

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

Panagiotis Fragkos<sup>1</sup>, Maria Iro Baka<sup>1</sup>, Eleftheria Zisarou<sup>1</sup>, Dirk-Jan Van De Ven<sup>2</sup>, Shivika Mittal<sup>3</sup>, Lorenzo Rinaldi<sup>4</sup>, Matteo Rocco<sup>4</sup>, Clàudia Rodés-Bachs<sup>2</sup>, Natasha Frilingou<sup>5</sup>, Conall Heussaff<sup>6</sup>, Alexandros Nikas<sup>5</sup>

<sup>1</sup> E3Modelling S.A., Athens, Greece

<sup>2</sup> Basque Centre for Climate Change (BC3), Leioa, Spain

<sup>3</sup> CICERO Centre for International Climate and Environmental Research Oslo, Oslo, Norway

<sup>4</sup> Department of Energy, Politecnico di Milano, Milan, Italy

<sup>5</sup> Energy Policy Unit, School of Electrical & Computer Engineering, National Technical University of Athens, Athens, Greece

<sup>6</sup> Bruegel, Brussels, Belgium

### **Highlights:**

We simulate impacts of socioeconomic, technical, trade/geopolitical, etc. constraints

Limited uptake of renewables intensifies reliance on gas, slowing the EU's transition

Biomass unavailability challenges the bloc's energy security, increasing fuel imports

Constraints on CCS development hamper biomass use & enhance the role of nuclear power

Our modelling exercise highlights the need for resilient energy system transformation

**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.

**Keywords:** European Union; Integrated Assessment Model; Technology; Climate Policy; Geopolitics; Trade

# 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. Policies 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 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. Among others, the large-scale and rapid expansion of renewable energy sources (RES), the development and deployment of carbon capture and storage (CCS), and the sustainable utilisation of biomass are key priorities. By heavily relying on these technologies, however, the envisaged transition may be up against considerable uncertainty, be that due to supply-chain disruptions, technological bottlenecks, or socio-political factors, any of which may impede the region's ability to meet its climate objectives in time.

A critical factor that could influence cleantech deployment is the availability of rare earths and critical materials [4]. These resources are essential for several vital low-carbon technologies, such as wind turbines and batteries, but are heavily concentrated in few regions outside the EU. China dominates the value chain of such elements [5], supplying the largest chunk of rare earths like neodymium and dysprosium, which are vital for permanent magnets used in wind turbines and electric vehicle (EV) motors. The EU's lithium imports, which are critical for battery technologies, are sourced from Australia and Chile [6], while the majority of its cobalt comes from the Democratic Republic of Congo [7]. Dependence on imports of rare earths and other strategic materials leaves the bloc vulnerable to supply disruptions caused by geopolitical tensions, trade restrictions, or market volatility. This was, for instance, the case in 2010, when China significantly reduced its export quotas due to environmental concerns and its need to conserve resources for domestic industries [8], heavily impacting European industry, causing delays in production and manufacturing particularly in the electronics, clean energy, and defense sectors [9]. Of course, the European energy system status quo is already prone to similar uncertainties and geopolitical risks, as the Russia-Ukraine conflict also showcased recently, and this is why, for the EU, achieving its ambitious climate targets is vital not only in the context of climate change mitigation but also for the purposes of enhancing its energy security, boosting its international competitiveness, and reducing its reliance on fossil fuel imports. Moreover, despite picking up pace [10], RES diffusion in the EU remains constrained by factors such as intermittent supply, grid limitations, and slow expansion of storage capabilities in most Member States [11]. Bioenergy, a critical piece of the EU's RES strategy puzzle, faces challenges related to land-use and food competition, particularly in terms of needs for food crops and forest protection. To add to a long list of potential cleantech bottlenecks, lack of public acceptance may further impede the transition; societal opposition to large-scale infrastructure projects concerns not only wind and solar farms,

but also CCS technologies, which are expected to play a key role in removing residual emissions but currently feature a rather small pipeline of mature projects and face strong commercialisation challenges [11].

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, Integrated Assessment Models (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., [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.

Our research tries to address this gap by adopting a multi-dimensional approach to assessing the risks posed by technological constraints on achieving climate targets, focusing on the EU and its latest climate ambition for a transition to a net-zero energy system by 2050. We examine these risks 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. To tackle structural uncertainties, we employ a diverse model ensemble comprising three IAMs of different economic theories, thereby expanding 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. These adjustments are quantified using an Input-Output model that tracks the impacts of geopolitical disruptions on cleantech costs and is soft-linked to the IAM ensemble, providing a robust mechanism to explore the technoeconomic impacts of these constraints.

## 2. Methodology

### 2.1. Models

The 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. To explore the impacts of geopolitical constraints, we use projections from the multi-sectoral MARIO model [25] 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 I<sup>2</sup>AM PARIS platform [26].

GCAM [27] 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 [28] 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 [29]. 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.

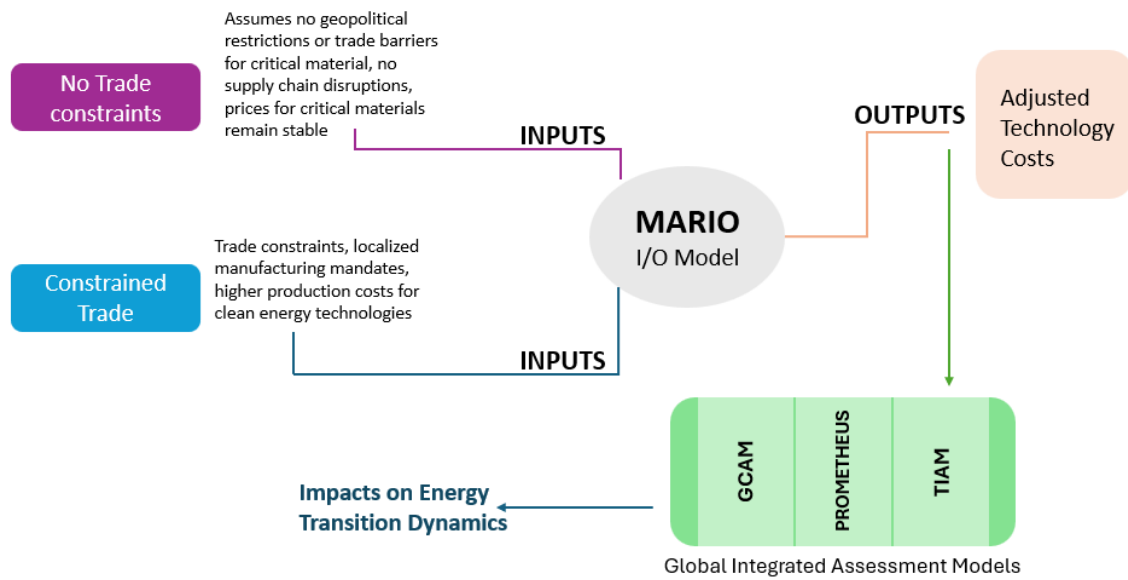
Finally, MARIO [25] is a versatile Python-based framework designed for Input-Output modelling. It facilitates the development and manipulation of Input-Output and Supply-Use models, allowing parsing major databases like EXIOBASE, EORA, and FIGARO, or customised datasets. One of its key features is its 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) [30], 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 **Figure 1** offers a high-level visualisation 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 [31], 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.

**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/dynorio">https://www.i2am-paris.eu/detailed_model_doc/dynorio</a>       |



**Figure 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.

## 2.2. 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 [32], 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.

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

| Scenario               | Short description                                                                                                                                                                                                                                                                                                                                              |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>NDC-LTT</b>         | Implementation of the NDC targets for 2030 and long-term targets for 2050 (e.g., net zero by 2050 in the EU)                                                                                                                                                                                                                                                   |
| <b>NDC-LTT-LimRES</b>  | 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. |
| <b>NDC-LTT-LimBIO</b>  | Restricted use of biomass for energy purposes in the EU, with a cap set at 5-6 EJ by 2050.                                                                                                                                                                                                                                                                     |
| <b>NDC-LTT- LimCCS</b> | Restricted deployment of CCS in the EU, with a cap set at 10-20 Mt CO <sub>2</sub> by 2050.                                                                                                                                                                                                                                                                    |

## 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 (**Figure 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

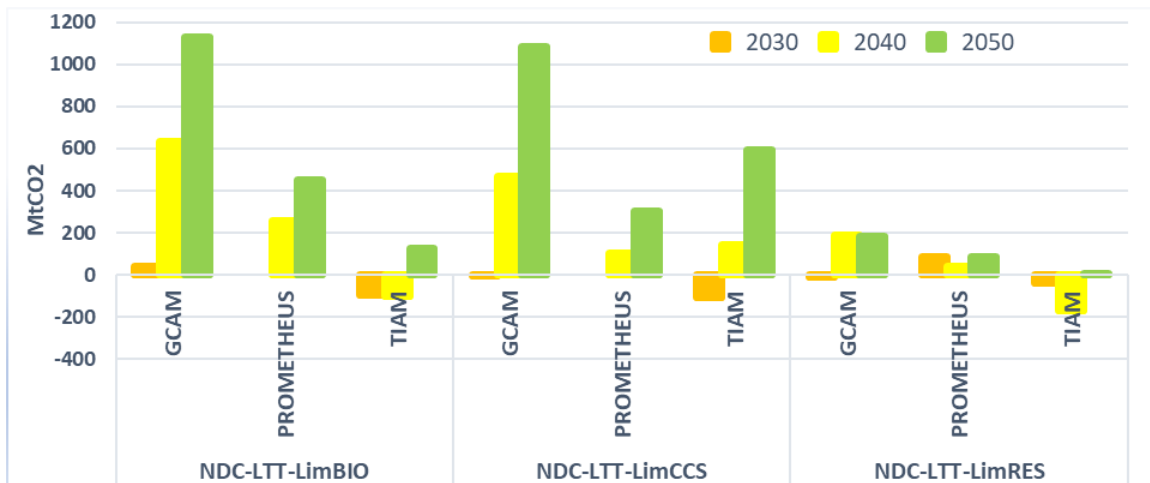
the main drivers of the projected RES growth and EV uptake by 2030, this scenario shows increasingly pronounced impacts on CO<sub>2</sub> emissions post-2030. In 2040, PROMETHEUS and GCAM project an increase in CO<sub>2</sub> emissions, over the baseline, by 40-190 MtCO<sub>2</sub>, primarily due to 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 103Mt 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) [33, 34] and the Intergovernmental Panel on Climate Change (IPCC) [35], 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, 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, 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.



**Figure 2.** Differences in EU CO<sub>2</sub> emissions between alternative scenarios with the baseline scenario in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM.

### 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 (**Figure 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 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.



**Figure 3.** Changes in primary energy consumption by fuel between the alternative scenarios and the baseline scenario in 2030-2050. Source: GCAM and PROMETHEUS

### 3.3. Sectoral insights

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

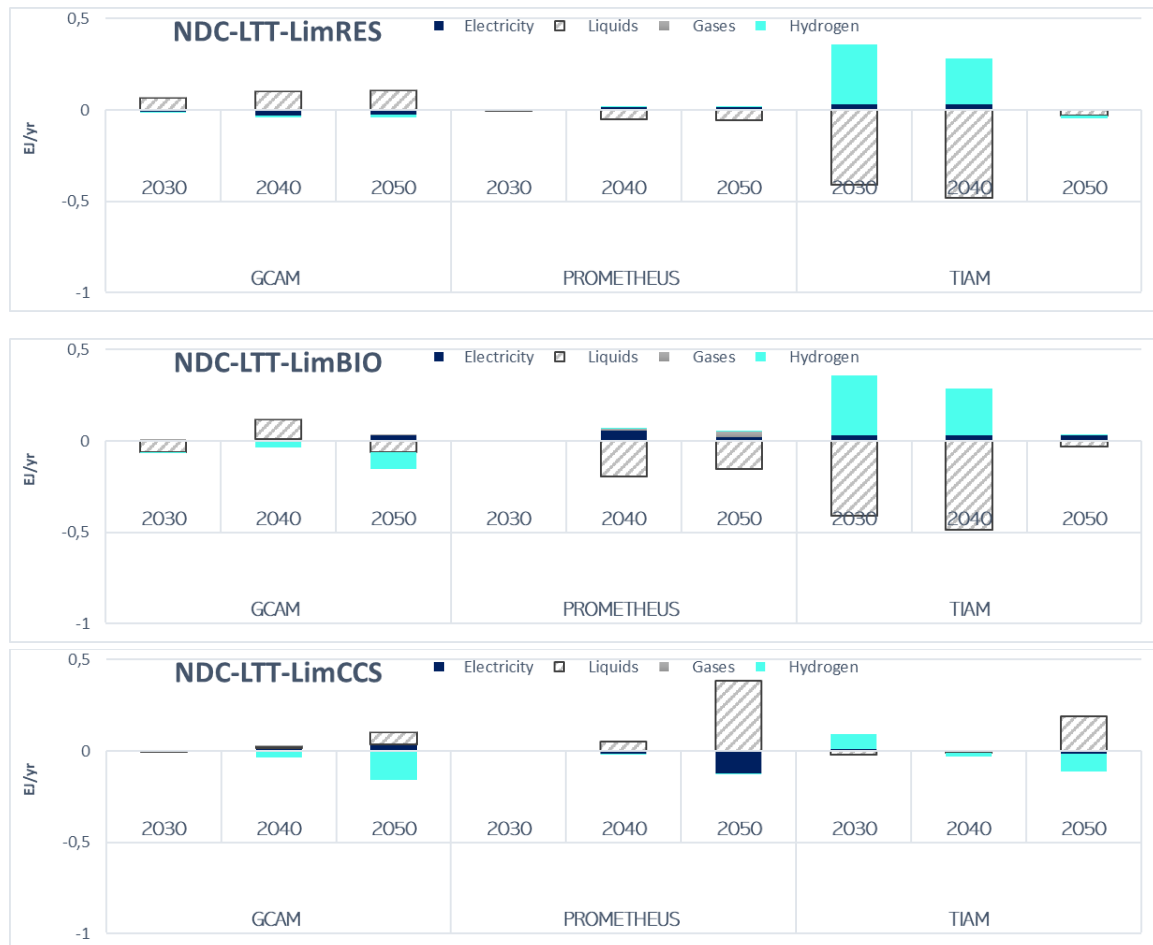
The transport sector has been a top priority in the EU's NDCs and long-term targets, due to its high reliance on fossil fuels, contributing to about a quarter of the bloc's GHG emissions. While there has been some progress in electrification and diffusion of low-carbon fuels such as biofuels, the road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

The limited RES scenario (**Figure 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 [36]. 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 impacts). 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.



**Figure 4.** Differences in transport fuels (comparison of alternative scenarios with the baseline scenario in 2030-2050). Source: GCAM, PROMETHEUS, and TIAM

### 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 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 (**Figure 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), 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.



**Figure 5.** Changes in EU building fuels between alternative scenarios with the baseline scenario in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM.

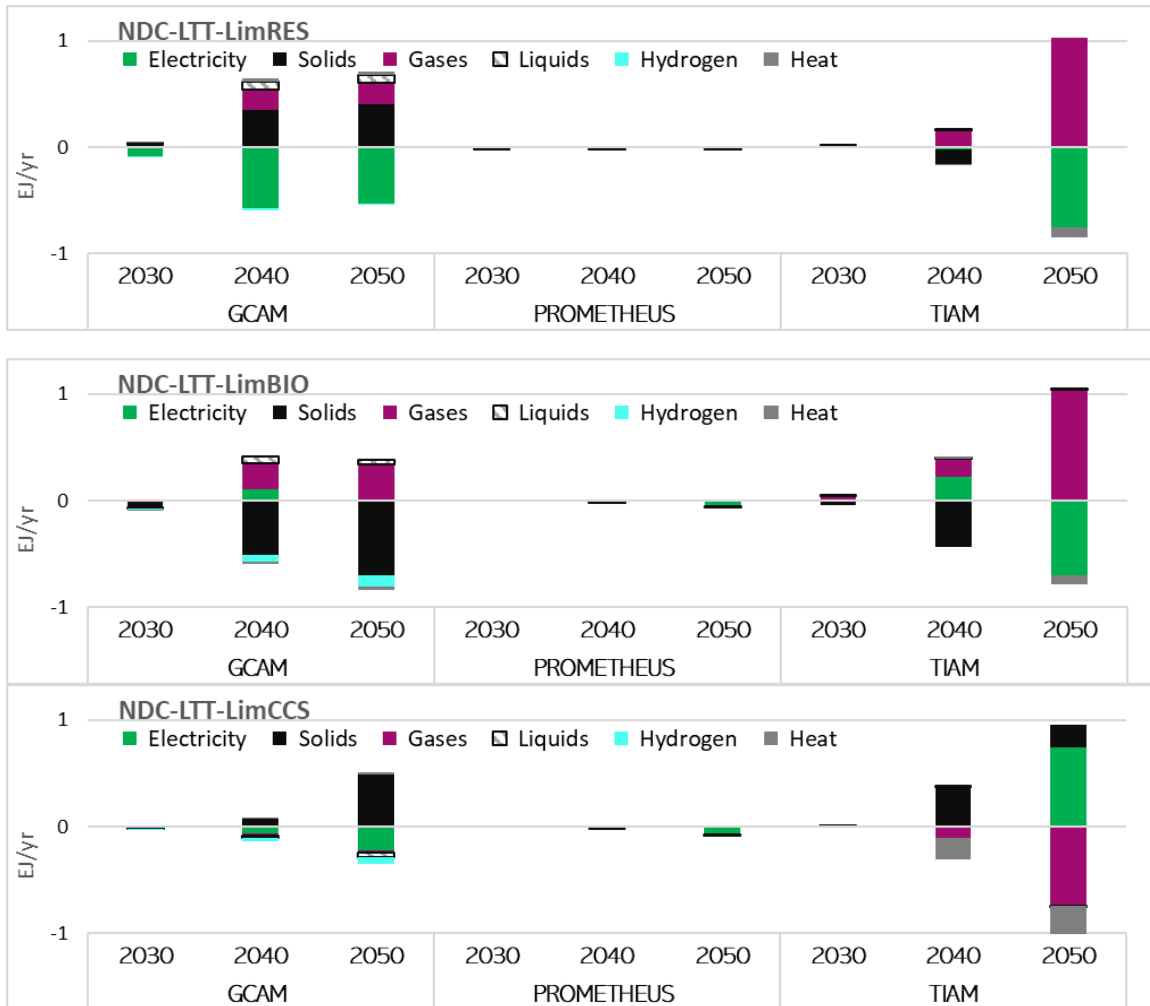
### 3.3.3. Prospects of EU industrial decarbonisation under technology limitations

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 (**Figure 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., [37]). 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 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].



**Figure 6.** Changes in industry fuels under different scenarios compared to the baseline in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM.

### 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 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 (**Figure 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) [39]. 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 [40]. 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 [41, 42]. 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.



**Figure 7.** Changes in power generation fuels across the three constraining scenarios, compared to the baseline in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM.

## 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.

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 attest to storage and grid flexibility being critical enablers of higher RES penetration and show batteries could play a more pivotal role by 2040, particularly as

transport and heating sectors are increasingly electrified. The International Renewable Energy Agency (IRENA) [42] 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 [43]: 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 [44] 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 [45]), longer-term RES targets could also be undermined by technological lock-ins following new investments in gas infrastructure [46] or even a nuclear renaissance, in a post-Ukraine war world and/or driven by the energy needs of the artificial intelligence revolution [47].

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 [48] 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 [49], 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) [50]—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.

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 [51]. IEA [52] 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.

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 5-6% 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.

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 protectionism 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., [53]) 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 [54], with a focus on multi-factor resilience.

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 [55]—meaning that stranded

assets and associated costs are not realistically modelled. 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.

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 [56], 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.

## Acknowledgement

This work was supported by the European Commission Horizon Europe programme “IAM COMPACT” under Grant Agreement No. 101056306. The sole responsibility for the content of this paper lies with the authors; the paper does not necessarily reflect the opinions of the European Commission or the granting authority.

## References

1. Nikas, A., Gambhir, A., Trutnevyte, E., Koasidis, K., Lund, H., Thellufsen, J. Z., ... & Doukas, H. (2021). Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy*, 215, 119153. <https://doi.org/10.1016/j.energy.2020.119153>
2. Council of the European Union. (2023). *Fit for 55: The EU's plan for a green transition*. Retrieved from <https://www.consilium.europa.eu/en/policies/fit-for-55/>

3. European Commission. (2024). *National Energy and Climate Plans (NECPs)*. Retrieved from [https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps\\_en](https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans-necps_en)
4. Gielen, D., & Lyons, M. (2022). *Critical materials for the energy transition: Rare earth elements*. International Renewable Energy Agency. Retrieved from [https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA\\_Rare\\_Earth\\_Elements\\_2022.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Technical-Papers/IRENA_Rare_Earth_Elements_2022.pdf)
5. Depraiter, L., & Goutte, S. (2023). The role and challenges of rare earths in the energy transition. *Resources Policy*, 86, 104137. <https://doi.org/10.1016/j.resourpol.2023.104137>
6. Bille, B. (2024). *Increasing lithium supply security for Europe's growing battery industry: Recommendations for a resilient supply chain*. The Hague Centre for Strategic Studies. Retrieved from <https://hcss.nl/report/lithium-supply-security-europe-battery-industry/>
7. Cobalt Institute. (2022). *Cobalt raw material in the EU: Initiatives overview*. Retrieved from <https://www.cobaltinstitute.org/news/cobalt-raw-material-in-the-eu/>.
8. Hao, Y., & Nakano, J. (2020). *China's rare earth industry and export regime: Economic and strategic implications*. Center for Strategic and International Studies. Retrieved from <https://www.csis.org/analysis/chinas-rare-earth-industry-and-export-regime-economic-and-strategic-implications>
9. European Parliament. (2020). *EU-China trade and investment relations in challenging times*. Retrieved from [https://www.europarl.europa.eu/RegData/etudes/STUD/2020/603492/EXPO\\_STU\(2020\)603492\\_EN.pdf603492\\_EN.pdf603492\\_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2020/603492/EXPO_STU(2020)603492_EN.pdf603492_EN.pdf603492_EN.pdf)
10. International Energy Agency. (2020). *Renewables 2020: Analysis and forecast to 2025*. Retrieved from <https://www.iea.org/reports/renewables-2020>
11. Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>, Licence: CC BY 4.0
12. Nikas, A., Elia, A., Boitier, B., Koasidis, K., Doukas, H., Cassetti, G., ... & Chiodi, A. (2021). Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. *Science of the Total Environment*, 793, 148549.
13. Boitier, B., Nikas, A., Gambhir, A., Koasidis, K., Elia, A., Al-Dabbas, K., ... & Mittal, S. (2023). A multi-model analysis of the EU's path to net zero. *Joule*, 7(12), 2760-2782.
- Emodi, N. V., Rekker, S., Wade, B., & Greig, C. (2022). *A systematic review of barriers to greenfield investment in decarbonization solutions*. *Renewable and Sustainable Energy Reviews*, 112586. <https://doi.org/10.1016/j.rser.2022.112586> [
14. van de Ven, D. J., Mittal, S., Gambhir, A., Lamboll, R. D., Doukas, H., Giarola, S., ... & Nikas, A. (2023). A multimodel analysis of post-Glasgow climate targets and feasibility challenges. *Nature Climate Change*, 13(6), 570-578.
15. Sognnaes, I., Gambhir, A., van de Ven, D. J., Nikas, A., Anger-Kraavi, A., Bui, H., ... & Peters, G. P. (2021). A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nature Climate Change*, 11(12), 1055-1062.
16. Cherp, A., Vinichenko, V., Tosun, J., Gordon, J. A., & Jewell, J. (2021). National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nature Energy*, 6(7), 742-754.
17. Kazlou, T., Cherp, A., & Jewell, J. (2024). Feasible deployment of carbon capture and storage and the requirements of climate targets. *Nature Climate Change*, 14, 1047-1055.

18. Zahasky, C., & Krevor, S. (2020). Global geologic carbon storage requirements of climate change mitigation scenarios. *Energy & Environmental Science*, 13(6), 1561-1567. <https://doi.org/10.1039/D0EE00674B>
19. European Environment Agency. (2013). *EU bioenergy potential*. Publications Office of the European Union. <https://doi.org/10.2800/92247>
20. Segreto, M., Principe, L., Desormeaux, A., Torre, M., Tomassetti, L., Tratzi, P., ... & Petracchini, F. (2020). Trends in social acceptance of renewable energy across Europe—a literature review. *International journal of environmental research and public health*, 17(24), 9161.
21. Nobletz C, Svartzman R and Dikau S (2024) The EU's dependency on critical minerals: meeting decarbonisation targets in the context of geopolitical risk. London: CETEx and Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science
22. Seth Monteith, Laura Aldrete, Tim Lau, Achieving global climate goals by 2050, Pathways to a 1.5oC future, Climateworks, 2023, Available online: <https://www.climateworks.org/report/achieving-global-climate-goals-by-2050-pathways-to-a-1-5-c-future/>
23. Neil Grant, Ajay Gambhir, Shivika Mittal, Chris Greig, Alexandre C. Köberle, Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO<sub>2</sub> storage capacity, *International Journal of Greenhouse Gas Control*, 2022, <https://doi.org/10.1016/j.ijggc.2022.103766>.
24. Keywan Riahi, Elmar Kriegler, Nils Johnson, Christoph Bertram, Michel den Elzen, Jiyong Eom, Michiel Schaeffer, Jae Edmonds, Morna Isaac, Volker Krey, Thomas Longden, Gunnar Luderer, Aurélie Méjean, David L. McCollum, Silvana Mima, Hal Turton, Detlef P. van Vuuren, Kenichi Wada, Valentina Bosetti, Pantelis Capros, Patrick Criqui, Meriem Hamdi-Cherif, Mikiko Kainuma, Ottmar Edenhofer, Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals, *Technological Forecasting and Social Change*, Volume 90, Part A, 2015, Pages 8-23, <https://doi.org/10.1016/j.techfore.2013.09.016>
25. Tahavori MA, Golinucci N, Rinaldi L, Rocco MV, Colombo E 2023 MARIO: A Versatile and User-Friendly Software for Building Input-Output Models. *Journal of Open Research Software*, 11: 14. DOI: <https://doi.org/10.5334/jors.473>
26. IZAM Paris Platform, Modelling Documentation, Available online: <https://www.i2am-paris.eu/>
27. Calvin, Katherine, Pralit Patel, Leon Clarke, Ghassem Asrar, Ben Bond-Lamberty, Ryna Yiyun Cui, Alan Di Vittorio et al. "GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems." *Geoscientific Model Development* 12, no. 2 (2019): 677-698.
28. Fragkos, P., Kouvaritakis, N., & Capros, P. (2015). Incorporating uncertainty into world energy modelling: the PROMETHEUS Model. *Environmental Modeling & Assessment*, 20(5), 549-569.
29. Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Computational Management Science*, 5, 7-40.
30. Lynas, M., Houlton, B. Z., & Perry, S. (2021). Greater than 99% consensus on human caused climate change in the peer-reviewed scientific literature. *Environmental Research Letters*, 16(11), 114005. <https://doi.org/10.1088/1748-9326/ac2966>

31. Merciai, S., & Schmidt, J. (2020). Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. *Journal of Industrial Ecology*, 24(3), 502-515. <https://doi.org/10.1111/jiec.12713> [<https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12713>]
32. Dekker, M. M., Daioglou, V., Pietzcker, R., Rodrigues, R., de Boer, H.-S., Dalla Longa, F., Drouet, L., Emmerling, J., Fattahi, A., Fotiou, T., Fragkos, P., Fricko, O., Gusheva, E., Harmsen, M., Huppmann, D., Kannavou, M., Krey, V., Lombardi, F., Luderer, G., Pfenninger, S., Tsiropoulos, I., Zakeri, B., van der Zwaan, B., Usher, W., & van Vuuren, D. (2023). Identifying energy model fingerprints in mitigation scenarios. *Nature Energy*. <https://doi.org/10.1038/s41560-023-01399-1>
33. IEA (2011), Combining Bioenergy with CCS, IEA, Paris <https://www.iea.org/reports/combining-bioenergy-with-ccs>, Licence: CC BY 4.0
34. IEA (2021), The world has vast capacity to store CO<sub>2</sub>: Net zero means we'll need it, IEA, Paris <https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-we-ll-need-it>
35. IPCC, 2023: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, (in press)
36. IEA (2023), Road transport, IEA, Paris <https://www.iea.org/reports/road-transport>, Licence: CC BY 4.0
37. Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fishedick, M., Lechtenböhmer, S., Solano-Rodriguez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production*, 187, 960-973. <https://doi.org/10.1016/j.jclepro.2018.03.107>
38. Perdana, S., Xexakis, G., Koasidis, K., Vielle, M., Nikas, A., Doukas, H., ... & Boitier, B. (2023). Expert perceptions of game-changing innovations towards net zero. *Energy Strategy Reviews*, 45, 101022.
39. European Parliament and Council of the European Union. (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources*. Official Journal of the European Union, L 328, 82-209. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018L2001>
40. SolarPower Europe & EIT InnoEnergy. (2021). *European Solar Initiative*. Retrieved from <https://www.solarpowereurope.org/advocacy/european-solar-initiative>
41. International Energy Agency. (2022). *Nuclear Power and Secure Energy Transitions*. Retrieved from <https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions>
41. IRENA (2019), Global energy transformation: A roadmap to 2050 (2019 edition), International Renewable Energy Agency, Abu Dhabi.
42. European Environment Agency, 2020, The European environment — state and outlook 2020, Available online: <https://www.eea.europa.eu/soer/publications/soer-2020>
43. IEA (2022), World Energy Outlook 2022, IEA, Paris <https://www.iea.org/reports/world-energy-outlook-2022>, Licence: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

44. Doukas, H., Nikas, A., Stamtsis, G., & Tsipouridis, I. (2020). The green versus green trap and a way forward. *Energies*, 13(20), 5473.
45. Kemfert, C., Präger, F., Braunger, I., Hoffart, F. M., & Brauers, H. (2022). The expansion of natural gas infrastructure puts energy transitions at risk. *Nature Energy*, 7(7), 582-587.
46. Castelveccchi, D. (2024). Will AI's huge energy demands spur a nuclear renaissance?. *Nature*, 635(8037), 19-20.
47. International Renewable Energy Agency. (2020). *Electricity Storage Valuation Framework: Assessing system value and ensuring project viability*. Abu Dhabi: IRENA. Retrieved from <https://www.irena.org/publications/2020/Mar/Electricity-Storage-Valuation-Framework-2020>
48. Köberle, A. C. (2019). The value of BECCS in IAMs: a review. *Current Sustainable/Renewable Energy Reports*, 6, 107-115.
50. Germany's Nuclear Energy Phase-Out, Explained, 2023, [Nuclear Information and Resource Service](https://www.nirs.org/germanys-nuclear-energy-phase-out-explained/) , Available online: <https://www.nirs.org/germanys-nuclear-energy-phase-out-explained/>
51. Eurostat. (2023). *Bioenergy report outlines progress being made across the EU*. Retrieved from [https://energy.ec.europa.eu/news/bioenergy-report-outlines-progress-being-made-across-eu-2023-10-27\\_en](https://energy.ec.europa.eu/news/bioenergy-report-outlines-progress-being-made-across-eu-2023-10-27_en)
52. International Energy Agency. (2022). *World Energy Outlook 2022*. Retrieved from <https://www.iea.org/reports/world-energy-outlook-2022>
53. Pickering, B., Lombardi, F., & Pfenninger, S. (2022). Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule*, 6(6), 1253-1276.
54. Wachsmuth, J., Warnke, P., Gambhir, A., Giarola, S., Koasidis, K., Mittal, S., ... & Doukas, H. (2023). Co-creating socio-technical scenarios for net-zero emission pathways: Comparison of five national case studies. *Renewable and Sustainable Energy Transition*, 4, 100064.
55. Gambhir, A., Mittal, S., Lamboll, R. D., Grant, N., Bernie, D., Gohar, L., ... & Lowe, J. A. (2023). Adjusting 1.5 degree C climate change mitigation pathways in light of adverse new information. *Nature Communications*, 14(1), 5117.
56. Hermwille, L., Hall, C., Fragkos, P., & Fragkiadakis, K. (2024). *Synergies and Trade-Offs of Climate Change Mitigation Policies: An Integrative Assessment Approach*. NDC ASPECTS. Retrieved from [https://www.ndc-aspects.eu/sites/default/files/2024-03/20240313\\_NDC%20ASPECTS\\_D6-3\\_paperB.pdf](https://www.ndc-aspects.eu/sites/default/files/2024-03/20240313_NDC%20ASPECTS_D6-3_paperB.pdf)