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1.1.1.

Fit-for-55 and beyond: European power system transition and its social impacts

Analysis of the long-term effects of restrictions on trade with Russia on the European energy system

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Executive summary

The European Union (EU) is facing significant challenges: on the one hand, it aims to achieve substantial reductions in emissions, with the Fit-for-55 (FF55) package emerging as a pivotal tool in attaining this ambitious goal; on the other hand, the EU's heavy reliance on fossil fuels, particularly natural gas, where Russia supplies nearly half of the total imports, has intensified the need for decisive action as the conflict with Ukraine persists. This policy brief summarizes two complementary research projects on the above issues.

The first research line assesses the transition pathway outlined in the FF55 package, emphasizing the technical feasibility and social implications of the EU energy system. Employing the Energy System Optimization Model for the European Union (ESOPUS) together with the general equilibrium model FIDELIO, the study offers a detailed representation of the energy system and captures socio-economic impacts across various scenarios, considering both technological and social aspects entailed by the achievement of carbon neutrality by 2050. The analysis reveals distinct regional variations in the EU's electricity generation shares and investments, emphasizing the need for differentiated policy approaches. Turning attention to Italy, the study analyses the socio-economic implications of increased electricity prices on households. Findings indicate a regressive impact, with low-income households bearing a disproportionate burden: changes in electricity consumption shares and consumer surplus underscore the importance of addressing the impact of the future transition on vulnerable populations.

The second research line employs the open software and open database energy system optimization model (ESOM) TEMOA-Europe. It considers different scenarios: one in which Russian fuel imports become unavailable from 2030, in line with the REPowerEU Plan, and another assuming no change in dependence on Russia. Both scenarios adhere to the constraints outlined in the European Green Deal, including greenhouse gas (GHG) emission reduction trajectories, energy service demand projections, and limitations on the supply of primary energy commodities. Results from the analysis reveal a substantial transformation in the total primary energy supply (TPES), displaying a shift towards renewables dominating over 50% of TPES by 2050. The scenarios emphasize the importance of a larger integration of renewable energy sources as a primary driver for a successful transition to net-zero emissions. The study concludes that moving towards cleaner energy sources in the long term requires considerable effort. Suspending fossil fuel imports from Russia is seen as an opportunity to facilitate the transition to a decarbonized energy system, rather than an obstacle.

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1. Presentation and description of the research activity undertaken

1.1 Fit-for-55 and beyond: European power system transition and its social impacts

To meet emissions reduction targets, the EU and its member states must undergo a systemic transformation of the energy sector, through a significant reduction in fossil fuel usage and a transition to renewable energy sources. The CMCC team research line aims to provide scientific evidence that outlines the transition pathway for the European energy system, focusing on the technical feasibility and social implications of the policy tools within the Fit-For-55 (FF55) package (Fit-for-55, 2023). This tool comprises various policy instruments to reduce EU greenhouse gas emissions by 55% by 2030 and to achieve climate neutrality.

This interim brief focuses on examining the implications and outcomes of the power system in Europe, with a particular regard for Italy. To conduct this analysis, we use two models tailored to the EU context: the Energy System Optimization Model for the European Union (ESOPUS) and the general equilibrium model FIDELIO (Rocchi et al., 2019). These models allow us to gain insights into the technological challenges associated with decarbonization and its potential societal implications. By considering shifts in electricity production costs and variations in power generation technologies, the study also provides insights into the macroeconomic impact of policy objectives. Particular attention is given to assessing the distribution consequences across EU member countries, with a specific focus on Italy.

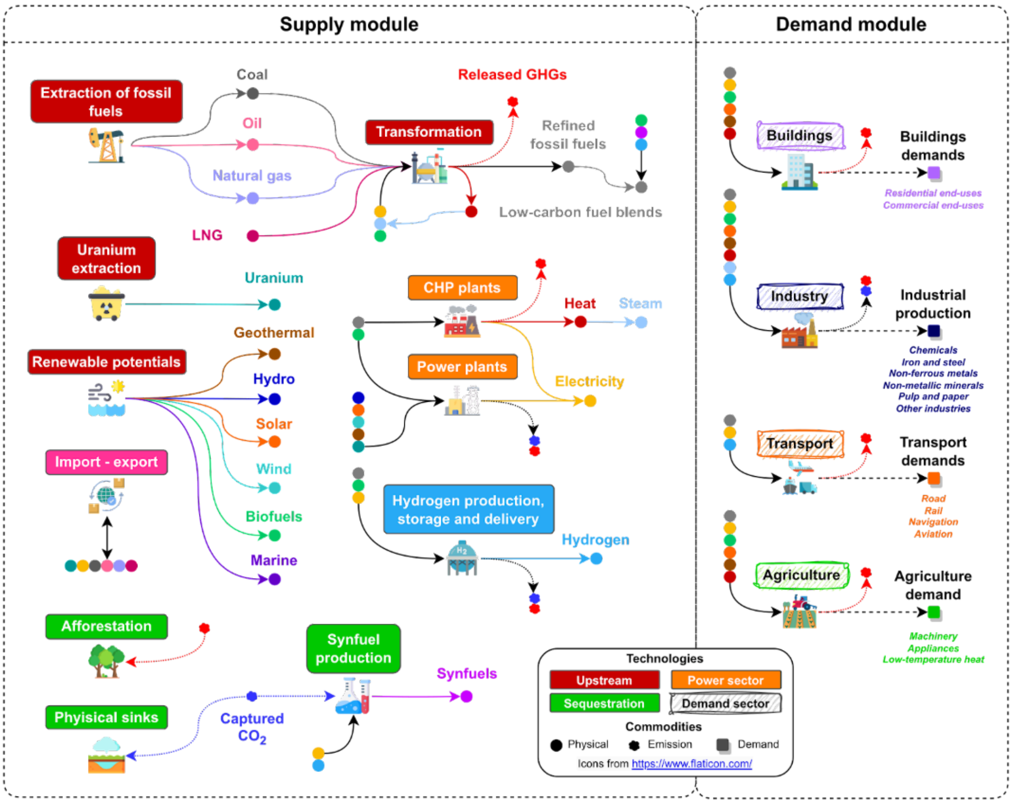
1.2 Analysis of the long-term effects of restrictions on trade with Russia on the European energy system

The EU has a strong dependence on fossil fuels and natural gas from other countries. In particular, the EU imports almost 90% of its natural gas, with Russia providing almost half of total imports (Perdana and Vielle, 2022). As the conflict with Ukraine, which started in February 2022, persists, the EU has adopted several measures to reduce import dependency on fossil fuels from Russia (European Commission, 2022), in the wider framework of the European Green Deal to reach carbon neutrality by mid-century.

If reducing coal and oil imports is relatively easy as their gradual replacement with cleaner fuels is an ongoing process and other countries are able and willing to provide these fuels, finding an alternative gas supply source is much more difficult due to the cost of transporting LNG (and the required infrastructure) and the cost of building new pipelines and facilities. Understanding the impact of changes in the gas import structure at the EU level is crucial as the energy mix may completely change from 2030 to 2050, with important implications for the emissions generated in several sectors.

The analysis is carried out using the TEMOA-Europe open software and open database energy system optimization model (ESOM), representing European OECD countries. Figure 1 illustrates the structure of the TEMOA-Europe Reference Energy System (RES).

Figure 1. Reference energy system of the TEMOA-Europe model



2. Relationship with the existing literature on the topic

2.1 Fit-for-55 and beyond: European power system transition and its social impacts

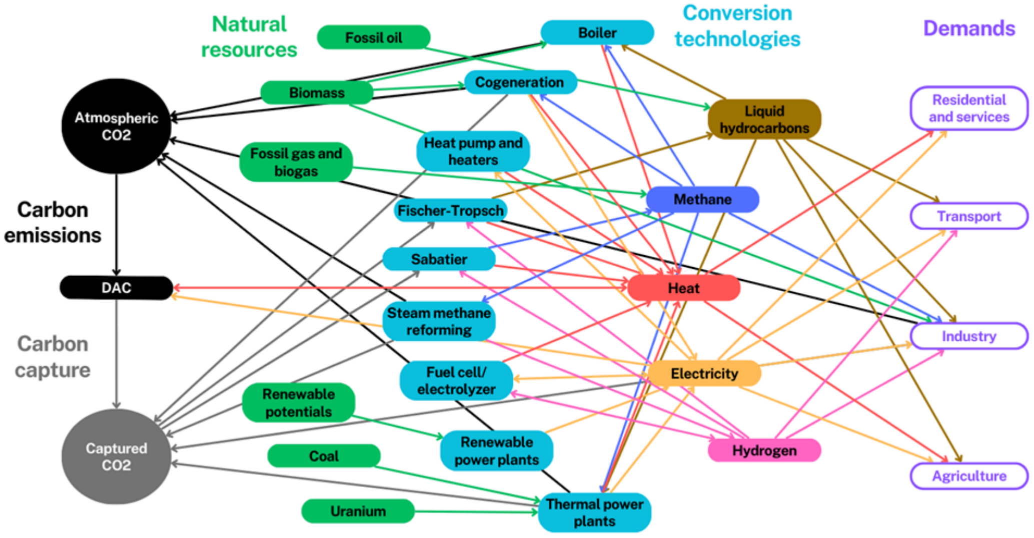
Although international and national plans for emissions reduction have gained popularity, they do not always align with the scientific literature and evidence-based targets set by data analysis (UNFCCC, 2022). Energy system models provide a robust and accurate analytical tool to analyze transition pathways and their technological complexities. In this study, we adopt an open-source energy model for analytical purposes.

Numerous studies have assessed possible pathways for the EU to achieve a carbon-neutral energy system by 2050 through energy system models (see Seck et al., 2022, Loffler et al., 2019, Victoria et al., 2020), comprising a vast literature resource evaluating climate policy targets via energy models without, however, evaluation social aspects and the implications on households and firms (Krumm et al., 2022; Süsser et al., 2022). In the economic field, various studies have evaluated social and distribution impacts generated by energy policy (see Orecchia et al., 2023).

Our study adheres to the impact assessment of the European Commission for the Fit-for-55 package (EC, 2020), with a deeper focus on Italy and a broader temporal perspective, including a long-term strategy analysis. To provide robust and coherent policy insights we first employ ESOPUS, an energy system model aimed at testing European laws and directives, as approved (see Table 2.1 for details). The structure of the model is summarized in Figure 2.

The study also includes the implications for society of achieving short and long-term European climate goals, in particular on household expenses and energy consumption. European climate policy protocols have the implicit risk of exacerbating social inequalities and producing adverse social effects, which can be alleviated or prevented through conscientious policy design and comprehensive energy planning (Markkanen & Anger-Kraavi, 2019). We employ the general equilibrium model, FIDELIO, to examine the socio-economic impact of the policy and the broader EU targets under scrutiny.

Figure 2. Energy System representation in Esopus



FIDELIO is an enlarged multi-regional multi-sector input-output (IO) model (see Table 1 for details). With a breakdown in 41 countries and 64 economic sectors, the model has an IO core that allows it to capture all sector and cross-country dependencies and spillover effects. The IO core is then enlarged to a full general equilibrium model.

Table 1. Esopus and Fidelio Resolution

	ESOPUS	FIDELIO
Geographic scope	33 European countries: EU27 (no Cyprus or Malta), Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, United Kingdom	45 countries: EU27, Argentina, Australia, Brazil, Canada, Switzerland, China, Indonesia, India, Japan, Korea, Mexico, Norway, Russia, Saudi Arabia, Turkey, United States, South Africa, Rest of the World
Sector scope	Electricity, industry, agriculture, heating, transport	64 industries/commodities
Time resolution	10-year period optimization up to 2050, hourly resolution	Yearly recursive dynamic, up to 2050

2.2 Analysis of the long-term effects of restrictions on trade with Russia on the European energy system

Since the oil crisis in the mid-70s, energy system models have proved useful tools for identifying optimal resource allocation in relation to the price of primary commodities (Bhattacharyya & Timilsina, 2010). From the mid-1980s, the focus of this class of model shifted to energy-environment interactions, producing models for long-term forecasts not only for energy but also for emissions, as highlighted in (Brown et al., 2021).

Given the current European framework, today energy system modeling is a very useful tool to drive policy prescriptions (European Commission, 2022). The choice of TEMOA as a modeling framework to develop TEMOA-Europe is due to the growing awareness of open science, which falls within the priorities of the European Commission (European Commission, 2022). The use of ESOM to simulate the effects of a shock in fuel prices is reported extensively in the literature, where the main contributions focus on North America (see Perdana & Vielle, 2022). At the EU level, there is still a gap in the literature on gas price shocks and energy system models. Moreover, an assessment of the effects of a gas crisis on leading energy-intensive sectors is still lacking.

Examining the effects of an interruption in the supply of gas specifically on the energy system, (Perdana and Vielle, 2022) focus on the effects of sanctions on the Russian economy and of several disruptions in fuel supplies, finding high prices and the potential shrinkage of gas demand in Europe up to 2030. The effects of sanctions and of the Russia-Ukraine war on energy prices are also analyzed in Balsalobre-Lorente et al. (2023). Corrective measures such as Pigouvian taxes are envisaged to guarantee an equal distribution of losses among different income groups. The analysis in the latest World Energy Outlook (IEA, 2023) highlights how lower Russian imports to the EU may be offset via alternative suppliers and by increasing LNG imports without particular efforts in the short term.

3. Research output

3.1 Fit-for-55 and beyond: European power system transition and its social impacts

3.1.1 Description of the scenarios

For power system decarbonization, ESOPUS provides two scenarios; the first is the reference scenario (REF), with investment optimization for the electricity system in Europe where no climate policy is introduced, considering only technological development. The second is the policy scenario, i.e., FF55+, where the FF55 package and the long-term strategy for climate neutrality in the European Union are modelled.

We consider four distinct scenarios to analyze the socio-economic implications of the FF55 package. The initial scenario (REF) serves as reference. The remaining three scenarios are policy-driven, incorporating variations in electricity prices and shifts in the technology mix, as determined by ESOPUS analysis. All policy scenarios assume that achieving the targeted objectives will involve an increase in the implicit costs associated with emissions from the electricity sector. This increased emissions cost is introduced in the model as a tax imposition, generating additional tax revenues for governments. The distinction between the three proposed policy scenarios lies in how the new tax revenue is allocated (see Table 2).

Table 2. Esopus and Fidelio scenarios

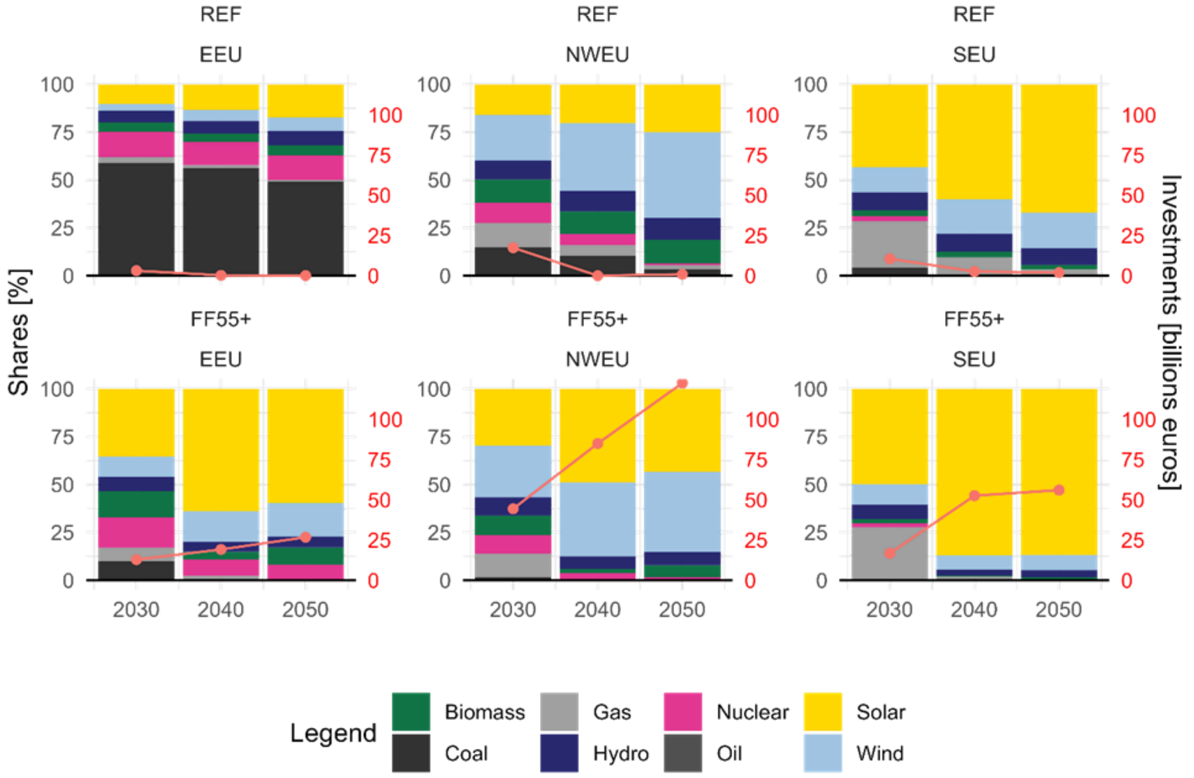
	REF	FF55+		
ESOPUS	No climate policy for the energy sector	FF55 in 2030, Net Zero CO2 emissions in 2050		
FIDELIO		FF55+_no_red	FF55+_hous_red	FF55+_mix_red
		FF55+, no revenue redistribution	FF55+, revenues to households	FF55+, revenues to households and government

3.1.2. Results

Firstly, our analysis will concentrate on the outcomes for the entire EU, followed by a more detailed assessment of the Italian peninsula. When looking at the results for Europe, EU countries are grouped in three regions: Eastern countries (EEU), North-Western countries (NWEU) and Southern European countries (SEU).

Results for investment optimization in the years 2030, 2040, and 2050 in the two ESOPUS scenarios are presented in Figure 3.

Figure 3. Electricity generation shares by technology and EU region



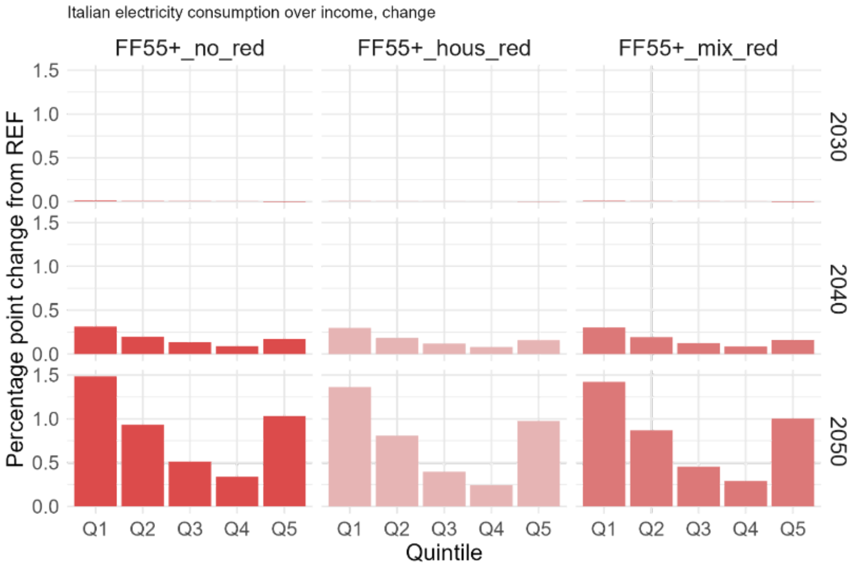
In Eastern European Union countries, coal generation remains dominant without policy changes, while the FF55 package requires rapid decarbonization to meet collective goals. In North Western EU nations, wind power is significant in both REF and FF55+ scenarios. However, FF55+ requires an increased commitment to solar tech due to limited resources, impacting investments. Southern European Union countries favor photovoltaic power. Comparing the two scenarios in SEU, electricity generation shares and investments look quite similar for the year 2030. On the other hand, for 2040 and 2050 the FF55+ scenario would require around 75% of the power supply to come from solar technologies.

We also aim to provide insights into the potential macroeconomic impact of these policies, with particular attention to some of the consequences in redistributive terms, across EU regions and in Italy.

The impact of policies on real GDP across EU regions varies significantly. Southern European countries initially experience a positive effect on GDP (around a 1% increase) but shift to a negative trend after 2030. Government redistribution decisions are crucial. For instance, in the final year, a policy involving household revenue redistribution reduces the impact on real GDP by 40% compared to a policy lacking this redistribution (resulting in a change from -3.4% to -2.1% GDP variation in SEU regions).

In the evaluation of the distributional impact in Italy, our focus is on understanding the effects of an increase in electricity prices on households, and we assess whether these effects differ among quintile groups. In this regard, we look at the electricity consumption share for each quintile. Figure 3 shows the change in the electricity consumption share comparing the policy scenarios to the reference scenario. The vertical axis of the graph represents the percentage point change in the share of electricity consumption compared to the reference scenario in each period and under each policy scenario.

Figure 4. Electricity consumption share, percentage point change from the baseline



The change in electricity consumption share is negligible in 2030, low in 2040, and more pronounced in 2050. In addition, it is U-shaped, suggesting a relatively stronger increase in particular for the first quintile. An increase in the electricity consumption share for low-income households means that a larger share of their total income is now allocated to electricity expenditure. The fact that the electricity consumption share increases more for low-income households suggests a regressive impact only slightly offset by the types of redistribution analyzed. These findings have important policy implications: measures should be taken to address the disproportionate impact on low-income households.

To check the robustness of the results, we look at an alternative metric for assessing the effects of an increase in electricity prices on different quintile groups, i.e., changes in consumer surplus. In particular, we focus on the policy scenario with full redistribution to households, the most equitable of those analyzed.

Our primary finding underscores that consumer surplus losses resulting from the policy exert a more pronounced impact on the less affluent quintiles, even in a scenario with redistribution to households. If the government redistributes resources in a balanced manner, as assumed in our scenario, this may not fully offset the adverse consequences of the policy on low-income households. Again, the result shows the regressive nature of the policies analyzed and the importance of the redistribution mechanism put in place.

3.2 Analysis of the long-term effects of restrictions on trade with Russia on the European energy system

The policy indications set out in the European Green Deal and the REPowerEU Plan (European Commission, 2022) represent the pillars of the analyses carried out via TEMOA-Europe and are given as constraints to the model to design future energy scenarios.

Two scenarios are analyzed here: the first replicates the anticipated unavailability of Russian fuel imports starting from 2030 as in the targets of the REPowerEU Plan (European Commission, 2022), while the second is based on no change in the willingness of European countries to depend on Russia for the supply of primary energy commodities. However, the two scenarios have other common features as described below.

GHG emission limits

The complete decarbonization of the European energy system is the basic hypothesis for all the scenarios presented, with a trajectory for the complete reduction of CO2 equivalents by 2050, setting the first constraint in 2030. CO2, CH4, and N2O emissions have combined their global warming potential for over 100 years (IPCC, 2021). The imposed emission reduction trajectories for CO2 and CO2 equivalents are shown in Table 2.

Table 2. GHG emission reduction trajectories implemented in TEMOA-Europe

Period	CO_2 limit (Gt)	$CO_{2\,eq}$ limit (Gt)	Reduction on 1990 (%)
2030	1.780	2.100	55.0
2035	1.190	1.400	70.0
2040	0.595	0.700	85.0
2045	0.297	0.350	92.5
2050	0.000	0.000	100.0

Energy service demands

The demand constraint is binding for TEMOA-based models so that all the energy service demands must be met precisely. In TEMOA-Europe, the levels of energy service demands are projected according to socio-economic drivers for OECD Europe, as retrieved from (U.S. Energy Information Administration, 2021).

Constraints on the supply of primary energy commodities

In TEMOA-Europe, fossil resources are supplied by inland production and imports. While TEMOA-Europe is forced to follow the historical data series (IEA, 2023) for fossil fuel production, imports and exports up to 2020, costs become a decision-making parameter starting from the 2025 period when the choices are made according to a cost minimization algorithm. The availability of natural gas and LNG imports from each region can grow according to the planned expansion of import capacities or medium-to-long-term agreements, as in Table 3.

Table 3. Constraints on imports of natural gas via pipeline and LNG in TEMOA-Europe

Commodity	**Import region**	**2020 import (EJ/year)**	**Maximum import (EJ/year)**	**Minimum import (EJ/year)**	**Motivation**
Gas pipeline	Africa	1.41	2.78 (starting in 2030)	-	Maximum current pipeline capacity (Bruegel, 2023)
	Central Asia (Azerbaijan)	0.281	0.703 (starting in 2030)	-	EU-Azerbaijan agreement (European Commission, 2023)
	Middle East Asia (Israel)	0.00	0.387 (2030) → 0.703 (2050)	-	EastMed-Poseidon project (Edison, 2023)
	Russia	13.7	Scenario-dependent	-	-
LNG	Africa	1.01	1.01	-	-
	Latin America	0.182	0.182	-	-
	Middle East Asia	0.989	1.357 (starting 2030)	1.357 (2030)	Long-term agreements with Qatar (Eni, TotalEnergies, Shell) (Reuters, 2023)
	Russia	0.568	Scenario-dependent	-	-
	USA	0.835	2.59 (2030)	2.59 (2030)	EU-USA agreement (European Commission, 2023); Educated guess (2050)

Constraints for maximum oil and coal imports are not applied since they inevitably require total phase-out in NZE scenarios.

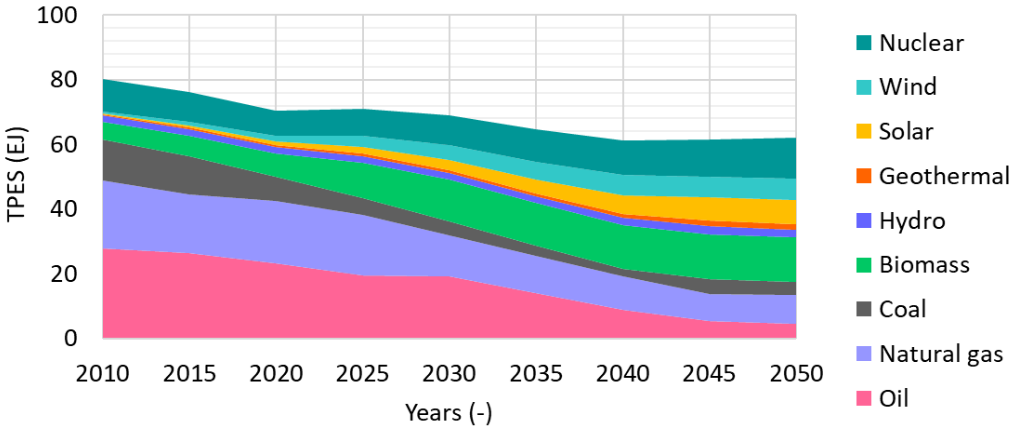
While all the features mentioned so far are valid for the TEMOA-Europe scenarios to be analyzed here, the only variables are the availability of Russian fuel imports and the amount of nuclear fission capacity that can sustain a transition towards a NZE energy mix.

3.2.1. Results

The results will cover the primary energy supply mix, the composition of the electricity generation sector, and the GHG emissions trajectory to reach NZE by 2050.

The total primary energy supply (TPES) for the scenario in which Russian fuel imports are not available starting from 2030 is shown in Figure 5. It highlights how the peak in fossil fuel consumption should have been reached by 2025. A complete revolution should be achieved by 2050 to comply with ambitious emission reduction targets. Renewable sources alone contribute to more than 50% of TPES by 2050, leading to a system dominated by clean sources (70% with the nuclear energy). Fossil fuels, and in particular natural gas, still represent a non-negligible contribution by mid-century, mainly due to their role in the hydrogen generation sector for gray and blue hydrogen production.

Figure 5. Projection for total primary energy supply in OECD Europe from 2010 to 2050



The evolution of the electricity generation sector illustrated in Figure 6 for the scenario considering the unavailability of Russian imports indicates a requirement of almost double 2020 production levels. Traditional fossil fuel plants are fully phased out only after 2040, while CCS-equipped plants become cost-effective but not crucial precisely mid-century (4% of total generation in 2050). Renewable sources represent more than 60% of total generation in 2050, while nuclear energy contributes 19%.

Figure 6. Computed electricity generation mix for OECD Europe from 2010 to 2050 for the scenario considering the unavailability of Russian imports

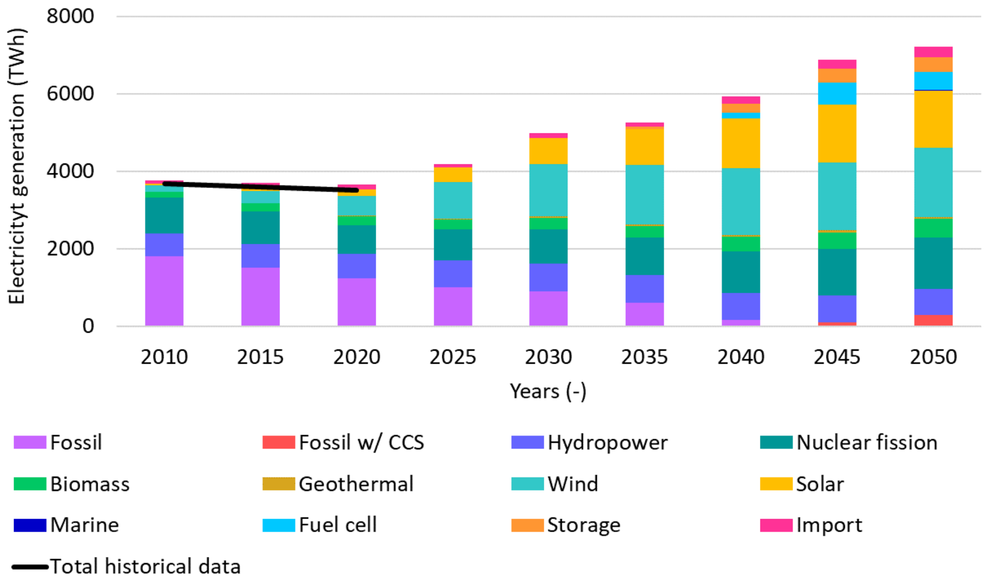
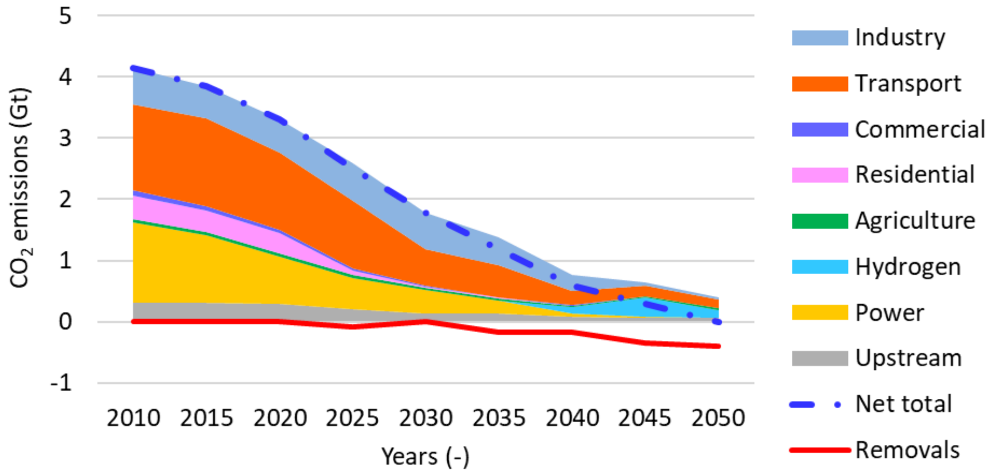


Figure 7 shows the trajectory for CO_2 emissions in the scenario considering the unavailability of Russian imports. CO_2 emissions can reach net zero thanks to the (limited via constraints) adoption of CCUS and afforestation measures. The hydrogen sector is the third major contributor to CO_2 emissions in 2050 with the adoption of gray and blue hydrogen technologies.

Figure 7. Computed CO2 emissions trajectory in the scenario considering the unavailability of Russian imports



4. Policy implications

4.1 Fit-for-55 and beyond: European power system transition and its social impacts

The FF55 package represents a notable step in addressing the pressing climate crisis. The European power sector is undergoing a positive trajectory even without explicit policy instruments. Emissions reduction targets for 2040, targeting a 90% reduction, are undeniably ambitious.

Our analysis has revealed significant variations in the technological development of electricity systems in European countries, with varying macroeconomic impacts. Policymakers should acknowledge these regional disparities and develop strategies to ensure fairness and sustainability throughout the EU. Addressing regional differences is a key priority in the EU, consistent with EU policies as well as with the broader aim of achieving economic and social cohesion across the EU.

The technological feasibility and economically optimal energy transition strategy in the ESOPUS model and the economic and social framework provided by FIDELIO are the basis for the analysis. However, neither of these models addresses the aspect of political feasibility, which may be a pivotal factor. Political choices made at the Union level might encounter different obstacles in some Member States. Vulnerable countries may need specific incentives and tailored instruments to boost co-benefits from energy decarbonization.

Looking specifically at Italy, our study indicates that solar energy will be pivotal to achieving policy targets in the electricity sector: boosting photovoltaic installations to reach climate neutrality may increase the investments needed in the transition by 2040 and 2050. These costs might negatively impact on the country's GDP, hitting lower-income households more severely with increased electricity prices. This raises concerns about the regressive nature of the policy, which has the potential to impact social conditions, reducing the overall well-being of vulnerable population groups. The design of the policy redistribution mechanism is pivotal in mitigating adverse effects on low-income households. Policymakers should pay particular attention to the effectiveness and fairness of these mechanisms. Implementation may involve the introduction of specific subsidies, strengthening safety nets, or providing exemptions for vulnerable populations.

4.2 Analysis of the long-term effects of restrictions on trade with Russia on the European energy system

Two main implications arise from the scenarios presented in the above section. Following the provisions of the REPowerEU Plan, greater integration of renewable energy sources is the main pillar of successful transition to NZE by 2050, as clear from Figure 5. On the other hand, the current trend of nuclear fission phase-out in Europe is in sharp contrast with climate targets. The achievement of a decarbonization scenario in TEMOA-Europe is only possible with at least 180 GW installed by 2050, against the current capacity of about 120 GW and a projected capacity decline to 80 GW according to (Lerede and Savoldi, 2023).

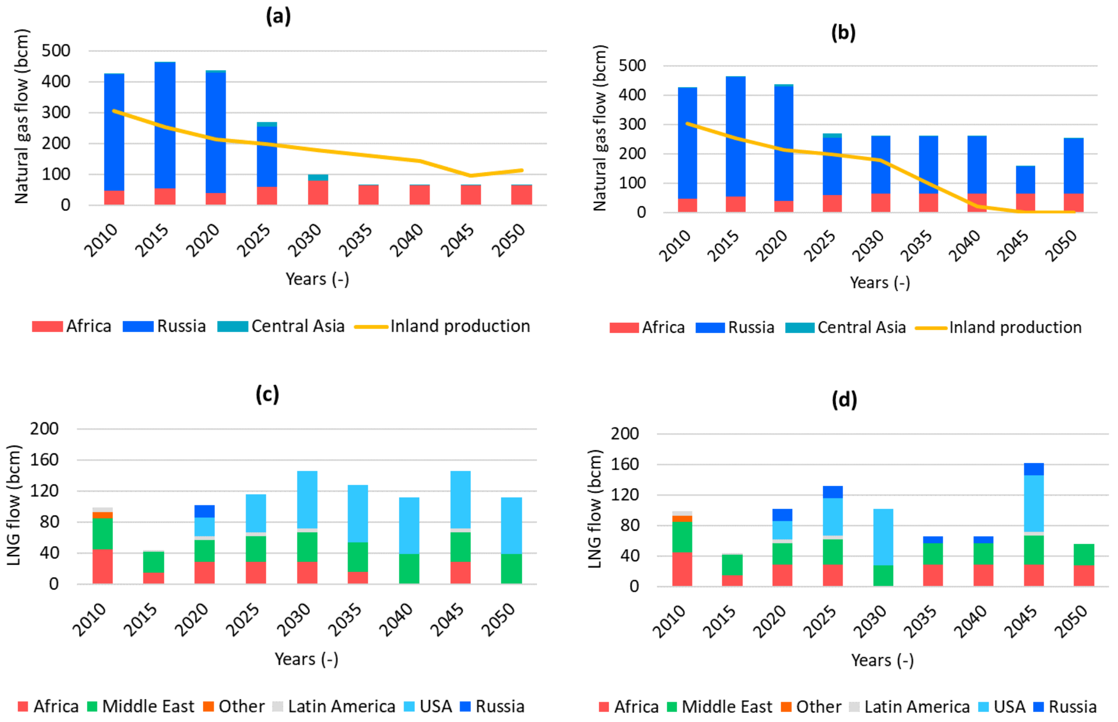
Bioenergy (as shown in Figure 5) is a serious candidate for supporting the transition. The implementation of CCUS and sequestration through synfuel production is not seen in TEMOA-Europe as a high potential decarbonization measure mainly due to the very high costs attributed to CCS-equipped technologies.

Despite the very extensive range of clean energy technologies in all supply and demand sectors, TEMOA-Europe is currently unable to trace a trajectory for the complete abatement of GHG emissions. Indeed, CO2 emissions may reach net-zero levels, while CO2 eq (which include CH4 and N2O) cannot be brought to zero.

4.2.1.The long-term effects of restrictions on trade with Russia on the European energy system

The assessment of gas supply through the TEMOA-Europe time scale when considering 1) the unavailability of Russian (not just gas) imports and the agreement for new LNG supply contracts as in Table 3 (see Figure 8a for gas by pipeline and Figure 8c for LNG) or 2) the availability of Russian gas (see Figure 8b for gas by pipeline and Figure 8d for LNG) shows that a slightly higher total quantity of gas is required in the latter scenario. Pipeline gas imports from Russia remain substantially higher until mid-century when available (see Figure 8b), while LNG imports from the USA replace the missing portion when trade with Russia is suspended.

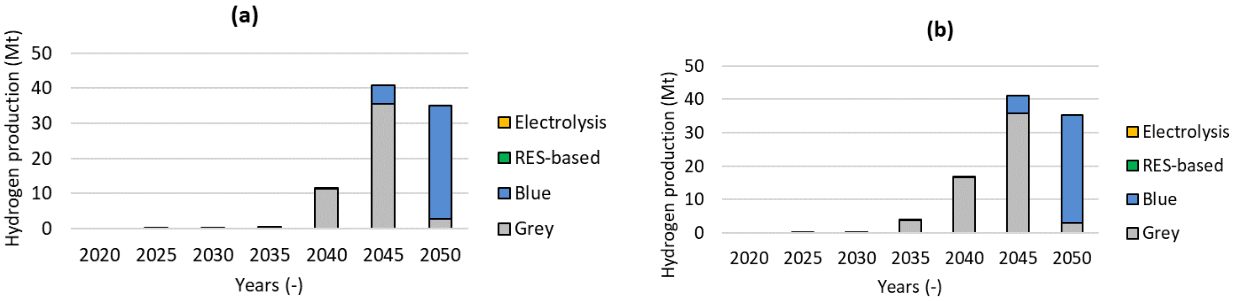
Figure 8. Composition of natural gas supply structure under different scenarios



Our results suggest that moving towards clean sources in the longer term requires more effort than thinking about how to replace Russian imports in the short term and that interrupting (fossil) fuel imports from Russia should be taken as an opportunity to press forward with the transition to a decarbonized energy system rather than an excuse not to succeed.

The model considers hydrogen production and consumption as a good decarbonization alternative starting from 2040, but electricity is mainly used to decarbonize hard-to-abate end-use sectors (as in the case of the transport and industrial sectors, see Figure 7) rather than to produce green hydrogen, as shown in Figure 9. Hydrogen cannot be considered a game changer in the analyses produced here and the quantities produced (corresponding to 4 EJ of consumable energy) are used principally in the electricity sector alone (see Figure 6), in fuel cell-based electricity generation plants. This leads to a dual conclusion. At currently anticipated cost levels, hydrogen may replace fossil fuels in the electricity sector alone and only by mid-century. On the other hand, the electrification of end-uses is required to foster the decarbonization process, while its use for hydrogen production may be pointless in a context in which most sectors are driven to net-zero emissions.

Figure 9. Composition of the hydrogen production sector in the scenario considering the suspension of energy trade with Russia (a) and in the opposite scenario (b).



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