Energy supply transformations to reach EU's net-zero goal

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SUMMARY

The study aims to explore alternative energy supply transformations in the EU towards meeting ambitious climate targets. Five alternative scenarios of technological failures and fuel limitations are developed and examined using four energy supply models representing the EU region and its Member States. The scenario results are compared in terms of emissions, technology development, and costs and used to identify key-enabling technologies required for net-zero emissions targets in the energy supply sector. We show that massive development and deployment of wind and solar is required with significant investment costs as zero emissions cannot be achieved when the uptake of RES is restricted.

EXTENDED ABSTRACT

In response to the urgent global climate crisis, the EU has accelerated its efforts to transition towards a sustainable, low-carbon future. The energy supply sector holds immense importance in achieving net-zero emissions due to its significant contribution to emissions and the potential role of electricity in all demand sectors to replace fossil fuel use. Transitioning from fossil fuels to clean energy sources to produce electricity and hydrogen directly mitigates emissions from the energy supply and enables decarbonization of energy demand sectors (transport, industries, buildings) through electrification.

Recent studies, including the latest EU Climate Target plan for 2040 [1], suggest that the energy supply sector is the easiest to decarbonize and thus it needs to achieve close to zero CO_2 emissions already in 2040 to ensure that the overall EU economy reaches net-zero emissions 2050. Four energy supply models representing the EU region are used for this multi-model exercise. An overview of the basic model features can be found in Table 1.

***Table 1**: Overview of basic model features*

Model	Institute	Model type/ solution concept	Time horizon /Regions represented	Supply sectors represented	Energy trade	Storage options	Energy grids represented
OSeMBE	KTH	Energy System Optimization Model	EU + Switzerland & Norway (30 regions) Until 2050	Energy supply & conversion	Electricity trade between countries;	The model does not include storage options.	Electricity production
Artelys Crystal Super Grid	Artelys	Optimal Dispatch and Expansion	EU-27 Member States (+7 neighboring countries) 2050	Power supply and power-to-H2 via electrolysis	Electricity trade within countries; import of primary energy from global market;	Batteries, (expanded), Open and closed loop pumped storage (scenarized), Hydro (scenarized), Hydrogen storage (scenarized), Demand-side flexibility (EV, load curtailment)	NTC (expanded)
MEESA	IOS-PIB	Energy System Optimization Model	EU + Switzerland & Norway + UK (27 regions)	Energy supply & conversion,	Electricity trade between	batteries, hydro-pumped, hydrogen,	Electricity production

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			Until 2050	electricity, district heating, green hydrogen	regions/ countries	(flexible EV charging)	
LIMES-EU	PIK	ETS model (Optimal investment and dispatch for power + Industry)	EU (w/o Malta and Cyprus) plus Norway, Switzerland, and EU Balkan countries (29 regions) 2010-2070 (5-year steps)	Power sector, centralized heat, Hydrogen electrolysis; large industry via MACC	electricity trade within countries; import of primary energy from world market;	batteries, pump hydro, hydrogen electrolysis/storage/hydrogen turbines	electricity via NTC

Through a stakeholder workshop with large participation by EU policymakers, industry representatives, NGOs, and academia, we co-designed a set of transition scenarios to explore cost-optimal energy supply transformations in the EU toward meeting its 2050 net-zero goals and assess the impacts of technological limitations and constraints on the development of energy supply and associated emissions and costs on the road towards net-zero. As electricity (and hydrogen) demand is an exogenous input in the supply models, we decided to impose the ENTSO-TYNDP demand assumptions. We use an exogenous carbon price trajectory with a linear increase from 130 USD in 2025 to 400 USD in 2040 and 580 USD in 2050 [2]. The same electricity demand and carbon price assumptions are imposed on all decarbonization scenarios.

The alternative scenarios examine the impacts of limitations on biomass, CCS, variable RES (wind and solar), and nuclear on the EU's energy supply sector. In particular:

i.) Optimal: no limitations are imposed on the development and deployment of low-emission technologies
ii.) LimBio: limited availability of biomass, around 3.5EJ used for electricity and hydrogen production
iii.) LimCCS: 100 -125MtCO2 in 2050 (60-80MtCO2 in 2040) in the energy supply sectors.
iv.) LimNuc: No new capacities, only the ones firmly decided (9.2GW) with only 2.12 GW under construction.
v.) LimRES: limitations in the development of PV and wind capacities, based on a linear extrapolation of the 2021-2022 growth and assuming constrained RES expansion following public acceptance issues (e.g. on new wind onshore) or policies to reduce PV installations in agricultural land. The total amount should be below 3230TWh/yr in 2050, and the limits for wind and solar are imposed separately assuming a 50/50 split between the two technologies.

A base scenario is also established, incorporating only existing climate legislation up to 2021. The overview of scenarios can be found in Table 2.

***Table 2**: Overview of scenarios*

	Name	Climate Target	Policy mix	Technology
1	Base	As in the EU Reference scenario		
2	OPT-MIX	Net zero in 2050	Carbon pricing	Optimal technology mix
3	OPT-MIX-LimBio	Net zero in 2050	Carbon pricing	Limited biomass
4	OPT-MIX-LimCCS	Net zero in 2050	Carbon pricing	Limited CCS
5	OPT-MIX-LimNuc	Net zero in 2050	Carbon pricing	Limited nuclear
6	OPT-MIX-LimRES	Net zero in 2050	Carbon pricing	Limited RES (wind & solar)

The electricity-related emissions drop massively in all scenarios (Figure 1). For all alternative scenarios, except for LimRES, zero or below zero electricity emissions are projected already in 2040 and even lower values are reached by 2050. The LimRES scenario does not achieve zero emissions in the power sector even in 2050, and emission projections are even higher than in the base scenario, illustrating the significant impact of limitations on wind and solar (RES) development. Constraints in biomass, CCS and nuclear have limited emission impacts since RES deployment is unrestricted and wind and solar can replace the other low-carbon technologies.

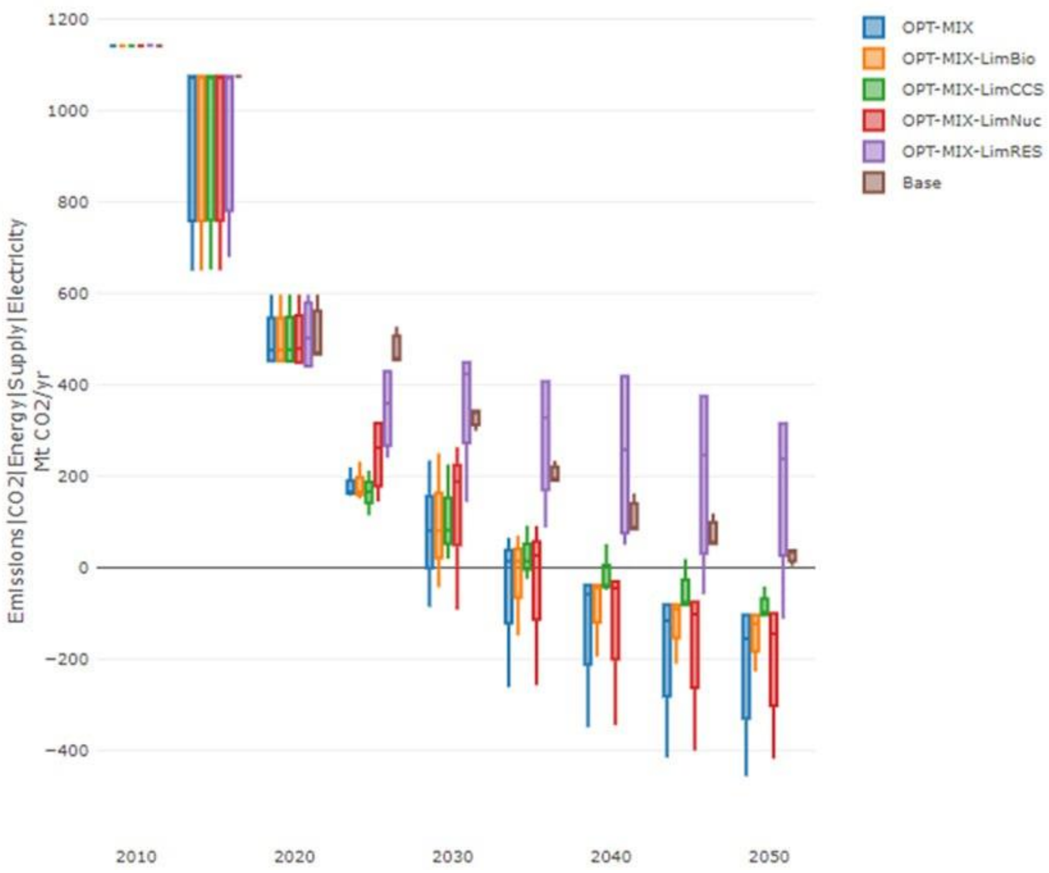

Figure 1: CO_2 emissions of power sector.

A more than 3-fold increase in EU power capacity is projected in the alternative decarbonization scenarios over 2020-2050 (Figure 2), with the exception of LimRES, driven by the mass investment in wind and solar, which requires huge investments directed both to new power capacities and to storage and grid expansion. The electricity capacity in the LimRES scenario is much lower, as investments are restricted for solar and wind which are highly volatile sources and have a lower capacity factor than other technologies. This also implies much smaller storage capacity requirements in LimRES scenario (right panel) due to the smaller needs to provide flexibility and balance for intermittent RES.

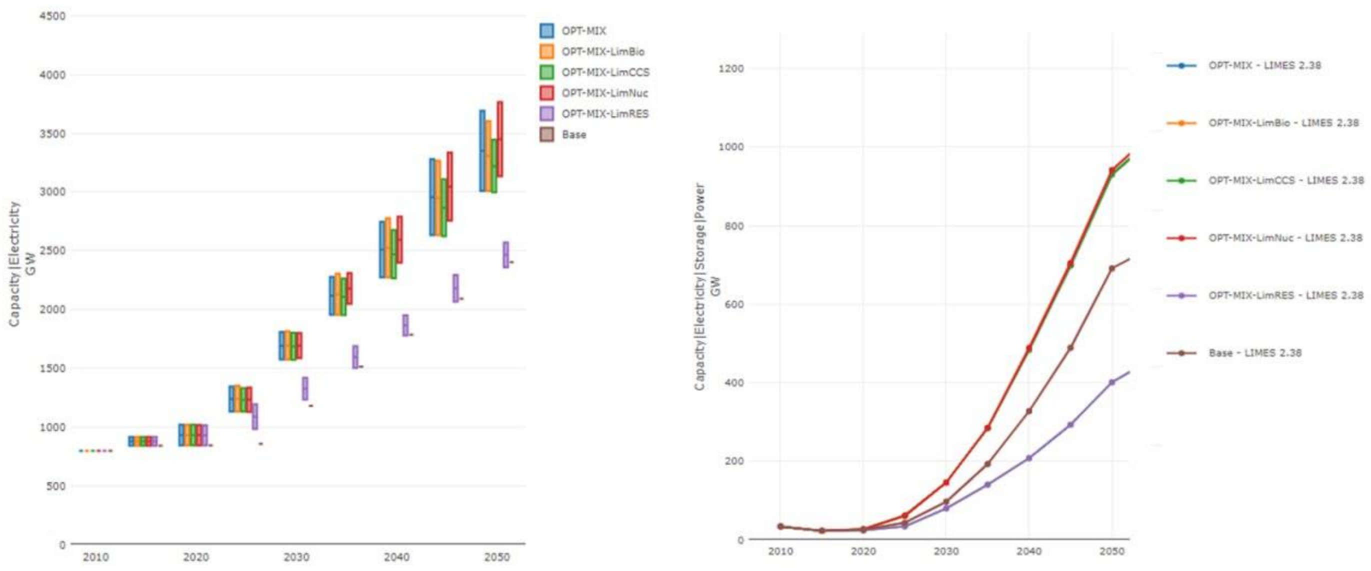

Figure 2: Capacity of electricity and storage of different scenarios.

The power generation mix for the different scenarios is shown in Figure 3 for 2050. In all models (and especially in LIMES and Artelys Crystal Super Grid), the constraints on biomass, CCS and nuclear do not affect the energy mix in the alternative scenarios as wind and solar are the dominant generation sources. In the LimRES scenario however, the restrictions on RES investments lead to a larger nuclear production, especially in LIMES and MEESA models. In contrast, the Artelys Crystal Super Grid, MEESA, and OSEMBE models increase the gas-based generation (mostly in combination with CCS). The feasibility of an increased gas-based generation should be further examined, since in the Artelys Crystal Super Grid the projected volume of captured carbon is ~1000Mt in the European region. In the LimNuc scenario, RES, specifically solar, production increases while the limitations in solar and wind lead to increased electricity production from gas. The optimal mix in OSeMBE consists of significant production from RES, biomass and nuclear.

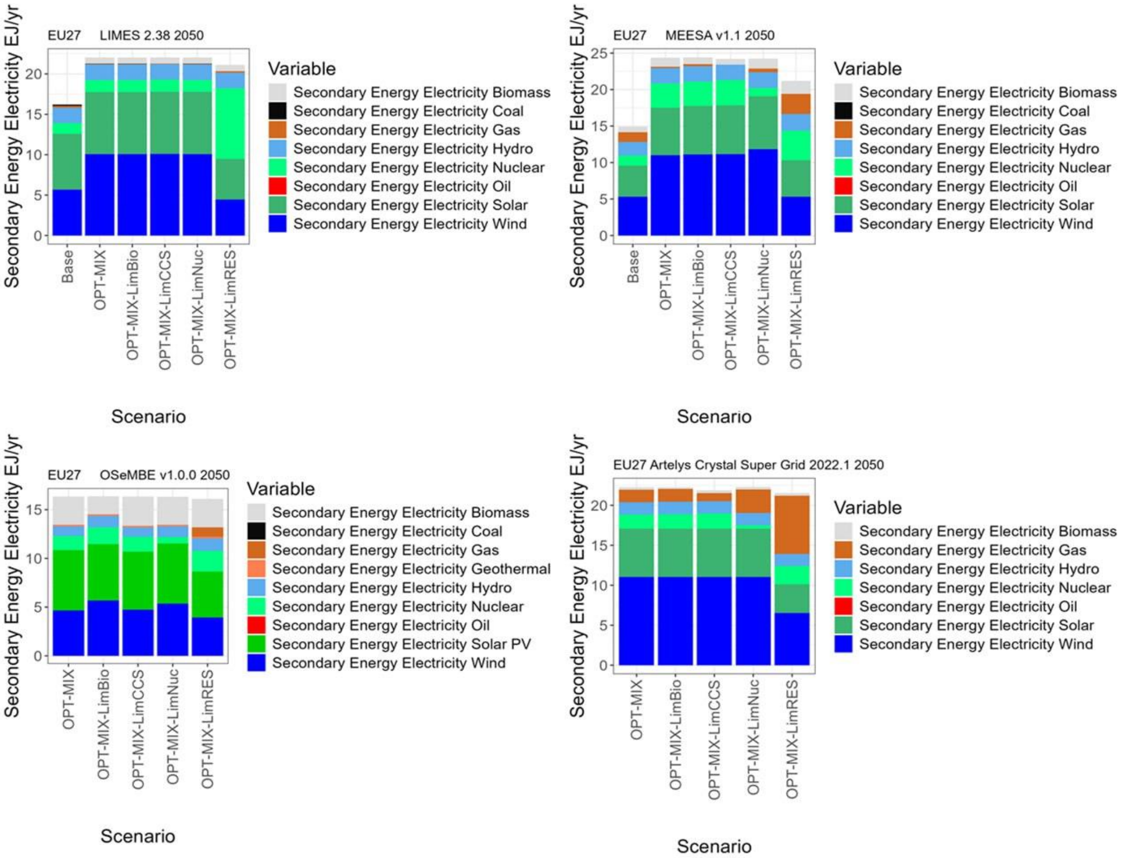

Figure 3: Secondary energy electricity mix of different scenarios in all models.

The energy supply transformation to reach the EU's carbon neutrality goal highly depends on the availability of low-carbon technologies. In order to decarbonize the EU's energy supply by 2050, large RES investments are required and due to the intermittent nature of solar and wind there is an extra need for power and storage capacity. The scenarios show a large increase of the power system CAPEX directed to new power plants, grids expansion and storage capacities accompanied by a reduction in system OPEX, mostly driven by the lower amounts of fossil fuel used in power plants. Limitations in biomass, CCS and nuclear can be managed based on accelerated deployment of renewable energy with limited increases in costs and emissions. In contrast, limitations in solar and wind pose serious threats to the achievement of the EU's net-zero goals as they lead to higher supply-side emissions and higher power system costs (as will be shown in the full article manuscript).

References

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