IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

Tech-constrained EU pathways to net zero: Impact of geopolitical disruptions and supply chain shocks

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Policy Brief

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Impact of geopolitical disruptions and supply chain shocks

About the project

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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1. In a nutshell: Takeaways for Policymakers

1. Urgency in strengthening Renewable Energy Capacity

RES plays a pivotal role in reducing carbon emissions, especially in the power sector. However, the findings of this study reveal that constraints on the expansion of renewables (due to material shortages, geopolitical tensions, or cost increases) could slow down decarbonisation. In such a scenario, the EU could see increased reliance on fossil fuels, leading to higher CO_2 emissions compared to the baseline scenario.

Policy Action: Policymakers should prioritise diversifying supply chains for critical materials required for RES and battery technologies while also incentivising domestic production. Policies should also focus on enhancing the resilience of renewable energy infrastructure through investments in energy storage and grid modernisation. Given the EU's dependency on renewables for achieving its 2030 and 2050 climate targets, any delay or limitation in their deployment could lead to significant overshoot (more than 183 Mt CO_2 in 2050 compared to the baseline) of EU's climate targets.

2. Biomass as a strategic resource for decarbonisation

Biomass, especially when combined with CCS (BECCS), is essential for achieving net-negative emissions, a key requirement for offsetting residual emissions from hard-to-abate sectors to ensure that the net-zero target is met. In a scenario constraining biomass availability, results show that the EU would rely more heavily on fossil fuels, increasing CO_2 emissions significantly. The analysis highlights the dual role of biomass in reducing emissions directly and enabling net-negative emissions through the uptake of BECCS.

Policy Action: There is a clear need for policies that support sustainable biomass production and ensure its sufficient availability for energy purposes. This could include the creation of sustainability standards for biomass to address concerns related to land use, food security, and biodiversity. Moreover, the deployment of advanced biofuels, which are less reliant on food crops, should be accelerated to reduce competition with agriculture and enhance biomass's role in decarbonisation.

3. Accelerating the Development of CCS Technologies

Results also show that CCS technologies are critical for reducing emissions from industrial processes and power generation. Without significant CCS deployment, CO_2 emissions would increase (by 305-1148 MtCO_2 in 2050 compared to the baseline), making it difficult for the EU to meet its climate neutrality goal. It would critically hamper BECCS deployment, which is vital for achieving negative emissions to balance residual emissions in sectors like heavy industry, aviation and agriculture.

Policy Action: Policymakers must accelerate the development and deployment of CCS technologies by providing incentives for research and innovation, establishing CO_2 transport and storage infrastructure, and fostering public-private partnerships. Additionally, specific targets for CCS deployment should be integrated into national climate and energy plans (NECPs) and coordination across Member States should be enhanced to scale CCS solutions cost-effectively. Without rapid CCS deployment, the EU's industrial decarbonisation and net-negative emissions may be compromised.

4. Energy Security and Resilience in the Transition

The study highlights potential challenges to energy security, as the scenarios examine limitations to key technologies. For instance, the scenarios constraining biomass and CCS show that the EU would increase its natural gas consumption, which in turn increases reliance on external energy suppliers and raises concerns about energy security, particularly in the light of geopolitical tensions. This reliance on fossil fuels underscores the need for a diverse and resilient energy mix.

Policy Action:	Policymakers should strengthen policies aiming to diversify the EU's energy mix, thereby reducing dependency on imported fossil fuels. This could include investing in low-carbon alternatives and advancing energy storage solutions to complement the intermittent nature of renewable energy. Long-term energy security strategies should also incorporate greater emphasis on demand-side management, energy efficiency measures, and electrification of sectors that currently rely on fossil fuels. Energy efficiency must be elevated as a central pillar in the EU's strategy to meet its net-zero emission goals by 2050. By focusing on energy efficiency, the EU can achieve a 'no regret' solution that not only drives significant CO_2 emissions reductions but also reduces energy consumption and energy costs. This approach minimises vulnerabilities to external geopolitical pressures, reduces reliance on energy imports and the energy import bill, enhances security of energy supply, and mitigates the risk of supply chain disruptions linked to critical technologies. Furthermore, investments in energy efficiency offer economic benefits as they reduce the energy costs for consumers and industries while driving innovation in energy-saving technologies. In this direction, enhanced regulatory frameworks are required as well as financial incentives for energy-efficient solutions and cross-sectoral cooperation to scale up these efforts across residential, industrial, and transport sectors.

5. Balancing Long-Term Climate Ambition with Technological constraints

The scenarios of this study assume limitations to key technologies, which lead to an increase in CO_2 emissions in the EU (ranging in 88-1128 $MtCO_2$ in 2050, depending on model and scenario, compared to the baseline) and compromise the bloc's ability to achieve net-zero targets. These results highlight the need for robust and flexible policies that are adaptive to potential disruptions or limitations in technological deployment.

Policy Action:	Policymakers should adopt a flexible, technology-neutral approach to decarbonisation, ensuring that multiple pathways are available to meet climate targets. This could include fostering innovation across a broad range of low-carbon technologies, such as advanced nuclear, hydrogen, and energy storage, while maintaining a strong focus on reducing emissions through demand-side measures like energy efficiency and behavioural changes.

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2. Introduction

IAM COMPACT is a Horizon Europe research project, with the objective to support the assessment of global climate goals, the collective progress towards them, and the feasibility space in delivering on those goals. It aims to involve relevant stakeholders in the process to help promote acceptable, robust, sustainable transitions, as well as to enhance trust on both ends, yielding outputs intelligible in terms of real-world implications and actionable in terms of concrete policy recommendations.

The European Union (EU) has committed to achieving net-zero greenhouse gas (GHG) emissions by 2050, in line with its Nationally Determined Contributions (NDCs) and Long-Term Targets (LTTs) under the Paris Agreement. To achieve these ambitious targets, a rapid phase-out of fossil fuels is required, combined with an accelerated deployment of key decarbonisation technologies. However, the scalability of these technologies is increasingly constrained by geopolitical risks, supply chain disruptions, environmental considerations, and resource limitations. These challenges can delay the deployment of key technologies such as solar panels, wind turbines, electric vehicles, battery storage systems, Carbon Capture and Storage (CCS), biomass and underpin the EU's climate ambitions.

This policy brief, part of the *Global Effects* theme within IAM COMPACT, investigates how supply chain constraints and geopolitical uncertainties may hinder the EU's decarbonisation efforts. Using three leading Integrated Assessment Models (IAMs), the analysis evaluates the implications of limitations and constraints in the uptake of key low-carbon technologies by developing four scenarios. The baseline scenario (*NDC-LTT*) implements the NDC targets for 2030 and the long-term mitigation goals for 2050. Three additional scenarios examine the impact of constraints on the uptake of 1) renewable energy and batteries, 2) biomass, and 3) carbon capture and storage (CCS), all critical for decarbonisation.

The brief aims to evaluate the risks and challenges faced by the EU's decarbonisation pathways and suggests strategies to enhance resilience against external disruptions. Key questions include:

1. How do supply chain constraints impact the ramp-up of clean technologies?

2. Are specific configurations of the EU's energy system more vulnerable to geopolitical disruptions?

3. How resilient are transition pathways if certain low-carbon technologies are unavailable?

This brief aims to provide policy-relevant insights to stakeholders and policymakers to better anticipate and address the risks posed by geopolitical and technological factors, ensuring a cost-efficient and resilient transition to a low-carbon economy. It emphasises the importance of building resilient, net-zero energy systems that can adapt to challenges and uncertainties. The results provide insights into the CO_2 emissions, primary energy supply, and electricity generation implications of geopolitical constraints and technology limitations. The findings highlight the importance of strategic planning, global cooperation, and diversification of supply chains to mitigate the risks associated with the decarbonisation challenge. The analysis shows that EU decarbonisation is heavily reliant on:

- the supply of zero-emission electricity (which underscores risks in renewable energy deployment, critical materials, grid infrastructure, and energy storage),
- low-carbon technologies and fuels for transportation (challenges in accelerating the upscale of electric vehicles and low-carbon fuels),
- slower decarbonisation in industry and power generation (dependency on CCS and bioenergy).

Moreover, policymakers need to explore alternative strategies to ensure the robustness and resilience of the EU's transition towards a low-carbon future.

3. Assumptions

This study assesses low-carbon transition pathways by implementing disruptions from geopolitical events and technological limitations in existing IAM COMPACT scenarios developed using global IAMs, focusing on supply chain constraints of specific clean energy technologies. Four scenarios are considered (*Figure 1*).

1. **Baseline scenario (*NDC-LTT*)** assumes the implementation of NDCs for 2030 and LTTs across countries. NDCs represent short-term climate ambitions, while LTTs are more ambitious but often lack concrete policy backing.

Building on the *NDC-LTT* scenario, this study introduces three additional cases to analyse the impacts of clean technology limitations on achieving European climate targets for 2030 and 2050:

2. **Limited renewable energy sources (RES) scenario (*NDC-LTT-LimRES*)** envisions challenges in adopting renewable energy, batteries, and electric vehicles due to geopolitical issues and material shortages, complicating the transition to sustainable energy systems.
3. **Limited biomass scenario (*NDC-LTT-LimBio*)** assumes a reduction in biomass usage in the energy mix due to environmental concerns and resource competition, necessitating alternative energy sources. Biomass consumption in the EU27 is projected to be limited to 5-6 EJ by 2050 (based on recent literature).
4. **Limited CCS scenario (*NDC-LTT-LimCCS*)** envisions constrained deployment of CCS technologies due to technological and social challenges. We assume CCS deployment is limited to 10-20 $MtCO_2$ by 2050, based on current pilot projects in EU countries.

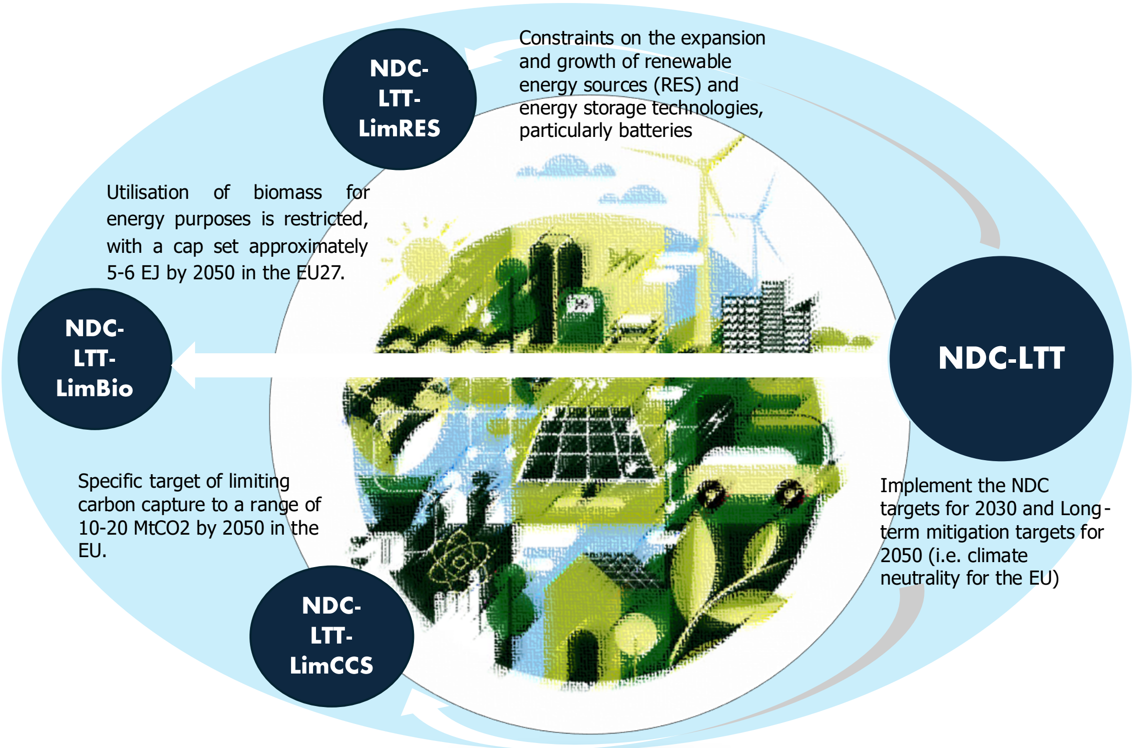

Figure 1. Illustration of disruptive scenarios.

All constrained scenarios use the same carbon pricing and policy framework as the *NDC-LTT* scenario, isolating the effects of technology limitations.

More detailed descriptions of the three IAMs used (GCAM, PROMETHEUS, and TIAM) can be found in the IAM PARIS platform[1].

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4. Model insights

4.1 The impact of technology constraints on EU climate targets

Table 1: Stakeholders' questions, key results, and implications on EU climate targets

Research Question	**Short answer**	**Key results**[1]	**Implications**
What would the impact of limiting renewable energy and battery technologies be on CO_2 emissions?	Limiting the growth of RES and batteries would increase the EU's reliance on fossil fuels and, thus, its CO_2 emissions.	In this scenario, our models project that CO_2 emissions in the EU could increase by 88 $MtCO_2$ by 2050 compared to the baseline.	This could lead to the EU missing its 2050 climate neutrality goal, underscoring the critical role of RES and energy storage. By 2030, limiting these key technologies would significantly slow down decarbonisation. This could jeopardise interim climate goals, making it harder and costlier for the EU to meet its 2050 climate targets.
How would limiting biomass availability affect emissions and energy security?	Biomass is identified as a strategic solution to replace fossil fuels, but constraints due to food security concerns could increase reliance on carbon-intensive energy sources.	In this scenario, our models project that the drop in bioenergy availability could raise EU CO_2 emissions by 255-636 $MtCO_2$ in 2040 and 125-1129 $MtCO_2$ in 2050, compared to the baseline.	By 2030, CO_2 emissions would increase, as alternative low-carbon energy sources may not be able to scale up quickly enough. The EU's pathway to net-zero emissions heavily relies on the uptake of bioenergy to replace fossil fuel use and/or generate net negative emissions via Bioenergy with Carbon Capture and Storage (BECCS) and limiting it would weaken resilience and yield increased use of fossil fuels.
What would the implications of limiting CCS development be on emission reductions?	CCS deployment is vital for capturing industrial and power generation emissions. Therefore, if constrained, emissions would increase significantly.	In this scenario, CO_2 our models suggest that emissions in the EU could rise by up to 103-497 $MtCO_2$ by 2040 and 305-1148 $MtCO_2$ by 2050 compared to the baseline.	By 2030, limiting CCS would have a minimal impact on emission cuts, as CCS technologies are expected to play a larger role post-2030. However, by 2050, this would significantly hinder decarbonisation, particularly in hard-to-abate sectors like heavy industry or power. This stresses the urgent need to scale up cost-effective CCS technology.
How do the models differ in terms of reliance on biomass and CCS?	GCAM shows stronger reliance on these technologies compared to PROMETHEUS and TIAM; the latter rely more on RES uptake and electrification.		Policymakers must ensure a diversified strategy towards net zero that strengthens resilience against technological and material constraints.

[1] Results constitute a range representing the variation in emissions according to modelling results.

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4.2 The impact of technology constraints on the EU's primary energy mix

What would the impact of limiting renewable energy be on the primary energy mix?

Despite the considered constraints on RES, the EU's power sector is still projected to double in size, with renewables making up the largest chunk of primary energy mix by 2050. By 2050, RES constraints would have a minimal impact on overall growth due to prior expansion of renewable energy capacity. According to GCAM, nuclear energy would increase by 1.52 EJ between 2030 and 2050 to compensate for the RES limitations, although another model (PROMETHEUS) projects a 1 EJ drop in nuclear by 2050 due to policy shifts in several EU Member States. The renewable energy transition remains largely intact, but alternative low-carbon sources (including but not limited to nuclear) may need to be scaled up to fill the gaps.

How could limiting biomass availability shift the primary energy mix?

Limiting biomass supply would lead to increased reliance on conventional fossil fuels, due to difficulties in fully replacing biomass across all sectors. Biomass constraints would, in fact, trigger a shift towards more carbon-intensive fuels unless clean energy alternatives were also developed at scale.

What would happen to primary energy if CCS deployment was limited compared to expectations?

Limiting CCS would also reduce the deployment of bioenergy, particularly BECCS. Bioenergy would decrease by 6-7 EJ/yr compared to the baseline, meaning that its role would be limited in emission reduction efforts. Unabated coal would be phased out by 2040, and the use of natural gas without CCS would diminish significantly by 2050. Apart from constraining bioenergy deployment, CCS constraints could force a turn to other technologies, with renewable sources slightly increasing overall.

How would near- and long-term targets impact overall primary energy consumption?

Our baseline scenarios, driven by NDCs and LTTs, show a reduction in primary energy use due to ambitious climate policies and increasing energy efficiency. Primary energy use is projected to decline more in one model (PROMETHEUS), which, however, features higher granularity and diversity of detailed energy efficiency measures and options, especially in the built environment. Further reductions of energy consumption are observed in the biomass- and CCS-constrained scenarios, driven by a shift towards more efficient, clean energy technologies—particularly wind and solar PV. Achieving net-zero targets would require deep energy efficiency improvements, with clean energy technologies playing a crucial role in reducing primary energy demand.

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4.3 The impact of technology constraints on EU's power generation mix

Table 2: Impact of technologically constraint scenarios on the use of power generation technologies

Technology	NDC-LTT (baseline)	NDC-LTT-LimRES	NDC-LTT-LimBio	NDC-LTT-LimCCS	Comments
Coal	Phased out by 2050	Almost phased out	Increased due to biomass constraints	Phased out by 2050	Coal is phased out by 2050. However, constraints on biomass and CCS might slow down the phaseout, forcing reliance on coal in some sectors (e.g., heavy industry).
Gas	Moderate use	Slightly increased	Increased due to biomass limitations	Increased due to CCS limitations (& biomass implications)	The increase in natural gas under LimBio and LimCCS raises concerns about energy security, especially with the EU's reliance on natural gas imports.
Solar PV and wind	Rapid growth	Slower deployment	Stable to baseline levels	Stable to baseline levels	Even with RES constraints, renewables still play a central role in decarbonisation pathways. The impact of geopolitical and material constraints on RES should prompt policymakers to diversify supply chains and invest in energy storage technologies.
Biomass	Increased use compared to current levels	Stable to baseline levels	Decreased significantly	Decreased	Biomass plays a critical role in achieving negative emissions when combined with CCS (BECCS). Limitations in biomass availability significantly weaken the EU's decarbonisation pathway. This suggests the crucial need to expand biomass availability in an environmentally sustainable manner or find alternatives.
Nuclear	Slight reduction from current levels	Increase from baseline levels	Moderate increase from baseline levels	Stable at baseline levels	In scenarios with renewable energy limitations, nuclear power can help bridge the gap, but public opposition and high costs are barriers. PROMETHEUS highlights a potential decline due to EU countries phasing out nuclear, while GCAM shows a more positive role for nuclear expansion.
CCS	Moderate expansion to 2040 and 2050	Stable to baseline levels	Reduced importance compared to baseline	Significantly reduced compared to baseline	CCS technologies are essential for mitigating emissions from industrial sectors and achieving net-negative emissions through BECCS. Policymakers should prioritise developing CCS technologies and infrastructure to ensure the EU reaches its climate neutrality goal.

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Changes in energy mix by 2030

In 2020, power and centralised heating plants accounted for ~ 25% of the EU's total GHG emissions. Coal & gas dominated these emissions, with coal playing a particularly significant role due to its high carbon intensity. By 2030, modelling results suggest that coal use in the EU would nearly halve (over 2020 levels), the uptake of RES would triple (mostly driven by the massive expansion of solar PV and wind power), while hydropower and nuclear power would see limited changes. Even with constraints on renewable energy sources, models consider that the market-driven push for sustainability and lower carbon emissions, combined with declining low-carbon technology costs, can incentivise the continued development of RES towards near full decarbonisation by 2050 (*Figure 2*).

The role of Policy in driving the renewable energy growth

EU NDCs and LTTs seem to be adequate to drive a large expansion of renewables. Even in the Lim-RES scenario, which assumes cost increases for PV, wind, and batteries due to geopolitical tensions, RES growth is robust. This demonstrates resilience of policy frameworks in maintaining momentum towards a low-carbon electricity system.

The impact of CCS limitations

Although the limitations on CCS would reduce the electricity generated from biomass by 2.4 EJ/yr in 2050 compared to the baseline (as there is no incentive to generate net negative emissions), coal is projected to remain at similar levels as in the baseline. Without the incentive to generate negative emissions, coal use remains relatively stable. This highlights the importance of CCS in achieving net-negative emissions.

Biomass and Gas as key players

Constraints on biomass would lead to a slight increase in RES electricity, with an even larger increase in gas-fired electricity despite the strong climate ambition of NDCs & LTTs by 2050. This is because existing gas-based power generation infrastructure is already in place and capable of accommodating increased electricity demand. Reliance on gas underscores the challenges of achieving deep decarbonisation when biomass and CCS are constrained.

The path to decarbonisation by 2050

The analysis suggests that, despite technological limitations and geopolitical tensions, the models can find ways to decarbonise the EU's electricity system by 2040/2050 based on a multitude of technological options deployed, including solar PV, wind (onshore and offshore), nuclear power, biomass, and CCS. However, when limitations to biomass and CCS are assumed, there is no possibility to generate net-negative emissions in energy supply, which are required to counterbalance residual emissions in hard-to-abate sectors (heavy industry, aviation, navigation, and agriculture). This creates significant challenges for the EU to achieve its climate neutrality goal by 2050.

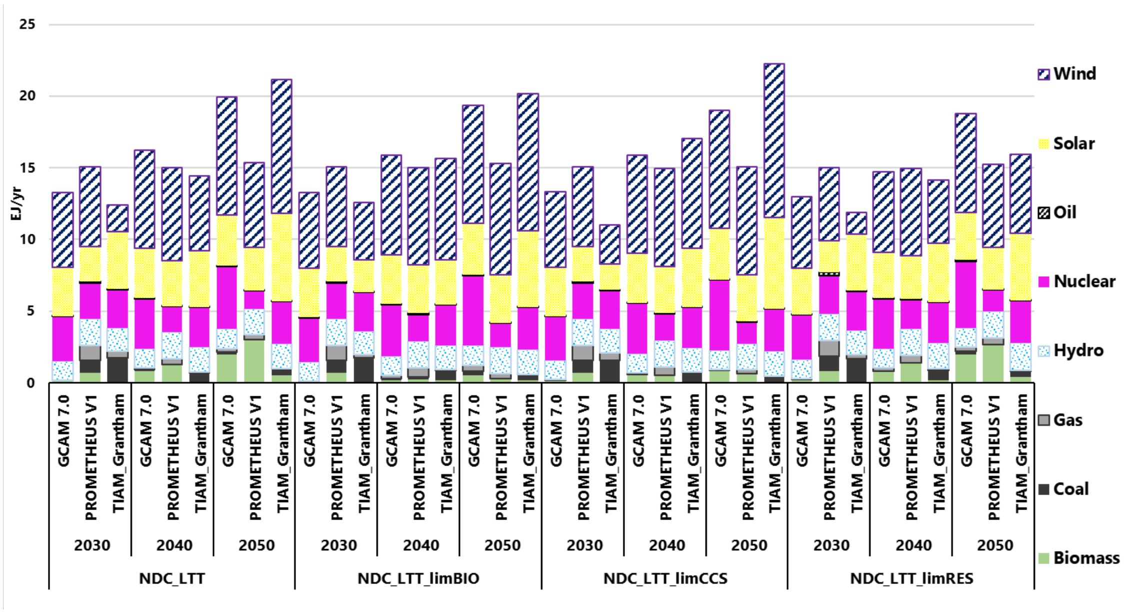

Figure 2. Electricity generation mix under different scenarios from 2030-2050; PROMETHEUS, GCAM, and TIAM results.

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5. Policy Implications

The findings of this study have significant implications for EU policy priorities in the context of achieving net-zero emissions by 2050, ensuring energy security and driving sustainable energy transition. The study demonstrates how constraints on key low-carbon technologies such as renewables, biomass, and CCS could affect the EU's ability to meet its long-term climate goals. The results point to critical areas where policy interventions are necessary to enhance resilience, diversify the energy mix, and avoid potential roadblocks in the transition to a low-carbon future. The critical areas identified in this study include addressing technology constraints on renewables, sustainable biomass utilisation, strategic deployment of CCS, and mitigating gas dependency to ensure energy security through diversification, which is key for achieving the EU's net-zero targets by 2050.

The EU's **Green Deal**, **'Fit for 55' package**, and **REPowerEU** strategies all prioritise the rapid expansion of low-carbon technologies, aiming to significantly reduce GHG emissions by 2030 and reach net-zero by 2050. This study aligns with these objectives as it explores how different energy configurations and technology pathways can support or undermine these ambitious targets, based on the availability of critical technologies.

Geopolitical tensions, particularly in the context of energy resources and technology supply, are critical concerns for European policymakers. The *NDC-LTT-LimRES* scenario provides insights into the potential impacts of such tensions on energy systems. This scenario aligns with the EU's **REPowerEU** strategy that aims to reduce dependency on external energy sources, particularly in the context of renewable technologies and batteries.

The study also emphasises the need for technological innovation, which is a core focus of the EU's **Innovation Fund and Horizon Europe programs**, to promote diversification of clean energy options and investment in R&D for advanced technologies and reduce the risks of high import dependency on specific materials and technologies. This suggests that policymakers must consider these innovation gaps when planning future energy systems, especially to maintain flexibility and avoid over-reliance on a narrow set of solutions.

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