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Geopolitically constrained pathways to carbon neutrality

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

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Highlights

- We simulate impacts of trade/geopolitical and technological constraints on EU net-zero
- 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
- Our modelling exercise highlights the need for resilient energy system transformation

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

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EU Climate Targets

Target Type	Year	Quantified Target	Description
NDC (Nationally Determined Contributions)	2030	At least 55% reduction in GHG emissions compared to 1990 levels	This is the EU's current NDC commitment under the Paris Agreement, aiming for significant near-term emission cuts.
LTT (Long term Targets)	2050	Climate neutrality (net zero GHG emissions)	The EU aims to reach net-zero GHG emissions by 2050, balancing emissions with carbon removal
Intermediate milestone	2040	Reducing the EU's net emissions by 90% by 2040	Deep cuts in emissions due to large-scale deployment of RES, CCS and alternative fuels

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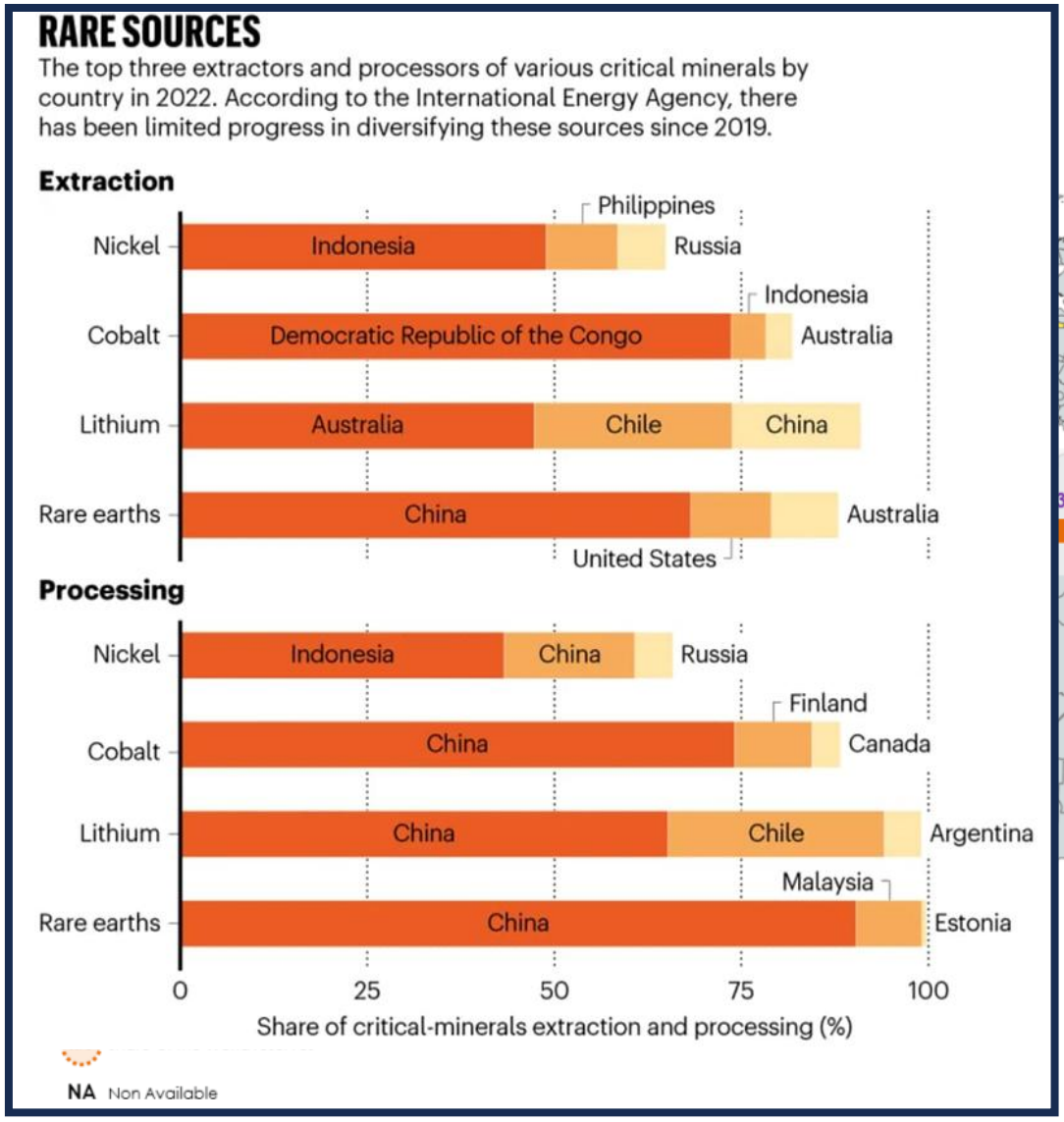
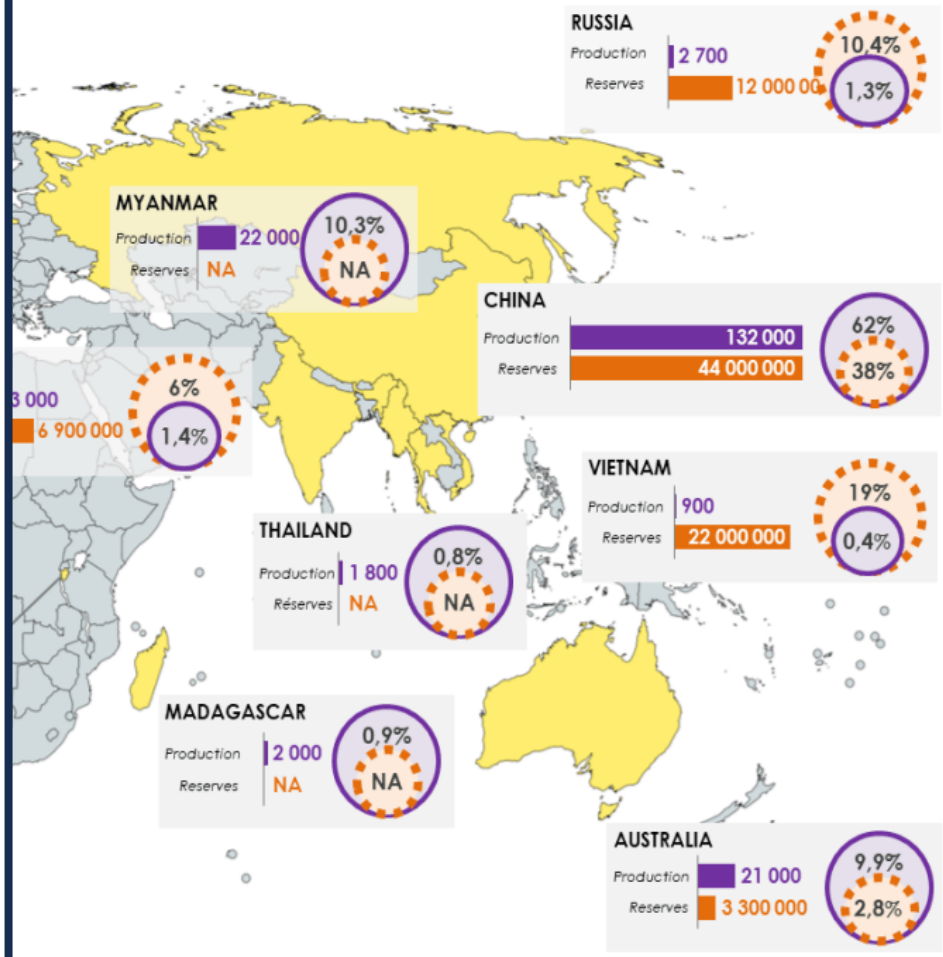
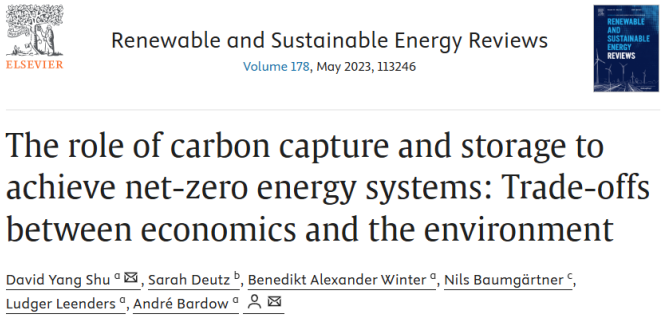


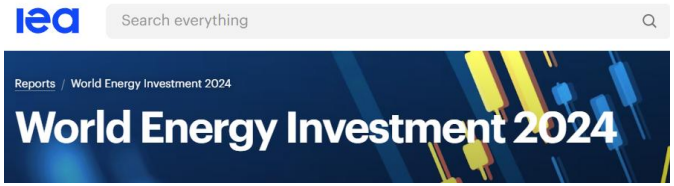


Source: U.S. Geological Survey, Mineral Commodity Summaries, January 2020
Map created by IFP Énergies Nouvelles with Mapchart.net

- Achieving net zero requires a massive scale up of clean energy technologies together with major energy efficiency improvements



- Diversifying the energy mix lowers system costs & reduces dependence on fossil fuel imports
- Without rapid deployment of low-carbon techs, EU risks falling short of its targets



- *But*: Few studies account for geopolitical disruptions (e.g. *critical materials controlled by a few countries, trade restrictions, export bans*)

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Multi-model analysis

(PROMETHEUS, GCAM, TIAM, MARIO)

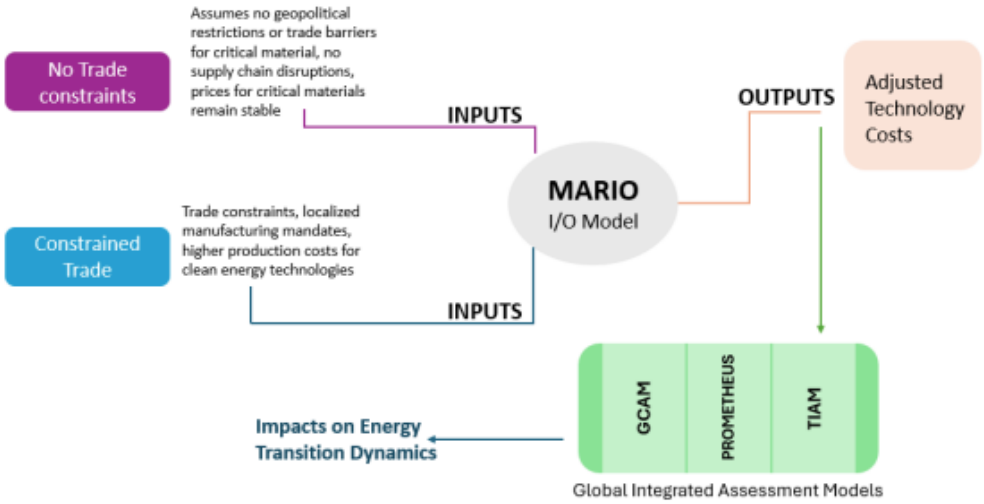

Figure 1. Methodological framework for examining the effect of geopolitical factors impeding the diffusion of RES and energy storage in the EU: integration of MARIO projections with the global IAMs to quantify geopolitical and supply-chain impacts on the energy transition

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Scenarios analysed

Scenario	Short description
NDC-LTT	Implementation of the NDC targets for 2030 and long-term targets for 2050 (e.g., net zero by 2050 in the EU)
NDC-LTT-LimRES	Limited expansion and growth of RES and energy storage technologies, including batteries, due to material unavailability and geopolitical tensions: cleantech costs increase due to import constraints in materials and clean energy technologies, as quantified in MARIO, and act as moderating factors on projected growth for RES and battery technologies.
NDC-LTT-LimBIO	Restricted use of biomass for energy purposes in the EU, with a cap set at 5-6 EJ by 2050.
NDC-LTT- LimCCS	Restricted deployment of CCS in the EU, with a cap set at 10-20 Mt CO_2 by 2050.

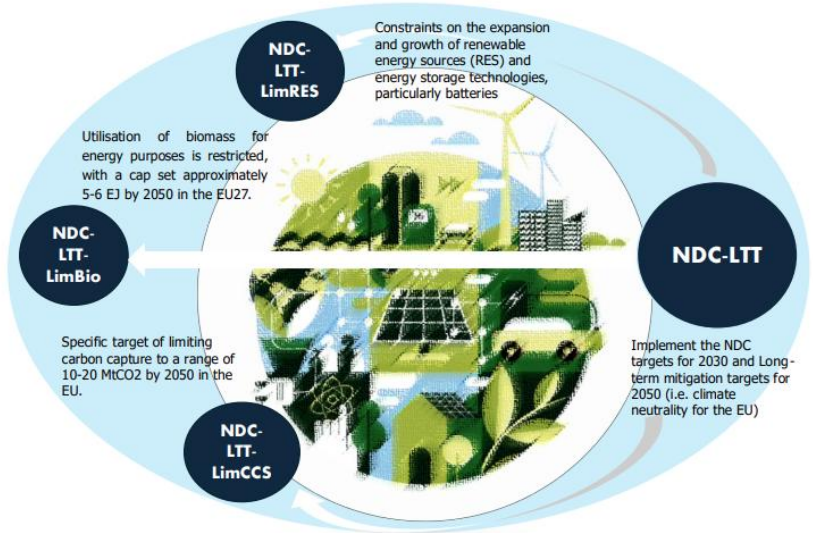

Figure 1. Illustration of disruptive scenarios.

Attainability of net zero by 2050 in light of technology constraints

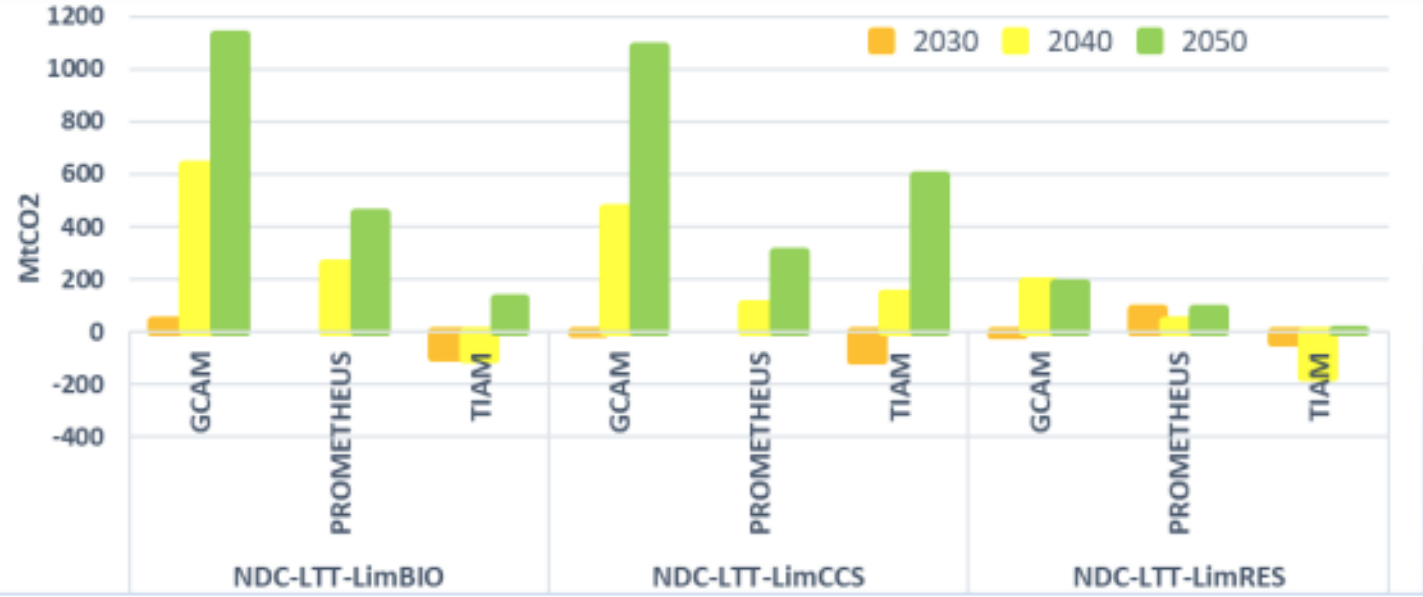

Figure 2. Differences in EU CO2 emissions between alternative scenarios with the baseline scenario in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM.

NDC-LTT-LimBIO	The system falls back on carbon-intensive fuels. Biomass is vital for decarbonizing transport & industry
NDC-LTT-LimCCS	Post-2035 impacts. CCS is crucial for hard-to-abate sectors (steel, cement, chemicals). Fewer options to reduce fossil fuels
NDC-LTT-LimRES	Modest changes by 2030 Post-2030 as electrification accelerates, the shortage of RES & batteries causes emissions to rise significantly

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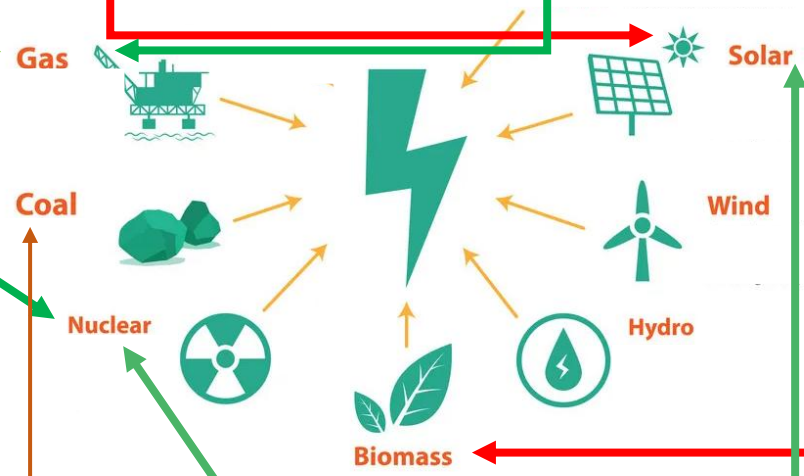
NDC-LTT-LimRES

NDC-LTT-LimBIO



NDC-LTT-LimRES

Other dispachable clean options (nuclear, hydro) expand; near-term gas acts as bridge fuel

NDC-LTT-LimBIO

Limits BECCS—Weaker potential for negative emissions

NDC-LTT-LimCCS

NDC-LTT-LimCCS

CCS cap forces increase in wind & nuclear to secure decarbonisation

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The impact of cleantech constraints on EU transport

Battery costs higher -> EV adoption slows
2040-2050: without cheap RES and batteries, electrification stalls
Oil demand in transport stays higher than baseline (especially in freight & aviation)
Gas would play a transitional role
Risk: EU imports more oil and gas -> weaker energy security

- 2040-2050: no large-scale biofuels for aviation/shipping
- Heavy reliance on synthetic fuels (hydrogen based) -> but very costly
- For road transport- faster push to EVs because liquid biofuels are unavailable

- **2030**: Not much immediate effect
- **2040-2050:**
- Without CCS, hard to abate sectors face higher residual emissions
- More reliance on direct electrification (EVs) but sectors like aviation get stuck with higher emissions

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NDC-LTT-LimRES
• **2030**: electricity prices rise, slowing heat pump adoption • **2040-2050:** • Slower electrification of heating -> households and firms hold on to gas boilers longer • District heating may rely more on fossil backup when RES are constrained • By 2050, buildings still decarbonize , but later and with more gas in the mix **->** higher costs, higher lock-in risks
NDC-LTT-LimBIO
2030: Small impact (biomass is niche in buildings already) **2040-2050:** • No biomass for heating (pellets, stoves, small boilers) • This means heavier reliance on heat pumps & electricity • In regions with slower electrification (e.g. Eastern EU), gas boilers persist longer ->higher emissions
NDC-LTT-LimCCS
• CCS is less relevant for buildings directly (since emissions are diffuse) • Indirect effect: district heating from waste/biomass with CCS disappears -> less negative emisisons • 2050: buildings may still decarbonize but residual emissions elsewhere must be balanced -> stronger pressure on buildings for deeper efficiency cuts

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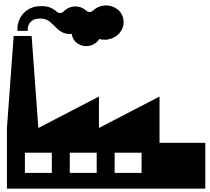
Prospects of EU industrial decarbonisation under technology limitations



LimRES

2030: Electricity prices rise, electrification slows
2040-2050:

- Gas & hydrogen from fossil sources used more as substitutes
- Nuclear-driven electrification partly compensates, but uneven across EU

LimBIO

2030: Biomass role small
2040-2050:

- No BECCS>no net negative balance, residual emissions in industry remain
- Shift to more gas

LimCCS

2030: Little change, since CCS is not yet central
2040-2050:

- No CCS->less decarbonization in hard-to-abate sectors
- Industry leans harder on hydrogen & electrification
- Residual fossil use persist->higher emissions

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EU is on track: coal declines, RES tripling by 2030 under the NDC-LTT

- Constraints on CCS and Biomass = higher emissions, no net-negative option, not meet the net-zero goal, higher costs

Constraints on RES & Batteries = more gas & oil reliance-> Energy Security Risk

- Multiple technology pathways are needed for resilience
- Policy must safeguard flexibility & diversify options

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Thank you!

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Timeline of Risks under Technology Constraints in the EU

Period	NDC-LTT	NDC-LTT-LimRES	NDC-LTT-LimBIO	NDC-LTT-LimCCS
By 2030 (short term)	Coal declines nearly 50%, RES begin massive expansion. Emissions fall in line with NDCs	Minimal Impact; existing infrastructure buffers short-term effects. Slight slowdown in electrification	Minimal impact	Minimal impact; CCS deployment still small
By 2040 (medium term)	RES and wind continue to grow	Slow electrification; fossil fuel use increases	Increase fossil fuel use	Constraints increase emissions in hard to abate sectors
By 2050 (long-term)	RES dominant, negative emissions active	Slower renewable penetration	BECCS constrained; emission rise	Emissions rise significantly in hard to abate sectors

Policy Implications
Policies should ensure early investment in RES, batteries and CCS, maintain current deployment momentum
Supply chain resilience becomes critical; alternative low-carbon technologies must be scaled; BECCS development accelerated
Diversified technology portfolio essential; policy must maintain BECCS and CCS deployment, secure material supply for RES/batteries; monitor emerging bottlenecks

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Reliance on (imported) fossil fuels

NDC-LTT-LimRES

Increased biomass consumption in 2030 and post-2030 increase in oil as EV deployment slows

NDC-LTT-LimBIO

Increased reliance on oil imports especially by 2050

NDC-LTT-LimCCS

Biomass loses role as negative emission option, increased fossil fuel dependence in power & industry

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

Resilience of a crippled EU power sector

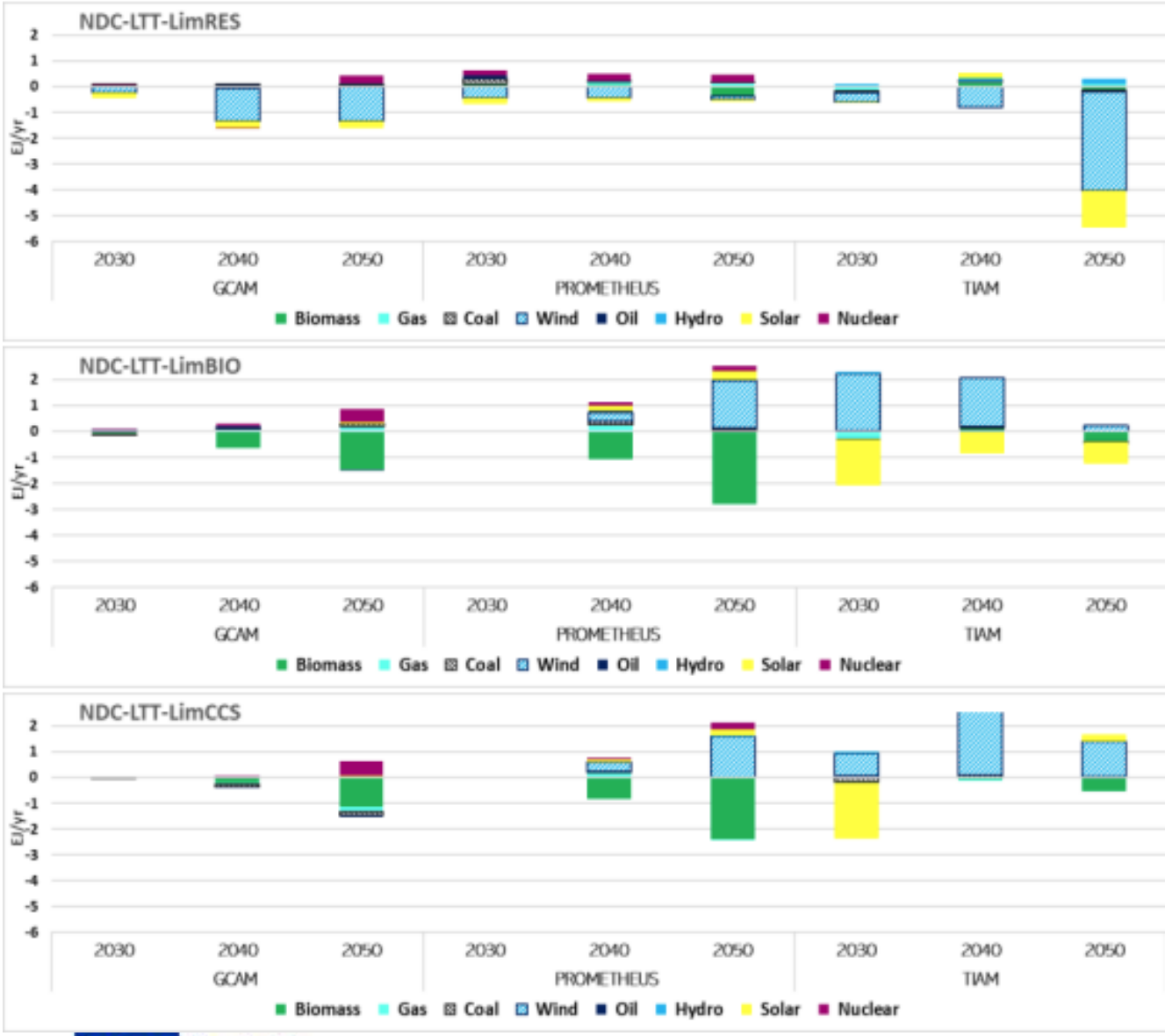

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Figure 4. Changes in power generation fuels across the three constraining scenarios, compared to the baseline in 2030-2050. Source: GCAM, PROMETHEUS, and TIAM

Prospects of EU industrial decarbonisation under technology limitations

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

NDC-LTT-LimRES

Higher electricity costs hinder industrial electrification, leading to increased reliance on fossil fuels—especially gases—to meet energy needs.

NDC-LTT-LimBIO

Reduced biomass availability drives industry toward greater use of natural gas

NDC-LTT-LimCCS

Without scalable CCS, heavy industry struggles to decarbonise, resulting in increased use of solids (like biomass).

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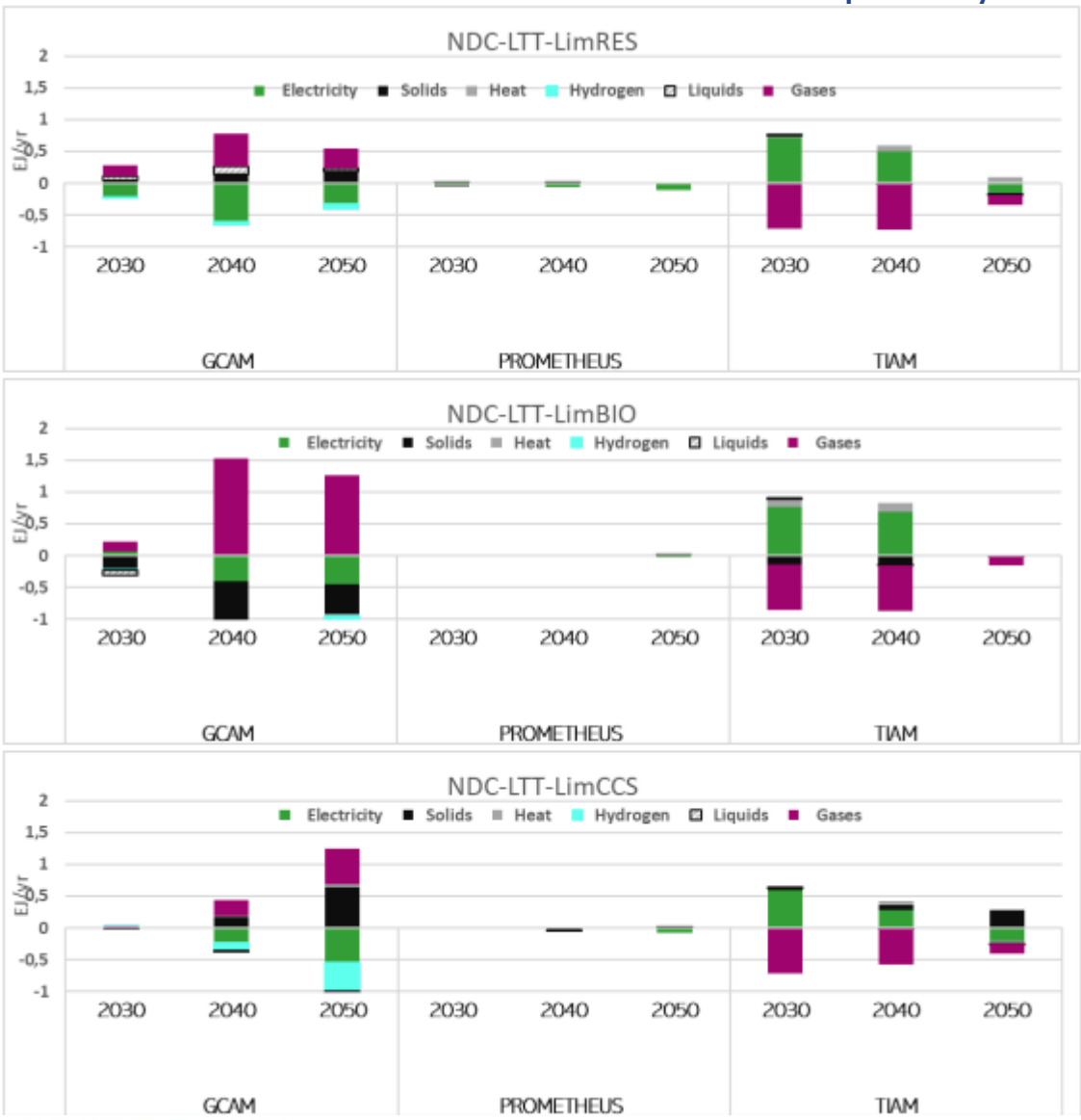
Adaptability of the built environment



NDC-LTT-LimRES

Higher electricity prices and limited storage capacity reduce electrification potential, increasing reliance on gases and liquids for building energy needs.

NDC-LTT-LimBIO

Reduced availability of solid biomass shifts energy use toward gases and electricity, with early electrification gains in some models offset by later convergence to baseline levels.

NDC-LTT-LimCCS

Rising electricity and hydrogen costs due to CCS limitations lead to reduced consumption of these clean energy sources in buildings, with a partial shift back to gases and biomass.

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

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

NDC-LTT-LimRES

Transport decarbonisation continues due to strong policy drivers (e.g. CO_2 standards), but battery limitations post-2040 lead to a partial shift back to liquid fuels

NDC-LTT-LimBIO

Reduced biofuel availability makes electricity and hydrogen more attractive for transport.

NDC-LTT-LimCCS

Indirect effects on transport via increased electricity prices due to costlier power generation.

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