low- and zero-carbon technologies instead of CCS technologies. As a result, the oil and gas regime would remain more prominent in the energy mix, as alternative technologies remain commercially immature and cannot be widely deployed as early. This changes somewhat in the longer term where, in the absence of CCS, decarbonisation efforts depend on the stronger uptake of other clean energy sources like wind (+1.6 EJ in PROMETHEUS) and nuclear (especially in GCAM)—with the latter in reality



**Fig. 3.** Differences in primary energy consumption by fuel type in the EU between alternative scenarios and the baseline scenario for the period 2030–2050. The figure illustrates how constraints on the deployment of clean energy technologies—renewables, batteries, biomass, and CCS—alter the composition of the EU's primary energy mix over time. In the baseline pathway to net zero, fossil fuel use declines steadily, replaced by low-carbon sources such as wind, solar, and biomass, driven by electrification. However, under constrained scenarios, fossil fuel consumption (especially oil and gas) increases to compensate for slower uptake of clean technologies. Biomass constraints lead to higher fossil fuel reliance, while limited CCS deployment reduces the potential for negative emissions, resulting in a more carbon-intensive energy mix. The figure highlights the long-term implications of technology constraints on both emissions and energy security, Source: GCAM and PROMETHEUS.

largely dependent on political decisions. Nonetheless, reduced biomass use coupled with higher fossil fuel consumption would make the EU miss its net zero goals and compromise its energy security targets.

### 3.3. Sectoral insights

#### 3.3.1. The impact of cleantech constraints on EU transport

The transport sector has been a top priority in the EU's NDCs and long-term targets, due to its high reliance on fossil fuels, contributing to about a quarter of the bloc's GHG emissions. While there has been some progress in electrification and diffusion of low-carbon fuels such as biofuels, the road to decarbonised transport remains challenging.

The limited RES scenario (Fig. 4) retains the main growth drivers of transport decarbonisation, such as stringent CO<sub>2</sub> standards and enhanced cost-competitiveness over conventional vehicles, although post-2040 GCAM shows signs of increased consumption of liquids at the expense of EVs given the limitations on and increased costs of batteries; in PROMETHEUS, these effects are counterbalanced by more pronounced efficiency improvements in EU transport. As a 'perfect foresight' model, however, TIAM invests in hydrogen, by as early as 2030, to compensate for caps on battery-based EVs, before eventually electrification and sustainable fuels gain ground.

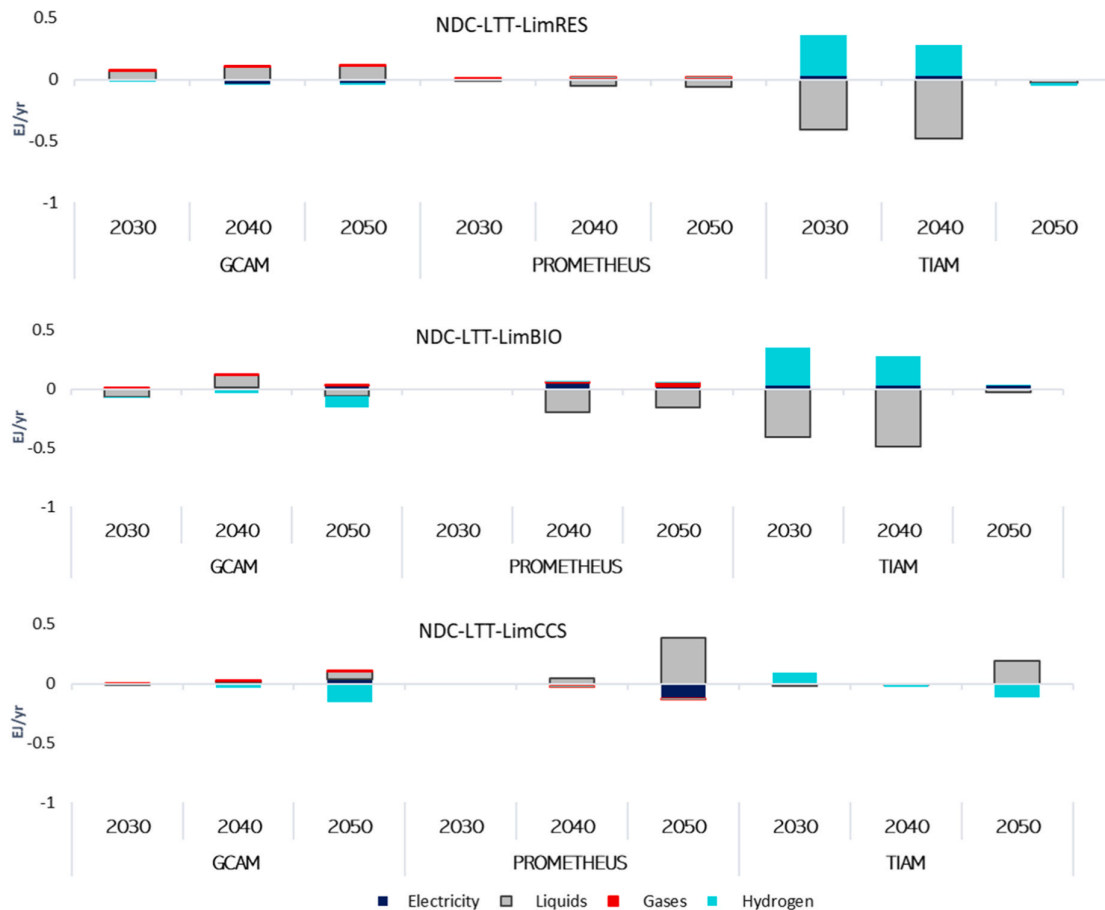
Reduced availability of biofuels due to limitations on biomass, on the other hand, renders electricity and hydrogen more attractive across

models, despite hydrogen infrastructure upscale facing challenges because of insufficient renewable energy for green hydrogen production [48]. In this scenario, the three IAMs agree on reduced consumption of liquid fuels (mostly due to reduced use of biofuels), albeit to different extents (with TIAM showing the largest impact). Electricity use in transport shows minimal differences compared to the baseline across IAMs and periods.

Expectedly, constraints on CCS only bring about indirect impacts on the EU's transport energy mix: costlier technologies are used to produce electricity in the region, leading to electricity price spikes, thereby reducing electricity use compared to the baseline and increasing consumption of liquid fuels, including petroleum products but also biofuels and—to some extent—synthetic fuels, especially post-2035 in all three IAMs.

#### 3.3.2. Adaptability of the built environment

The transformation of the buildings sector to align with the EU's 2030 and 2050 goals largely relies on improvements in energy efficiency and increasing use of clean electricity and renewable energy to replace fossil fuels. In the absence of any constraints, modelling results suggest that natural gas use would decline significantly as regulations tighten and low-carbon options become cheaper. By 2050, in the baseline scenario, electricity is projected to dominate the sector's final energy mix (64-82% across the three models). Diverging model dynamics in the



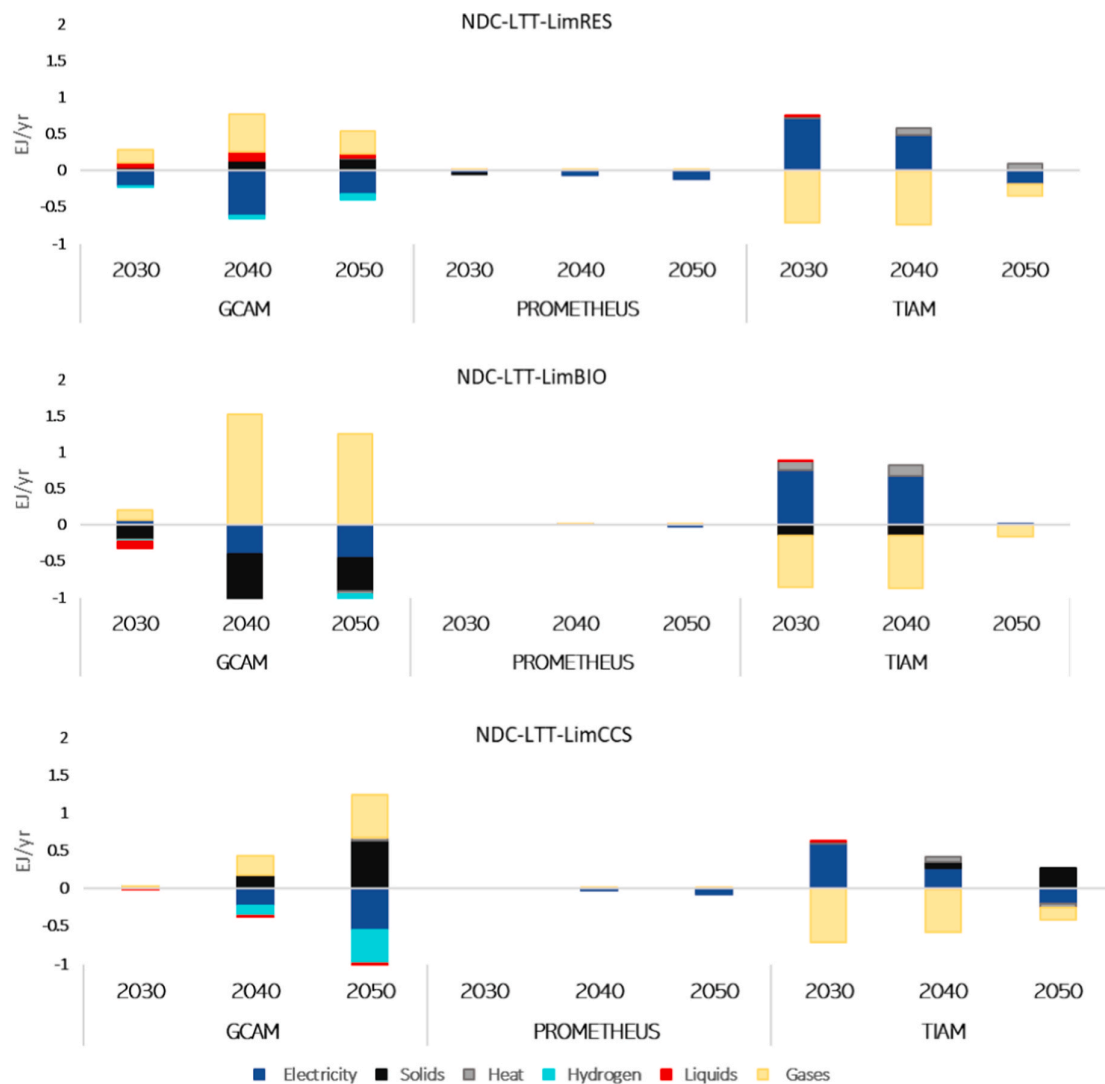
**Fig. 4.** Differences in transport fuel consumption between alternative scenarios and the baseline scenario for the period 2030–2050. The figure illustrates how constraints on key clean energy technologies—such as renewables, biomass, batteries, and CCS—affect the evolution of the EU's transport energy mix across three Integrated Assessment Models (GCAM, PROMETHEUS, and TIAM). The results highlight the sector's sensitivity to technology availability and cost, particularly post-2040, with notable shifts between electricity, hydrogen, and liquid fuels. While electrification remains a dominant decarbonisation pathway, limitations on battery deployment and biofuel availability lead to increased reliance on hydrogen and, in some cases, fossil-based liquids. CCS constraints indirectly affect transport by raising electricity prices, thereby reducing EV uptake and increasing liquid fuel consumption. Source: GCAM, PROMETHEUS, and TIAM.

baseline as well as different theories (myopic vs. perfect foresight) among the three IAMs make the assessment of this sector's resilience to the three scenarios harder to pin down, with PROMETHEUS prioritising energy efficiency to make up for the introduced technological shocks and GCAM and TIAM showcasing conflicting behaviours in terms of electricity and gas consumption (Fig. 5).

A limitation on renewables and battery technologies would yield increased electricity prices, reducing electricity use in both recursive-dynamic, myopic IAMs, PROMETHEUS and GCAM, with the latter showing more pronounced effects. Battery storage constraints, in particular, would make it difficult to rely on dispersed renewables for consistent energy supply of the built environment, boosting reliance on gases (+0.5 EJ) and liquids (+0.2 EJ) in GCAM. In contrast, TIAM projects a 0.7 EJ reduction in gases in 2030 alongside an equal increase in electricity, although by 2050 it converges to the other models in terms of electricity use reductions as RES and battery technology limitations hinder full electrification.

Constraints in biomass use would drive a reduction in solid biomass in GCAM, with gases again gaining ground (both fossil and clean gases) at the expense of costlier electricity, in the absence of BECCS to generate electricity, while TIAM—similar to the limited RES scenario, and given its consistent behaviour in prescribing early action in response to high carbon prices later in the time horizon—shows higher electrification instead, early in the time horizon, before returning to baseline levels.

As CCS *de facto* does not play a major role until much later, the myopic solution in the CCS-heavy GCAM model displays strong divergence from the baseline scenario from 2040 onwards: the constraints on CCS technologies would significantly increase the use of more expensive technologies for electricity and hydrogen production, driving their prices higher than solid biomass and gases and thus reducing their consumption in the building sector. PROMETHEUS shows similar trends with GCAM based on the same modelling logic, but much smaller in magnitude as the electricity price effects are marginal. Again, TIAM shows opposite trends, projecting an early shift towards gases (+0.7 EJ),



**Fig. 5.** Differences in EU building sector fuel consumption between alternative scenarios and the baseline scenario for the period 2030–2050. The figure captures how constraints on key clean energy technologies—renewables, batteries, biomass, and CCS—affect the decarbonisation trajectory of the buildings sector across three Integrated Assessment Models (GCAM, PROMETHEUS, and TIAM). In the baseline, electricity emerges as the dominant energy carrier by 2050, driven by efficiency improvements and policy support. However, technology constraints introduce divergent dynamics: battery and RES limitations lead to increased reliance on gases and liquids, particularly in GCAM, due to reduced electrification potential. Biomass constraints shift consumption toward gases and costlier electricity, while CCS limitations indirectly affect the sector by raising electricity prices, thereby reducing its share in final energy use. Source: GCAM, PROMETHEUS, and TIAM.

with the anticipation of its constrained availability (which is a priori knowledge in this model) boosting electrification (+0.6 EJ) and earlier integration of renewables, already in 2030.

3.3.3. Prospects of EU industrial decarbonisation under technology limitations

Achieving the NDC target in 2030 and net zero emissions by 2050 in the EU (baseline) entails electrification of industrial processes, from 21% today to 34-38% in 2030 and 42-64% in 2050. Hydrogen is also projected to play a role in the longer term in hard-to-abate sectors like steel manufacturing and chemicals, and this is coupled with a strong reduction in the use of all fossil fuels. Nonetheless, some coal would remain in the bloc's industrial energy mix, as the phase-out of older systems (e.g., coal-fired boilers and industrial kilns) alongside new clean investments would need more time to develop.

In the limited RES scenario (Fig. 6), a significant decline in electricity use reflects the higher costs (and prices) of renewable electricity and

storage, which render them less competitive for industrial applications—in line with other studies highlighting cost-related barriers to industrial electrification in case of constrained renewables diffusion (e.g., Ref. [49,50]). The drop in electricity use is counterbalanced by an increase in fossil fuel consumption, especially gases. PROMETHEUS projects similar trends with GCAM and TIAM but overall better resilience of EU industry in this case, due to limited implications for electricity prices.

Constraining biomass, which is a vital component of the EU industry's energy mix on the road to net zero, in our modelling exercise hints an increase in gas use (and to a lesser extent in liquids) to meet industrial energy requirements, reflecting persistent use of well-established and reliable sources, particularly for high heat processes in industries like steel, chemicals, and cement, which are difficult to electrify. Increased electricity prices drive moderate drops in electricity consumption (−0.1 EJ in PROMETHEUS, −0.7 EJ in TIAM) in 2050. In the absence of biomass, industry becomes more reliant on imported natural gas and

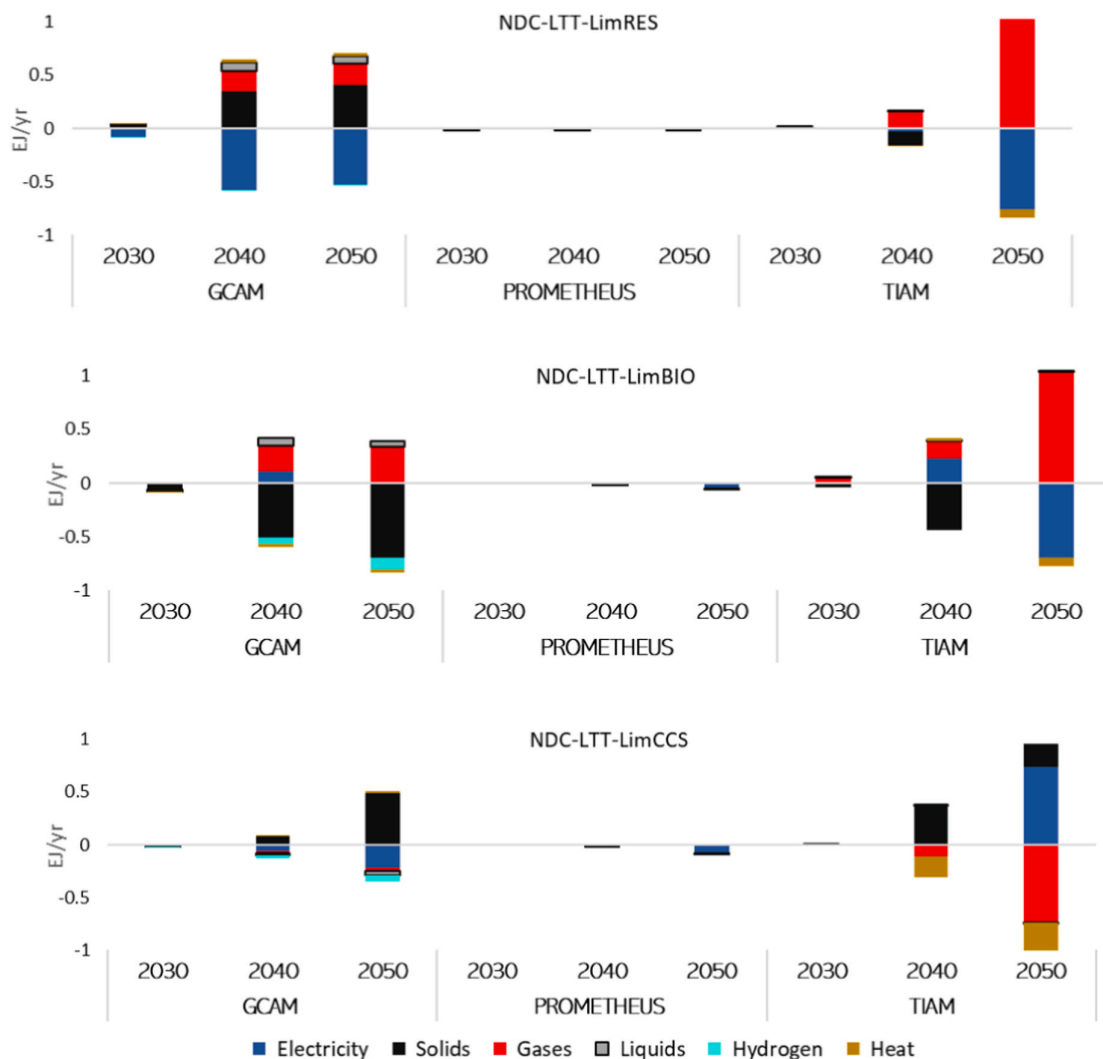


Fig. 6. Differences in EU industrial fuel consumption between alternative scenarios and the baseline scenario for the period 2030–2050. The figure illustrates how constraints on key clean energy technologies—renewables, batteries, biomass, and CCS—affect the decarbonisation of the industrial sector across three Integrated Assessment Models (GCAM, PROMETHEUS, and TIAM). In the baseline, electrification and hydrogen uptake drive significant reductions in fossil fuel use, aligned with EU climate targets. However, technology constraints introduce sectoral shifts: limited RES and battery availability raise electricity prices, reducing electrification and increasing reliance on fossil gases. Biomass constraints lead to greater use of gases and liquids, especially in high-temperature industrial processes. CCS limitations result in higher emissions and reduced heat generation, as industries struggle to decarbonise without viable alternatives. Source: GCAM, PROMETHEUS, and TIAM.

other gaseous fuels, posing risks to the bloc's energy independence and emission targets.

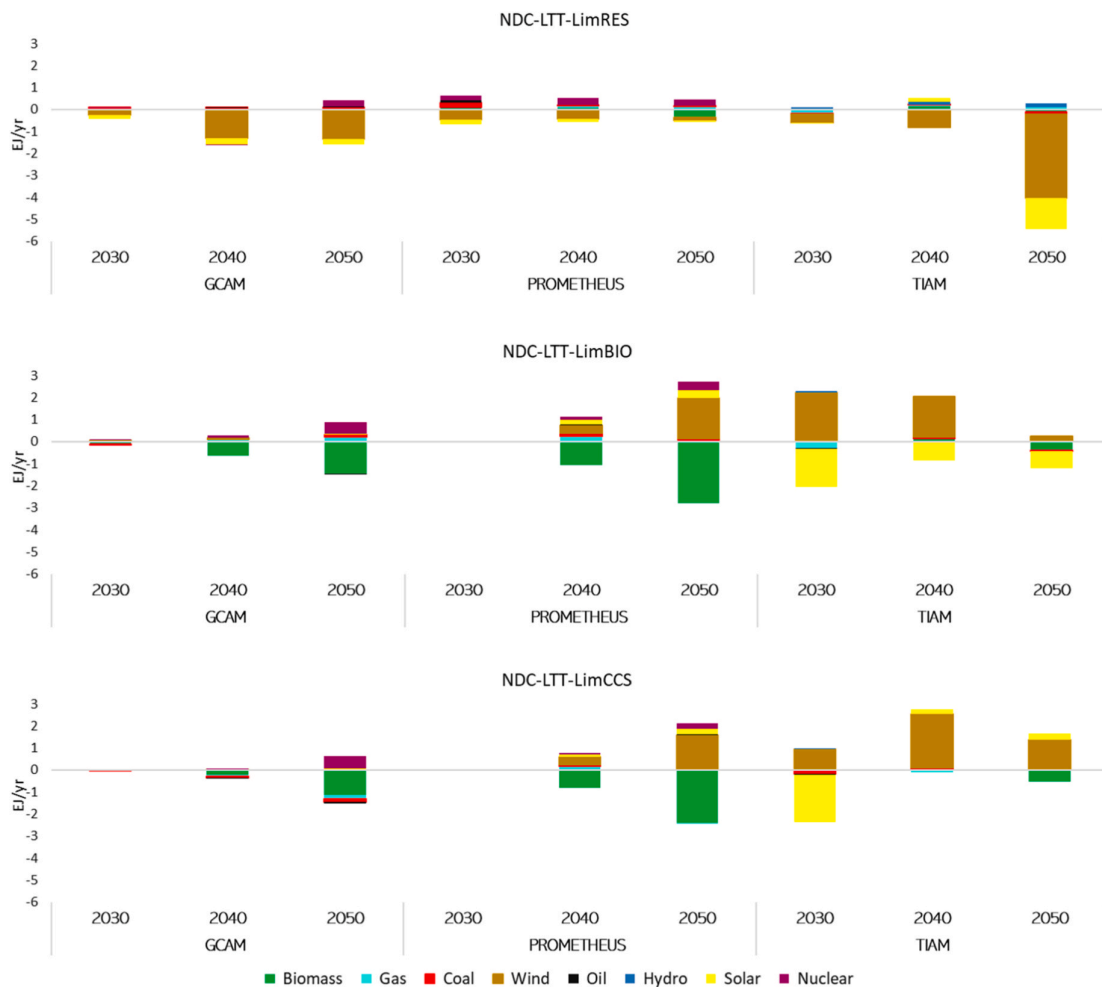
CCS is the most critical emerging technology in decarbonising heavy industry. Constraining it would primarily result in increased industrial emissions compared to the baseline scenario, as there are limited alternatives to decarbonise specific industrial processes. The three IAMs show different responses, with PROMETHEUS again pointing to small effects in the energy mix, as mitigation options are already optimally used and additional efficiency improvements are introduced. Both GCAM and TIAM project an increased use of solids (especially biomass) that compensate for reduced electricity, driven by higher electricity prices (GCAM), or gas (TIAM). Without CCS, heavy industry—including cement and steel manufacturing—face challenges in maintaining production levels, resulting in a decline in heat generation (−0.2 EJ and −0.35 EJ in 2040 and 2050, respectively, in TIAM). Industries would, in this case, turn to solids as an alternative to meet industrial demand despite the environmental drawbacks, highlighting the need for a more adaptive and resilient mitigation strategy in the bloc's industry in the case CCS technologies are not available at scale to the levels typically

projected/expected towards net zero [38].

### 3.3.4. Resilience of a crippled EU power sector

The power sector is expected to become net zero much earlier than 2050 in the NDC-LTT (baseline) scenario to enable decarbonisation in all other sectors, mainly based on the rapid uptake of renewables (especially wind and solar driven by accelerated cost reductions and enhanced grid integration accompanied by storage) and phaseout of fossil-fired power plants. In this baseline scenario, solar power grows to 17–23% of the EU electricity mix by 2050, while wind emerges as the dominant power generation source (39–54%). Other low-carbon options are also deployed, to either complement variable renewables and provide flexibility (e.g., biomass, hydro) or provide zero-carbon baseload (e.g., nuclear, where politically acceptable).

The limited RES scenario would expectedly impede wind and solar growth the most, delaying the phaseout of coal and oil, especially in countries where generation from these sources remains critical for grid stability—as also reflected in an increase even, albeit limited, of fossil fuels (PROMETHEUS) until 2030. Despite the constraints and increased



**Fig. 7.** Differences in EU power generation fuel mix between alternative scenarios and the baseline scenario for the period 2030–2050. The figure illustrates how constraints on key clean energy technologies—renewables, batteries, biomass, and CCS—affect the decarbonisation trajectory of the EU power sector across three Integrated Assessment Models (GCAM, PROMETHEUS, and TIAM). In the baseline scenario, rapid deployment of solar and wind enables early decarbonisation, supported by flexible and baseload low-carbon options such as hydro, biomass, and nuclear. Technology constraints introduce shifts in the generation mix: limited RES and battery availability delay the phaseout of fossil fuels and increase reliance on dispatchable clean sources, particularly nuclear. Biomass constraints reduce BECCS potential, prompting compensatory increases in wind and solar (especially in PROMETHEUS and GCAM), while TIAM shows early solar losses due to its perfect foresight logic and time-slice optimisation. CCS limitations similarly reduce BECCS deployment, leading to increased investments in wind, solar, and nuclear, with model-specific dynamics shaping the timing and magnitude of these shifts.

costs of solar, wind and storage, the EU power sector would still decarbonise before 2050, as models turn to other dispatchable clean energy technologies (hydro, nuclear) to make up for the lost solar- and wind-based generation. The share of nuclear power grows in GCAM and PROMETHEUS, reflecting policies in those member states that are open to lifetime extension of existing reactors or to development of next-generation technologies (e.g., small modular reactors). The role of biomass remains limited, as the three IAMs focus only on the sustainable use of biomass resources and prioritise its use for high-value applications in sectors with limited mitigation options (i.e., increased use of biofuels in transport)—PROMETHEUS even shows a decline in biomass use for power generation in 2050 (−0.4 EJ) as there is smaller need for flexible options to manage the variability of solar and wind (Fig. 7).

A cap on biomass would automatically hamper the potential to generate net negative emissions using BECCS. The impact is more pronounced in PROMETHEUS that prioritises the use of the limited biomass resources in harder-to-abate sectors, namely transport and industry, meaning other low-carbon technologies are upscaled to compensate, including onshore and offshore wind and solar PV, in line with the near-term ambition set in the EU's Renewable Energy Directive (RED II) [51]. TIAM suggests a drop in solar energy with reductions of 1.8 EJ in 2030 and about 0.8 EJ from 2040 onwards. This is because TIAM optimises model solution along the entire horizon on the time slice level, contrary to the other two IAMs, meaning that a cap on biomass forces the model to seek alternatives that can substitute it throughout all time slices of a day—which is not the case for solar, given the absence of battery technology development until later. Nuclear is seen as a reliable alternative in PROMETHEUS and GCAM (about +0.5 EJ by 2050), highlighting the potential of nuclear power to offset biomass limitations in power sector decarbonisation [52]. Gas demand would, in this case, also increase—either as a transition fuel in the near term (PROMETHEUS) or as a bridging fuel coupled with CCS in the longer term (GCAM).

Constraints on CCS would have a similar, lingering effect, in terms of significantly reducing BECCS deployment for power generation [53,54]. Making up for it could come in the form of increased wind investments (in PROMETHEUS that again prioritises biomass use in hard-to-abate sectors, as well as TIAM). Again, nuclear deployment would also grow to substitute for the CCS limitations, and so would solar power. However, this is not the case for TIAM, where solar showcases losses in 2030: like in the case of biomass constraints, and in tandem with its perfect foresight nature dictating that a priori knowledge of later cost-effectiveness of solar, this IAM is instead seeking to substitute CCS across all time slices in the day, as is the case with wind, before eventually a marked increase in solar by 2050 (+2.5 EJ), which is driven by advancements in battery storage and system integration.

#### 4. Discussion

Our results suggest that potential limitations onto any of the technologies that are critical for the EU energy system and its transformation towards net zero, including renewables and batteries, biomass, and CCS, could pose different but significant risks to the bloc and jeopardise its climate goals in the near (NDC) and longer term (net zero)—particularly in sectors heavily reliant on these technologies—increasing transition costs and reducing energy security.

##### 4.1. Risks from constraints on renewables and storage

Restrictions on the uptake of renewable energy and battery storage could compromise the region's ability to fully decarbonise the energy sector, leading to increased reliance on fossil fuels, particularly gas and coal. This would create tensions between policies aiming at rapid decarbonisation and pragmatically ensuring affordable and reliable energy supply. Our findings suggest that storage and grid flexibility are critical enablers of higher RES penetration and show that batteries could play a more pivotal role by 2040, particularly as transport and heating

sectors are increasingly electrified. The International Renewable Energy Agency (IRENA) [54] recently emphasised that battery storage is essential for integrating large-scale renewable energy capacity into the grid. Without sufficient storage, renewables become less viable as they may face grid integration bottlenecks and high curtailment risks, forcing the energy system to revert to more stable, but carbon-intensive sources. This aligns with the European Environment Agency's recent state and outlook report [55]: while the current deployment of renewable capacity in the EU stands at levels compatible with its goals, energy storage infrastructure appears to lag behind, risking bottlenecks for further integration. IEA's Global Energy Review [56] also highlights that, in the absence of sufficient energy storage, gas-fired power plants may see increased use as a backup for intermittent renewable power. Regardless of the factors driving such developments (e.g., geopolitical disruptions, environmental trade-offs and/or societal opposition [57]), longer-term RES targets could also be undermined by technological lock-ins following new investments in gas infrastructure [58] or even a nuclear renaissance, in a post-Ukraine war world and/or driven by the energy needs of the artificial intelligence revolution [59].

##### 4.2. Uncertainties in biomass availability

Traditionally deemed a renewable resource, biomass faces criticism over its overall sustainability, particularly in the light of competition with food production and biodiversity concerns. IRENA [60] highlights that biomass can play a critical role in future energy systems, but its availability and sustainability are increasingly contested. Should biomass availability be stressed in the future, mitigation efforts in hard-to-abate sectors like heavy industry and transport would be heavily impacted, where low-carbon alternatives are limited. This could drive increases in imported oil and gas to make up for the lost biomass. The economy, however, would see different impacts, depending on the resource's role in the decarbonisation roadmap: strained biomass resources might be best put to use in harder-to-abate sectors or in sectors needing negative emissions to offset remaining emissions—in the latter case, wide-scale deployment of BECCS technologies, which is prerequisite to achieving long-term emissions goals in most modelled pathways [61], would not be an option. With limited biomass use, increased reliance on imported fossil fuels could lead to a less resilient energy system that is susceptible to price volatility and geopolitical tensions, as illustrated by the profound energy price impacts of the recent energy crisis. Nuclear energy could replace biomass use for electricity generation in the longer term, according to our results, and these findings align with recent discussions within the EU on extending the lifetime of existing nuclear plants and investing in technologies such as small modular reactors (SMRs) [62]—acknowledging that nuclear power is among those technologies that could also be severely constrained (e.g., due to concerns over safety, waste disposal, and public acceptance) but are not examined in our scenario design.

##### 4.3. CCS, a critical technology in the long run

CCS technologies are also critical in mitigating emissions from fossil fuel use in industry, but also in power generation. However, their role in the transition is not as prominent in this decade and, if taken out of the equation, our results show negligible impacts in the short term. In the longer run, however, in the absence of CCS, reliance on fossil fuels in industrial sectors would persist at high levels, while biomass use would no longer be a lever for net-negative emissions in electricity [63]. IEA [64] also suggests that, without at-scale CCS availability, gas and coal might still play a big role in Europe's energy system, especially in regions with slower infrastructure development. The risks in such a case are clearly reflected in our model runs: the EU would rely longer on fossil fuels and thus struggle to meet its net-zero emissions target in time.

#### 4.4. Towards a just transition: balancing climate ambition with socioeconomic resilience

Technological constraints and geopolitical tensions do not only impact the achievement of EU climate targets, clean technology deployment, and energy security; they also come with important socioeconomic repercussions. In particular, our modelling analysis showed overall increases in total energy system costs in the EU in case of technological limitations; this ranges from 5 to 6% in the *LimBio* scenario, 5–9% in *LimCCS*, and 6–10% in *LimRES*. Higher energy system costs would come on top of the mitigation costs of achieving the EU's NDC and LTT targets and may pose significant challenges to final energy consumers (industries, households, businesses), who would ultimately pay for these increases. Increased energy prices would increase the risks of energy poverty and affordability for EU households and threaten industrial competitiveness with increasing risks of relocation of manufacturing activities outside the EU. The EU climate policy framework should thus be well integrated with the broader social and industrial policies to ensure a just transition that improves, rather than hampers, socioeconomic resilience.

#### 4.5. Limitations and future work on compound risks

An important caveat of our analysis lies in the individual assessment of each technology constraint, while in reality technological limitations may be intertwined if certain risks materialise; for example, geopolitical tensions or protectionist measures may impede the imports of PV modules necessary for the solar power deployment levels compatible with the EU's climate goals, while capping biomass imports and delaying CCS research and development and knowledge sharing in a fragmented world. Moreover, a multiplicity of risks and/or unfavourable developments may play out at the same time, meaning that constraints may be imposed onto various technologies here examined independently. Our motivation, however, has not been to develop a multi-dimensional option space (e.g., Ref. [65]) in response to different risk levels or constraints, but to provide policy-relevant insights into what each technology constraint may bring about in the EU's energy system transformation. Future work could, therefore, put together storylines of factors imposing constraints on a diversity of technologies to different extents with the help of experts or stakeholders [66], with a focus on multi-factor resilience.

#### 4.6. The importance of integrating constraints into the model frameworks

Another important consideration lies in the model ensemble itself and the way constraints such as the ones examined may be interpreted based on the modelling theory underlying our three IAMs: despite securing some diversity in mathematical framework (optimisation vs simulation), solution horizon (inter-temporal vs. recursive-dynamic optimisation), time slicing, or technology choice (logit vs. winner-takes-all)—see Table 1—we acknowledge that technology constraints may come about along the way [67]—meaning that stranded assets and associated costs are not realistically modelled. Although not explicitly modelled in terms of financial losses or asset write-offs, stranded capacity is reflected through reduced utilisation rates. For instance, in the combination of NDCs and LTTs scenario, much of the coal capacity installed in recent years becomes underutilised or idle, indicating stranded assets through low-capacity factors relative to technical availability. We also acknowledge that little focus has been placed on alternative cleantech options, such as wave and tidal energy, enhanced geothermal systems, circular economy, or green hydrogen; despite limited model representation, the EU policy framework should consider investing in and accelerating innovation in these directions towards reducing costs and overcoming technical barriers in a coordinated effort, to reduce the risks if one of option fails to deliver and to increase overall resilience towards climate neutrality.

#### 4.7. Outlook for stronger and better integrated policy

Additional analysis is needed in hard-to-decarbonise end-use sectors like heavy industry, where constraints in biomass and/or CCS are likely to increase both reliance on fossil fuels and production costs with significant impacts on competitiveness and potential industrial relocation. Policymakers should consider implementing stronger regulatory frameworks for energy storage, especially in the face of growing geopolitical tensions that could disrupt supply chains for batteries and critical minerals. Given that geopolitical tensions, such as trade disputes and resource nationalism [67], are key drivers of technology constraints, policies must ensure supply-chain diversification while reinforcing ties with preferable international suppliers and considering the development of strategic reserves for critical materials like lithium and rare earths. Finally, it is crucial to link energy policy with foreign/trade policy to mitigate the impact of geopolitical risks in cleantech deployment; developing a resilient energy system adaptable to disruptions in global trade is paramount to achieving the bloc's climate goals cost-effectively and ensuring energy security.

### 5. Concluding remarks

This research presents a comprehensive analysis of the challenges for and impacts on the EU's energy transition under scenarios where key clean technologies are constrained in the future due to factors such as geopolitical tensions and/or protectionist policies, unavailability of resources, limited technological development and maturity, societal resistance, etc. Although such developments could impact any technology in the energy mix, we focus on those technologies that would be impacted the most: renewables and battery storage, biomass, and carbon capture and storage. These are capped to specific levels, the implications for cost adjustments of which are quantified in an input/output model (MARIO), towards assessing how these adjustments in turn could impact the EU's energy-system transformation and capacity to achieve its near- and long-term climate goals. We use three well-established IAMs of different economic theory and solution paradigm, offering distinct perspectives on the potential consequences of these limitations (GCAM, PROMETHEUS, and TIAM).

While the EU's commitment to climate neutrality remains firm, pathways to achieving this goal require coordination efforts, robust policy frameworks, and continuous cleantech innovation. Our findings are consistent with recent literature, emphasising the importance of cleantech (infrastructure) in achieving net-zero targets: without robust infrastructure for sufficient battery storage and CCS, there is a real risk the EU backslides into higher carbon emissions from fossil fuels. Limitations on RES and battery deployment would delay progress toward grid decarbonisation, reinforcing reliance on natural gas; despite efforts to accelerate renewable deployment in the bloc, the lack of storage capabilities would render renewables less effective, thereby reducing their share in the energy mix. Likewise, relative biomass unavailability would increase dependence on imported fuels, exposing the EU to geopolitical vulnerabilities and potential price volatility in global energy markets. Similarly, constraints on CCS technologies would reduce the viability of low-carbon options, including biomass, which are essential for net-negative emissions in electricity. Apart from interdependence between the two latter technologies, in case of constraints on one or the other, we also see that the role of nuclear power may become increasingly important, albeit also highly prone to uncertainty and political decisions.

Finally, our study shows that any constraints in the uptake of low-carbon technologies would not only jeopardise the bloc's long-term targets but also increase the cost of decarbonisation for European industries and households. The extent of emissions increase crucially depends on the potential of low-carbon options to replace those constrained. CCS and biomass limitations considerably risk failures in climate targets, as there exist limited alternatives, especially in heavy

industry and transportation—in contrast to limitations in renewables, where effective (albeit costlier) domestic substitutes can be used instead. Low-carbon technology limitations would also increase transition costs for European consumers and the risks for industrial relocation of heavy industry. It is thus paramount for the EU climate policy framework to be efficiently integrated into the broader societal, industrial, and trade policy efforts towards reducing the risks of technology failures and ensuring a resilient, cost-efficient, and just transition towards climate neutrality.

#### Credit author statement

Panagiotis Fragkos: Conceptualization, Methodology, Supervision, Writing – review & editing.

Conceptualization, Visualization, Writing – original draft.

Methodology, Software, Writing – review & editing.

Software, Investigation, Validation, Writing – review & editing.

Software, Formal Analysis.

Matteo Rocco: Validation, Writing – Review & Editing.

Writing – review & editing.

Writing – review & editing.

Conall Heussaff: Writing – Review & Editing.

Conceptualization, Methodology, Writing – original draft, Supervision.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

Data will be made available on request.

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