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Energy vulnerability and resilience in the EU: concepts, empirics and policy

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Abstract
This paper analyses energy vulnerability and resilience in the EU. First, a comprehensive review of the relevant literature is carried out, discussing key concepts and indicators used to assess countries' relative positioning vis-à-vis energy shocks. Second, we rely on a large set of indicators (i.e., share of energy intensive industries, import dependency and market concentration, productive and technological capabilities in the renewables domain, policy efforts to increase energy resilience) to provide a thorough mapping of EU Member States' positioning in terms of energy vulnerability and resilience. Third, we assess industrial and energy policy actions put in place at both the EU and the national level, highlighting relevant heterogeneities and discussing whether policy efforts are consistent with the degree of vulnerability of Member States.

Keywords Energy vulnerability · Energy resilience · Europe · Industrial policy

JEL classification C38 · O13 · Q43 · Q48

1 Introduction

Since the explosion of the war in Ukraine, accelerating the energy transition has become a top policy priority in Europe (Tagliapietra et al., 2023). This is not surprising, though. Energy is in fact one of the main drivers of the surge in inflation that,

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albeit attenuated, is still conditioning monetary policy and, hence, growth in most economies, including the European Union (EU) (Ferreira et al., 2024). To mitigate the risks of a renewed inflationary crisis, economic policy toolboxes are being updated in an effort to reduce vulnerabilities as well as strengthening resilience vis-à-vis energy shocks. In the context of a generalized (and, yet, contradictory) rediscovery of industrial policy, the European Commission (EC) shifted from merely incentivizing green consumption and investments, to interventions aimed at reinforcing not only renewable energy production, but also productive and technological capabilities in key supply chains (e.g., solar panels, batteries, wind turbines) (Kleimann et al., 2023; Veugelers et al., 2024). A paradigmatic example is the RePowerEU plan, which intends to make the EU carbon-neutral by 2050 and decouple from Russian energy imports by 2027. Nonetheless, as the interdependencies along energy-related supply chains start being 'weaponized' (Drezner et al., 2021), Europe had to experience first-hand its structural vulnerability (Caravella et al., 2024). While the supply of energy from renewable sources is still grossly inadequate to meet the demand stemming from a rather energy-intensive manufacturing base, dependence on imported fossil fuels proved to be significantly high (Carfora et al., 2022). On the other hand, diversification capacity turns out to be asymmetrical across Member States and, in many cases, not up to the challenge (Celi et al., 2022).

Indeed, what explains such a policy urgency are the potentially heavy socio-economic consequences of energy shocks. Growing energy bills may jeopardize competitiveness and growth, turning into industry-level crises, unemployment and rising inequalities. The less diversification capacity and resources are available to put in place both short- and long-term policy actions, the stronger and more persistent such effects can be. The scale of the problem has been highlighted by the significant amount of resources that the EC and most member states have to put on the ground, since February 2022, to protect incomes and support businesses facing skyrocketing energy prices (Sgaravatti et al., 2023). Yet, these efforts risk being frustrated by the peculiar flaw that has already weakened the EU economy during recent crises (i.e., the GFC and the Covid-19 crisis): its internal divergence and the parallel lack of cooperation/coordination in terms of both fiscal and industrial policy (Celi et al., 2020).

In the case of the energy crises, this problem is further exacerbated by the fact that EU economies face significantly heterogeneous conditions (Celi et al., 2018, 2020; Massetti & Exadaktylos, 2022; Rhinard, 2019). As some member states are characterized by a relatively large share of energy-intensive industries, others have a more service-oriented industrial structure. Likewise, while in some member states the share of energy stemming from renewable sources has already reached remarkable levels, in others imported oil and gas represents the fundamental source of supply. Similar heterogeneities can be detected if one looks at productive-technological capabilities in key green sectors. Unsurprisingly, such a structural divide matches with asymmetries concerning EU member states' room for manoeuvre on the fiscal and industrial policy side and, unfortunately, the mismatch is often the unlucky one: resources tend to lack where are needed the most. Such heterogeneity adds to the core-periphery divide that has accumulated in parallel with the process of monetary integration, making the situation even more complicated (Gräbner et al., 2020).

In this context, research may play an important role, allowing to identify the relevant dimensions of energy vulnerability and, relatedly, to empirically map the positioning of economies with respect to such dimensions. This is the goal of this article, which is articulated in three steps. First, building on the recent literature (e.g., Gatto et al., 2024), the key supply, demand and policy drivers affecting energy vulnerability and resilience are discussed; and the main indicators used to measure it are illustrated (Sect. 2). Second, relying on a comprehensive set of empirical indicators, EU member states are mapped focusing on all the relevant dimensions that may affect their degree of vulnerability to adverse shocks, as well as the factors that may improve their resilience. The analysis is carried out over a rather long-time span, to highlight country-specific patterns as well as relevant discontinuities (Sect. 3). Third, an assessment of key EU policy actions aimed at reducing vulnerability and increasing energy resilience is provided, discussing whether there is consistency between size and characteristics of such policy efforts and the structural conditions of member states (Sect. 4). We conclude by discussing policy implications and avenues for future research.

2 Assessing economies positioning vis-à-vis energy shocks: concepts and definitions

As often happens, complex issues that become ubiquitous in the policy debate are exposed to the risk of inaccurate or partial representations. This is true also regarding economies' ability to cope with energy shocks or, using the most common concepts found in the literature, their degree of energy vulnerability and resilience. The two are intertwined yet not overlapping concepts (Stirling, 2014), as two entities facing the same degree of vulnerability vis-a-vis energy shocks—for instance, because both have a large share of employees in energy intensive industries risking to lose their job should an energy shock occur—might be heterogeneously endowed concerning the resources (e.g., relative diversification of the supplier base, ability to produce energy in house from renewable sources, technological-production capabilities in the green domain) needed to minimize socio-economic costs and accelerate post-shock adjustment. Both concepts, in turn, are linked to the dependence on specific energy sources, as well as the security of their supply. Indeed, resilience and vulnerability are multifaceted phenomena, assuming different shape and intensity according to the aspects that are emphasized (e.g., import dependency, geopolitical risks associated to the dependency on specific suppliers, degree of diversification of the energy portfolio) or the structural characteristics (e.g., sectoral specialization) of the entity (e.g., country, region, supply chain) taken into consideration. As a result, a proper assessment requires identifying the relevant determinants driving the phenomenon at stake, possibly grasping the relationships between them.

From an empirical viewpoint, in turn, this calls for the use of composite indicators (Nardo et al., 2005; OECD, 2008; Percebois, 2007). As Sovacool and Mukherjee (2011) emphasize, trying to comprehensively measure energy vulnerability or security relying on single indicators is "akin to trying to drive a car with only a fuel gauge, or to seeing a doctor who only checks your cholesterol" (Sovacool & Mukherjee, 2011, p. 5343). In what follows, we, first, present the available definitions of vulnerability and resilience as provided in the energy economics literature, illustrating their main dimensions and the relevant indicators used to measure them. Second, we discuss the man supply, demand and policy-related factors that may shape their intensity and territorial distribution.

We define energy vulnerability as the degree to which a country is prone to adverse energy-related shocks, such as supply disruptions and price volatility, highlighting weaknesses (e.g., reliance on a single energy source, high import dependency, or a large share of energy-intensive industries) that may increase the likelihood and severity of negative impacts (Gatto & Busato, 2020; Gnansounou, 2008; Gupta, 2008). In contrast, energy resilience refers to a country's capacity to absorb and adapt to such shocks, emphasizing systemic strengths (e.g., own energy reserves, supply diversification) that may mitigate the same negative effects (Aldieri et al., 2021; Dong et al., 2021; Gatto & Drago, 2020a, b, 2023). A country[1] characterized by high energy vulnerability is, therefore, expected to face severe consequences in the event of an energy shock, as compared to less vulnerable economies. Yet, as argued, magnitude and length of such consequences may vary even among countries facing the same degree of vulnerability, due to the potentially heterogeneous distribution of the resources needed to mitigate them. That is, the ultimate impact of energy shocks will be determined by the combination of factors shaping both vulnerability as well as resilience. In this respect, the energy crisis that struck the EU as a consequence of the war in Ukraine is a relevant case in point. Despite virtually all member states proved vulnerable to disruptions affecting the oil and gas supply chains, their capacity to preserve production levels, protect those most affected by growing energy prices or to promote a fast structural adjustment (e.g., supplier diversification, increasing the amount of energy produced relying on renewable sources) has been highly heterogeneous (Celi et al., 2022).[2]

The economic literature does not uniquely characterize and perhaps does not offer a clear-cut definition for these concepts (Cherp & Jewell, 2010), mostly because the focus of researchers and policymakers has shifted over time, driven by prevailing contingencies. Originated in research on natural disasters and conflicts in the 1960s, the concept of energy vulnerability entered economics debate during the oil crisis of the 1970s (Ebinger, 1984; Janssen et al., 2006; Plummer, 1981) and gained track in research over the last decade. While initially focusing prominently on *availability* of fossil fuels (particularly oil), during the 1990s there has been a progressive pressure to include other dimensions, with research focusing on *affordability* and its impact on national welfare (Sohn, 1990; Toman, 1993); *technological efficiency* of the energy

[1] Notice that the regional level is another key unit of analysis to be considered, as different territorial entities may be heterogeneously positioned vis-à-vis energy shocks. Yet, this kind of investigation goes beyond the scope of our analysis and will be left for future research.

[2] Other concepts/dimensions analysed in the literature, which overlap in most aspects with 'vulnerability' and 'resilience' are that of 'energy security' (defined by the International Energy Agency as the "uninterrupted availability of energy sources at an affordable price"), or 'energy poverty' ("the inability of households to afford sufficient heating and energy for needs such as cooking, heating, and lighting"; Hihetah et al., 2024, p. 2; see also Huong & Ha, 2023).

and industrial systems, together with its adaptive capacity; and, finally, *environmental sustainability* concerns, with the recent attention on emissions and pollution.

These five dimensions and their components are reported in Table 1, along with the related indicators/statistics used to measure them (Ang et al., 2015; Dong et al., 2021; Gatto & Drago, 2023; Liu et al., 2023; Sovacool & Brown, 2010; and the references therein). The choice regarding which indicators to include in the analysis was guided, on the one hand, by the availability of data for all EU countries and, on

Table 1 Energy vulnerability and resilience: dimensions, components, and indicators

Dimensions	Components	Indicators => higher leads to	Effect on vulnerability	Effect on resilience
Energy availability	Security of supply and production	Energy reserves*	–	+
		Energy primary production*	–/+	+/–
		Reserves-to-production ratios*	–	+
		Energy supply mix	–	+
		Energy consumption (by fuel type)	+	–
		Installed electricity capacity	–/+	+/–
	Dependency	Import dependency rate (by fuel type, by material)	+	–
	Diversification	Energy production mix	–	+
		Supplier diversification (Herfindahl-Hirschman index)	–	+
		Energy consumption mix	–	+
Energy affordability	Price stability	Electricity prices and volatility (by type of consumers)	+	–
	Access and equity	Household energy consumption (level and mix)	+/–	–/+
		Arrears on utility bills	+	–
		Inability to keep home adequately warm	+	–
Technological efficiency	Innovation and research	R&D in energy^	–	+
		Energy patents^	–	+
		Public and private research intensity (% of energy R&D on total R&D)^	–	+
	Investment and employment	Number of green plants°,†	+	–
		Direct/indirect employment in energy sector°,†	+	–
		Investment in energy sector	–	+
Energy intensity	Energy use	Energy intensity (i.e., TPES/GDP)	+/–	–/+
		Energy intensity in manufacturing	+/–	–/+
	Industrial structure	Share of energy-intensive industries	+/–	–/+
Environmental sustainability	Use of soil	Land use with heavy environmental impact	+	–
	Climate change and pollution	GHG emissions (by sector)	+	–

Source: Own elaboration based on Eurostat; (*) IEA; (^) JRC SETIS; (°) EurObserv'ER and (†) Bruegel data

Notes: the inclusion of indicators is based on: (i) a review of Ang et al. (2015); Gatto and Drago (2023); Liu et al. (2023); Sovacool and Brown (2010); and the references therein; (ii) the availability of comparable time series data for EU countries the other, by the presence of fairly long time series, which allow tracking long-run dynamics.[3]

Energy availability. As European countries are generally resource-poor, the energy availability dimension critically depends on import diversification and geopolitical factors. Through diversification of supply sources, energy importers can reduce and better mitigate the risks of import disruptions. Concerns about geopolitical issues include events such as outbreaks of wars, destabilized regimes, or regional tensions which can lead to oil or gas supply disruptions. From a domestic standpoint, the availability of energy mainly refers to the security of supply for the production system, including the available stocks of reserves or the installed electricity capacity. Looking instead at trade relationships, two aspects are paramount. First, the country's import dependency, with large heterogeneities among fuel type. All else equal, a country which is highly dependent on a specific fuel type is particularly vulnerable to shocks in that market. Second, what matters is the diversification of both its energy mix, and the diversity and the political risks of supply sources (Le Coq & Paltseva, 2009). Stemming from financial portfolio theory, the concept of energy supply diversity implies that the more diversified the portfolio of suppliers, the higher the energy security (Cohen et al., 2011; Gupta, 2008).[4]

Energy Affordability. This dimension relates to the ability of the private sector, particularly households, to freely access energy goods and services at affordable and stable prices (Bielecki, 2002; Fan et al., 2022; Willand et al., 2023). Also in this case, some factors—as heat pumps, solar panels, or wind turbines—may improve the systems' resilience, mitigating the effects of shocks (Ghasemieh et al., 2015), while others—a high number of energy-consuming appliances, price volatility, or taxes on energy goods and services—increase the overall vulnerability of the system, as the private sector has less buffers to cope with the shock.

Technological efficiency. This dimension is also key, as it affects both vulnerability and resilience in different ways. An important role is played by investments in innovation and research, such as R&D expenditure in energy and the number of energy-related patents, which can drive advancements in technology crucial for safeguarding critical infrastructure and minimizing disruptions. Moreover, knowledge spillovers from environmental innovations can reduce inefficiency, therefore strengthening the resilience of economies adequately investing in the transition to more sustainable technologies (Aldieri et al., 2021). Technical resilience and adaptive capacity are, in turn, vital for maintaining uninterrupted energy supply, reflected in metrics like capacity margins, utilization rates, and emergency stockpiles, which ensure a robust response to emergencies and crises. Finally, investment and employment dynamics play a crucial role in bolstering national resilience, shaping the overall capacity for growth and innovation across industries.

[3] This led us to exclude other important components and indicators, such as the degree of decentralization, which affects energy affordability, and is measured through the use of heat pumps, solar panels, wind turbines, etc.; or security risks associate to geopolitical tensions, affecting energy availability; safety and reliability dimensions, measured with the frequency and costs of natural disasters; or technical efficiency, measured by electricity capacity utilization or margins.

[4] Notice that, for some energy goods such as LNG, diversification goes beyond country of supply origin. The route of transport—pipeline or seaborne shipment—also matters.

Energy intensity. The structural characteristics of the productive system also affect vulnerability and resilience (He et al., 2017, 2019). A country that is specialized in energy-intensive manufacturing is generally more vulnerable to disruptions in energy markets, especially if the switch to other energy sources in the production process is difficult - either because of non-substitutability of energy goods or because of lack of alternative sources—or if they are systemically relevant as suppliers of key intermediate and final goods.

Energy sustainability. In recent years, environmental concerns have gained momentum, prompting a focused approach from researchers and policymakers towards enhancing *energy sustainability* (Chen & Lei, 2018; Escribano Francés et al., 2013; Genave et al., 2020; McLellan et al., 2012). This dimension has two main components, one related to the use of soil—including indicators relative to waste generation, percent of land use with heavy environmental impact, or water usage—and another one prominently focusing on emissions of greenhouse gas (GHG). These components not only affect environmental sustainability but also play a significant role in shaping energy vulnerability and resilience (Zhang et al., 2024). For instance, excessive energy-related waste generation and deforestation can increase environmental vulnerability, leading to resource depletion and heightened risks of supply disruptions. Similarly, unsustainable water usage practices can exacerbate vulnerabilities in regions dependent on water-intensive energy production.

In the analysis of energy vulnerability and resilience, the effects of individual indicators are often complex and context dependent. While many indicators have opposing effects on vulnerability and resilience, their impact can vary depending on country-specific characteristics, structural conditions, and interactions among different dimensions. For example, diversification of the energy supply mix generally enhances resilience by reducing reliance on a single energy source. However, diversification that increases reliance on carbon-intensive fuels, such as coal or oil, can undermine resilience and heighten vulnerability over the long term. Similarly, import concentration—heavy dependence on one or a few suppliers—reduces resilience by amplifying risks associated with supply disruptions. At the same time, achieving supplier diversification through imports from geopolitically unstable regions may inadvertently increase vulnerability. By the same token, overcapacity in terms of high installed electricity may increase resilience by improving readiness/flexibility to meet energy demand (improving resilience) but may also raise the risk of inefficiencies related to underutilization in certain contexts, thereby exacerbating vulnerability through increased costs.

The interplay of these factors underscores the need for a multidimensional approach. By examining a range of indicators and their interdependencies, rather than focusing on a single determinant, it is possible to provide a more comprehensive understanding of energy resilience and vulnerability. This approach, in turn, facilitates the design of targeted policies that address specific weaknesses while leveraging existing strengths.

Following the definitions given above, the next section maps EU member states focusing on several components of the four dimensions highlighted in Table 1 that may affect their degree of energy vulnerability and resilience.

3 Mapping energy vulnerability and resilience in the EU

In this section, we provide a detailed analysis of the energy profiles and degrees of vulnerability and resilience across EU member states, tracing their evolution over time. Special attention is given to country-level heterogeneities, discussing differences in the domains where countries show the greatest vulnerability. We further disentangle the five dimensions of energy availability, affordability, technical efficiency, energy intensity and environmental sustainability as well as the key factors shaping their intensity. Understanding these different dimensions and regional disparities is crucial for evaluating the adequacy of the EU's green industrial policy, which we will be discussed in Sect. 4.

3.1 The EU energy profile at times of war

The EU's energy landscape is characterised by a significant amount of heterogeneity, related to the availability of natural resources and differences in terms of sectoral specialisation (Hafner & Raimondi, 2022). Looking at data from the Energy Institute, as of 2020 only a handful European countries have proved reserves of natural energy sources.[5] Germany and Poland still have significant coal reserves (equal to 3.3% and 2.6% of world reserves, respectively), followed at distance by Czechia, Hungary, Greece, Bulgaria and Spain (ranging from 0.33% to 0.11% of world reserves). For gas and oil, the situation is even starker. Only the Netherlands, Poland, Romania, Italy, Germany and Denmark have gas reserves, but numbers are relatively small: for the Netherlands, the country with the highest reserves—the share in world reserves is just 0.1%. Finally, only Romania, Italy and Denmark have some oil reserves, thanks to their Black Sea, Mediterranean and North Sea fields but, again, numbers are negligible: for Romania, which has the largest stock of proved reserves, the reserve-to-production ratio stood at 22.7, while it is just below 15 for Italy. Yet, being resource-poor also has an upside, as it urges country to foster green technologies and improve energy efficiency.

The empirical analysis starts by examining how the energy mix and relative efficiency of each country have changed over the last decade. Figure 1 provides an overview of the gross available energy in the EU—that is, the quantity of energy necessary to satisfy the EU's energy needs—showing how the energy mix has evolved over the last thirty years. Despite the steady rise of renewable energy sources over this period, the EU energy portfolio still heavily relies on fossil fuels. As of 2022, oil and natural gas still play a dominant role, making up about 60% of the total energy supply. Unsurprisingly, there is considerable heterogeneity across EU Member States in terms of energy mix, as shown in Fig. 2, reflecting the varied natural resources, geopolitical and economic ties with major global (fossil fuel) players. It also signals the potential challenges and opportunities each country faces in transitioning towards more sustainable and resilient energy systems.

[5] See the annex to the 2024 Statistical Review of World Energy, available at https://www.energyinst.org/__data/assets/excel_doc/0020/1540550/EI-Stats-Review-All-Data.xlsx.

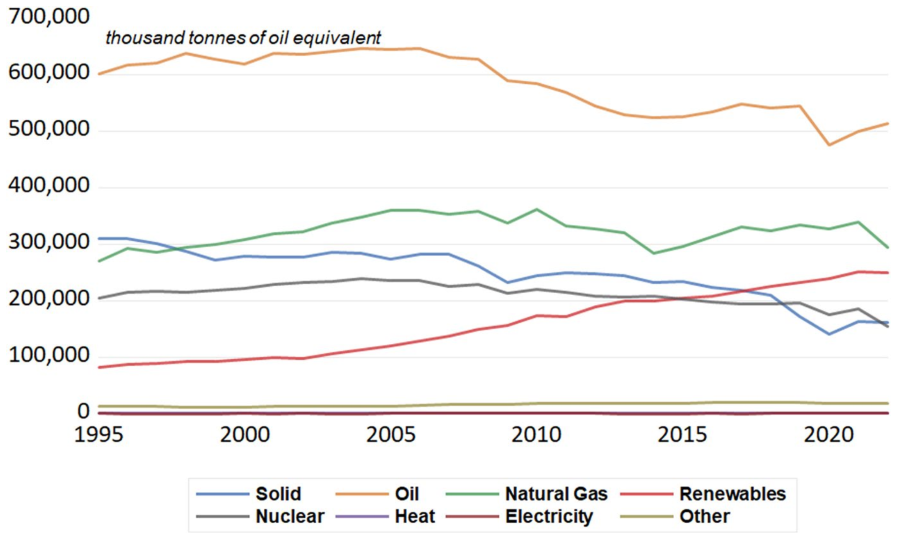

Fig. 1 Energy portfolio—gross available energy by source, EU27. 1995–2022. Source: Own elaboration based on Eurostat data

The Nordic countries—Sweden, Latvia, Denmark and Finland—are leading the green transition with renewables exceeding 40% of their energy use. In contrast, many Eastern European countries, including Bulgaria, Czechia and Poland, continue to rely heavily on solid fuels like coal, which make up almost one-third of their energy portfolio. Meanwhile, reliance on natural gas is particularly high in Italy, while Estonia relies heavily on 'other' sources, namely domestically produced shale oil. Although nuclear energy generally plays a minor role in the EU's energy mix, it remains significant in France, Belgium and the Visegrad countries. These nations not only reap benefits but also face challenges like high operating costs, the complex process of decommissioning old plants and waste management. France, which produces nearly half of the EU's total nuclear power, exemplifies these issues. In 2022, due to reactor maintenance, France's nuclear power production was reduced by nearly one-fourth with respect to 2021, exacerbating the energy crisis triggered by the war in Ukraine.[6]

Having explored the differences in the energy mix across the EU, we now turn our attention to the efficiency with which these energy resources are transformed in the production process, as well as their environmental impact.

Figure 3 shows the coevolution of energy and carbon intensity of GDP for all EU countries between 2010 and 2022. On the horizontal axis, countries are ranked according to their energy intensity levels, which is a proxy of a country's energy efficiency.[7] Two key observations emerge. First, it is evident that all countries have

[6] https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240112-1.

[7] Although the two concepts are related, they are not the same. Energy Intensity (EI) measures the amount of energy required to produce one unit of GDP. It reflects an economy's overall energy needs and is influenced by factors such as the structure of the economy, weather conditions, and living standards.

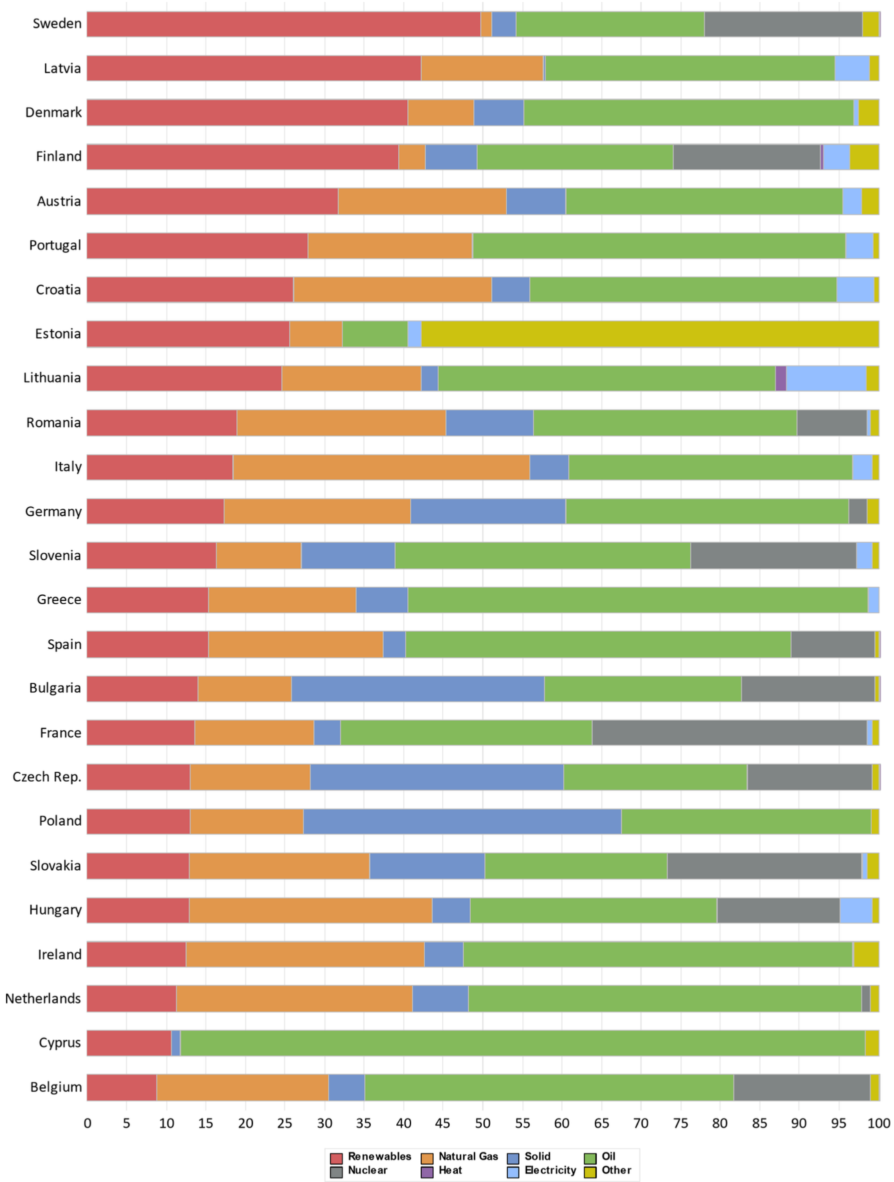

Fig. 2 Energy mix across EU Member States, 2022 (%). Source: Own elaboration based on Eurostat data. Notes: Figures refer to the share of various energy sources in Gross Available Energy. Countries are sorted by the share of renewables

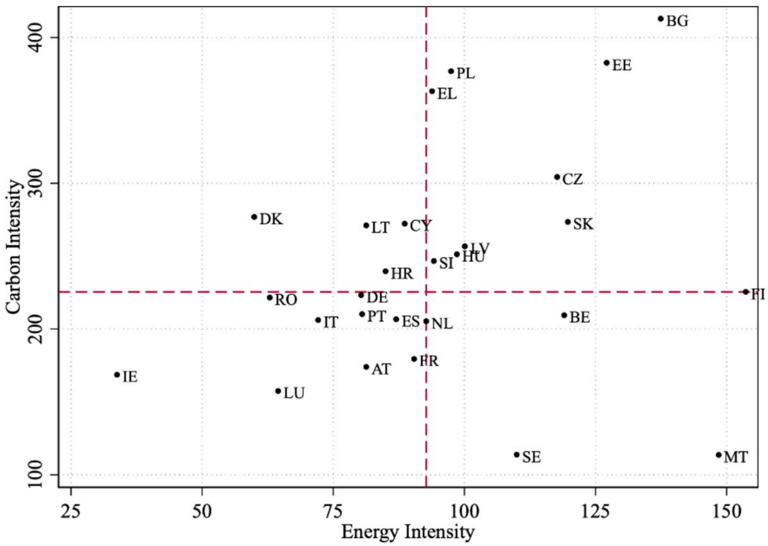

Fig. 3 Energy and carbon intensity of GDP, 2022. Source: Own elaboration based on Eurostat data. Notes: Dashed red lines denote median values. Energy intensity is defined as Gross Available Energy, expressed in thousand tonnes of oil equivalent, per million euro of GDP. Carbon intensity is defined as Greenhouse Gas emissions, expressed in thousand tonnes, per million euro of GDP. GDP is expressed at current prices, in purchasing power standards

seen a decline in energy intensity over the last decade. This reduction is commonly used as an indicator of improvements in energy efficiency, though it may also reflect shifts in the economic structure towards less energy-intensive industries. Second, energy intensity ranged from as much as 150 KGOE per thousand euro for Malta and Finland to below 65 for Italy, Luxembourg, Romania and Denmark.[8] On the vertical axis, we have instead the carbon intensity of GDP, that is the amount of Greenhouse Gas emissions (GHG) per point of GDP, expressed in PPS. Also in this case, there has been a general reduction in carbon intensity in the last decade. Yet, some countries, especially in the Eastern Periphery (and Greece), still face pressing challenges in this

For example, countries with a high concentration of energy-intensive industries, such as iron and steel manufacturing, tend to exhibit higher energy intensity due to the significant energy required by these sectors. Energy Efficiency refers to the ability to produce the same output using less energy. It is typically associated with technological advancements, optimized processes or behavioural changes that reduce energy consumption in specific contexts. For instance, an energy-intensive industry can improve its energy efficiency by adopting advanced technologies to lower the energy required to produce one unit of output. Eurostat publishes an energy efficiency indicator, which measures either primary or final energy consumption, and is used to monitor EU targets relative to Directive 2012/27/EU and Directive (EU) 2023/1791 on energy efficiency. Improving energy efficiency in specific industries can reduce energy intensity at the aggregate level, but the relationship is not always direct. A country specializing in energy-intensive industries may continue to have high energy intensity, even if those industries are highly energy-efficient. Conversely, structural changes that reduce the share of energy-intensive sectors, such as a shift toward a service-based economy, can lower energy intensity without necessarily improving energy efficiency.

[8] The very low figure for Ireland is due to its very high GDP, inflated by profit-shifting activities of multinational companies headquartered in the country.

domain, with Bulgaria, Estonia and Poland recording the highest values. Another concerning aspect relates to the use of soil (Figure 17). Although still far from the (worrisome) levels seen in the European 'core', where the share of land use with heavy environmental impact as of 2018 was as high as 13.9% in the Netherlands, 7.4% in Belgium and 6.7% in Germany, countries in the eastern periphery experienced among the largest increase in this indicator over the years.

These differences in energy efficiency levels are driven by a variety of factors, such as technological advancements, implementation of energy-saving policies and/or a shift towards a service-based economy which generally demands less energy than a manufacturing-oriented one (Duro et al., 2010; González-Torres et al., 2021; Su, 2023). In this respect, what plays a key role is the relative importance of the industrial sector and the degree of energy efficiency therein. Using a multi-factor energy input-output model on a panel of EU countries, Guevara et al. (2021) show that cross-country heterogeneities in terms of energy efficiency are mostly driven by industrial direct energy intensity, as well as by the mix of final energy demand; while what goes on in the rest of the economy—even in the energy sector—tends to play a minor role.

Interestingly, two Scandinavian countries, Finland and Denmark, exhibit significantly different energy intensity profiles. While Denmark has a strong service sector and high-tech industries that typically require less energy per unit of GDP, Finland, instead, has a strong manufacturing base, including pulp, paper and metal industries, which are more energy-intensive. Furthermore, Denmark is a leader in wind energy, whereas Finland, given its vast forests, has made progress in bioenergy. While nominally included among the renewable energies, the latter may however increase the overall energy intensity of the economy, due to the energy-intensive industrial processes that it entails (Ranta et al., 2020).

A high energy intensity, therefore, indicates that a country needs a large amount of energy to produce its goods and services, which suggests either lower efficiency or heavy industry. In 2010, Estonia was one of the EU countries displaying the highest energy intensity, partly due to its shale oil-based energy sector. Although its efforts to diversify and modernize led to a considerable decline in energy intensity over this period, its energy intensity is still high relative to other EU nations, with the second-highest level of GHG-to-GDP ratio.

3.2 Import dependency and vulnerability: trends and drivers

As the EU navigates a 'new global order' marked by escalating conflicts, disruptions in global value chains (GVCs), technological competition, and energy crises (Guarascio et al., 2025; Rodrik & Walt, 2022), it becomes essential to disentangle the multifaceted dimensions of energy vulnerability and resilience. Our analysis begins by examining the extent of import dependency across member states and identifying its primary drivers. We then explore the EU's position in renewable energy production and technologies, highlighting the asymmetric distribution of productive and technological capabilities across countries and the growing reliance on foreign goods and technologies critical for the transition to a net-zero economy. This focus is intentional: while reducing dependency on imported fossil fuels addresses immediate

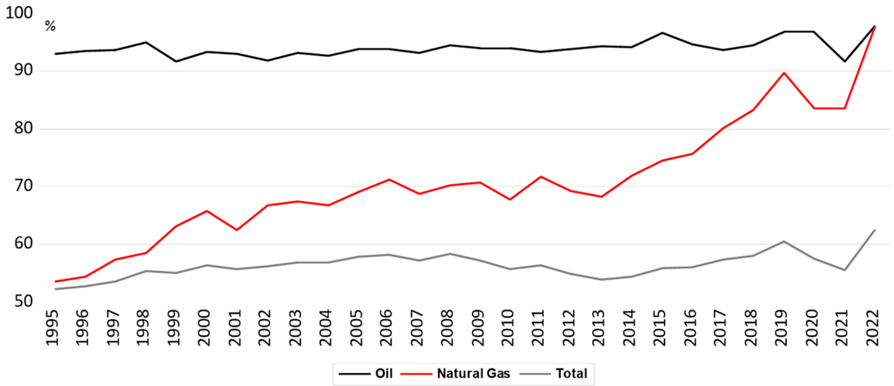

Fig. 4 Import dependency rate by source, EU27, 1995–2022. Source: Own elaboration based on Eurostat data. Notes: EID rate is calculated as the ratio of net energy imports of source *j* to gross available energy of source *j*

energy security concerns, it raises a parallel challenge of avoiding new dependencies on external suppliers of green technologies.

Eurostat defines the Energy Import Dependency (EID) rate as the share of imported energy required by a country to meet its total energy needs.[9] More formally, it is calculated as the ratio of net energy imports to gross available energy:

$$ED_i^j = \frac{(M_i^j - X_i^j)}{GAE_i^j} \tag{1}$$

where *i* denotes a country, *j* denotes an energy source, M and X represent imports and exports, respectively and GAE stands for Gross Available Energy.[10] This rate can be calculated for individual fuels (e.g., crude oil, natural gas) or as an aggregate across all energy products, since all energy sources are expressed in thousand tonnes of oil equivalent. It is noteworthy that EID rates can be negative, indicating a net export status, or exceed 100%, representing stockpiling of energy products.

Figure 4 shows the evolution of the total EID rate as well as specific trends for natural gas and oil and petroleum products. The overall dependency increased by 11% points, going from 52% in 1995 to 63% in 2022. While the import reliance for oil has remained steady and close to 100% since the mid-1990s, the dependence on natural gas imports saw a substantial rise of nearly 30% points since 2014, reaching nearly 100% in 2022.

[9] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Energy_dependency_rate.

[10] Note that according to the IEA methodology for computing Energy Balances, "*all nuclear energy production counts as domestic production, regardless of the origin of fuel for nuclear fission/fusion. In similar manner, all renewables and biofuels count as domestic production, regardless of the origin of feedstock (biomass or waste) from which it was produced.*" However, this may mask a significant import dependency for nuclear production intermediate goods and technologies, as well as fuels. For instance, while France has a high share of nuclear energy production, it imports most of nuclear-related technologies from Russia and most nuclear fusion/fission materials from Niger and Russia. As geopolitical tensions with both its main suppliers are on the rise, France may be said to be highly vulnerable in this respect.

Aggregate figures for the EU, however, mask considerable heterogeneity between countries. Indeed, in 2022, the total EID rates ranged from as low as 6.2% for Estonia to nearly 100% for Malta, with eight countries falling within the 70–80% range (see Fig. 5). Furthermore, also the evolution of EID over the last decade has varied greatly among countries. While half of the EU countries managed to reduce their dependency—with Sweden leading the way by reducing its EID rate by 11.6 p.p.—the other half experienced an increase over the same period.

Moreover, a closer look at the import dependency rates for gas and oil reveals an even more alarming scenario, with nearly all EU nations approaching or exceeding a 100% dependency rate (as detailed in Figure 18). Romania, Denmark and the Netherlands stand out as exceptions, maintaining an import dependency below 100% for these fuels, which reflects their domestic production.

Reliance on imported energy goods isn't inherently problematic; having nonzero values for import dependency is both normal and expected. This situation arises when a country's domestic production, whether from renewable sources or other natural resources, falls short of fulfilling its energy needs. In such cases, importing energy goods becomes the only viable short-term solution. While advancing the green transition will gradually decrease the EU's energy import dependency, this is a lengthy process that leaves some critical questions about today's energy resilience

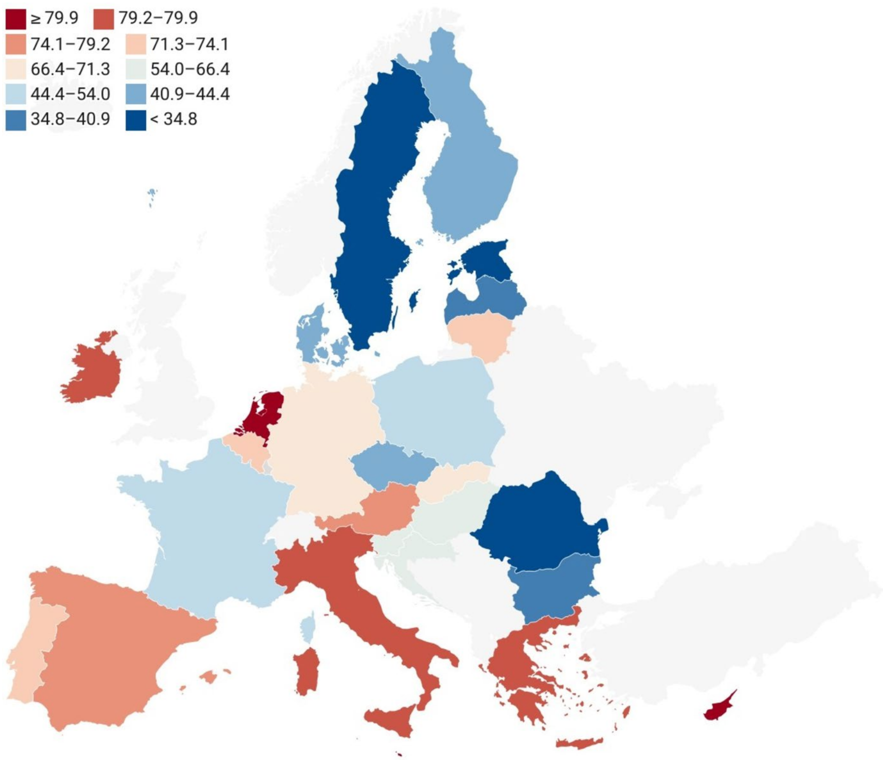

Fig. 5 Import dependency rate, 2022 (%). Source: Own elaboration based on Eurostat data. Notes: EID rate is calculated as the ratio of net energy imports to gross available energy

unanswered. Specifically, when does import dependency amplify a country's vulnerability to geopolitical risks and supply disruptions? To address this question, it is essential to consider two additional layers of dependency: imports from non-EU countries and the diversification of suppliers.

A higher proportion of energy imports from outside the EU can increase a country's overall energy vulnerability due to the risk of sudden supply disruptions in the event of geopolitical tensions, as the volatile relationships with non-EU partners can be unpredictable. As argued, the Russia–Ukraine war, which saw the weaponization of Russian gas, serves as a stark example of this dynamic (Celi et al., 2022). Additionally, the uneven geographical distribution of natural resources means that 'regionalisation' or nearshoring of energy supply chains to reduce external dependency is not always a practical solution and many EU countries must rely on non-EU partners. Vulnerability is not solely about the volume of energy imported but also how concentrated these imports are among different suppliers. In this context, the Herfindahl-Hirschman index (HHI) serves as a measure of the potential risk associated with limited supplier diversity. High HHI values indicate a higher risk of supply disruption due to geopolitical tensions or market volatility.

Figure 6 shows total energy import dependency against external import dependency (from extra-EU countries) and import concentration (as measured by HHI),

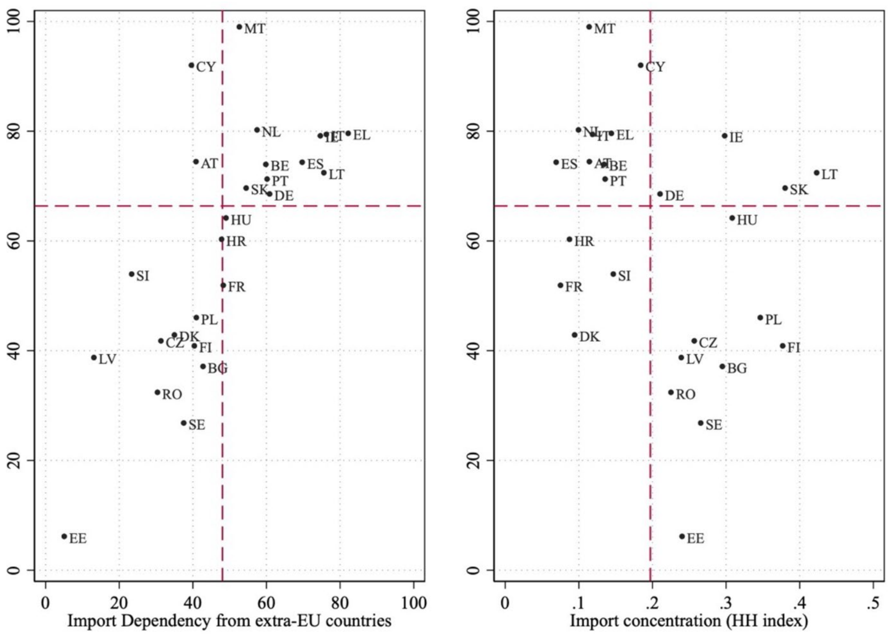

Fig. 6 Import dependency,dependency from extra-EU countries and concentration, 2022. Source: Own elaboration based on Eurostat data. Notes: Import dependency from extra-EU countries refers to the share of energy imports coming from partners outside the EU in total energy imports. Import concentration shows how varied import origins of energy sources used in a country are, and is measured by the Herfindahl-Hirschman index. This indicator can reach values only between 0 and 1. Lower values of this index means more diversified origins; higher values mean more concentrated origins

respectively.[11] The panel on the left-hand side shows how countries positioned further to the right are more dependent on energy imports from outside the EU, thus more exposed to geopolitical risks and supply chain vulnerabilities. Lithuania, Italy, Spain and Greece are notable examples. A higher HHI suggests greater vulnerability due to a lack of diversification among import sources—a critical aspect of energy security. Lithuania, Slovakia and Hungary, positioned further to the right, exhibit high import concentration, which may necessitate targeted actions to diversify their energy import portfolios. The HHI highlights the critical need for supplier diversification to mitigate the risks associated with high import dependency.

Table A1 and Table A2 provide an overview of the top suppliers of oil and gas for EU countries in 2022, shedding light on the degree of reliance on specific suppliers. This breakdown not only illustrates the predominant influence of certain countries but also the diversity—or lack thereof—in the EU's energy supply chains.

For oil, Russia remains the predominant supplier for many EU countries (appearing 21 times in the top three), with import shares ranging from 8.7 to 73.3%. Top importers include countries such as Slovakia (73.3%), Hungary (57.2%) and Poland (40.5%), mostly due to their geographical proximity and historical ties with Russia (Celi et al., 2022). In contrast, other EU member states display a relatively more diversified portfolio of suppliers. Norway, for example, is the principal supplier for Sweden and Finland, while Ireland predominantly relies on the UK for its oil imports.

In the gas sector, Russia also stands out as the primary supplier for several EU countries (appearing 21 times in the top three, followed by USA, 13, and Norway, 11), with dependency rates reaching as high as 82.4%, underscoring major reliance particularly in Hungary, Austria and Finland. On the other hand, the United States plays a crucial role as a gas supplier for six EU countries, potentially offsetting some dependence on Russian gas. Notably, Ireland depends entirely on the United Kingdom for its gas imports. The diversity in these import shares illustrates the different levels of reliance and potential vulnerability each EU country faces concerning its main energy suppliers. While some member states have a broad base of suppliers, others are heavily reliant on a single external source, which necessities strategic measures for enhancing energy security and resilience.

Figure 7 introduces the concept of the Energy Import Vulnerability (EIV), which combines import dependency from non-EU countries with the import concentration.[12] This index acts as a proxy for the overall vulnerability of EU countries to energy supply risks by integrating both dependency and supplier concentration factors. A higher index level suggests substantial risks from dependency on a limited number of non-EU sources. This figure categorises EU countries into four groups, with those in the top-right quadrant facing the most significant vulnerabilities, including Lithuania, Slovakia, Germany, Spain, Italy, Portugal, Belgium and Ireland. These

[11] Both indicators are used to report progress towards implementation of quantifiable national objectives and targets for Energy security, of Commission Implementing Regulation (EU) 2022/2299 of 15 November 2022, which lays down the rules for the structure, format, technical details and process for the integrated national energy and climate progress reports.

[12] Of course, geopolitical risks are also relevant in this regard and should be appropriately accounted for. However, existing indexes for geopolitical risks, such as the GPRI of Caldara and Iacoviello (2022), is not available for all EU countries.

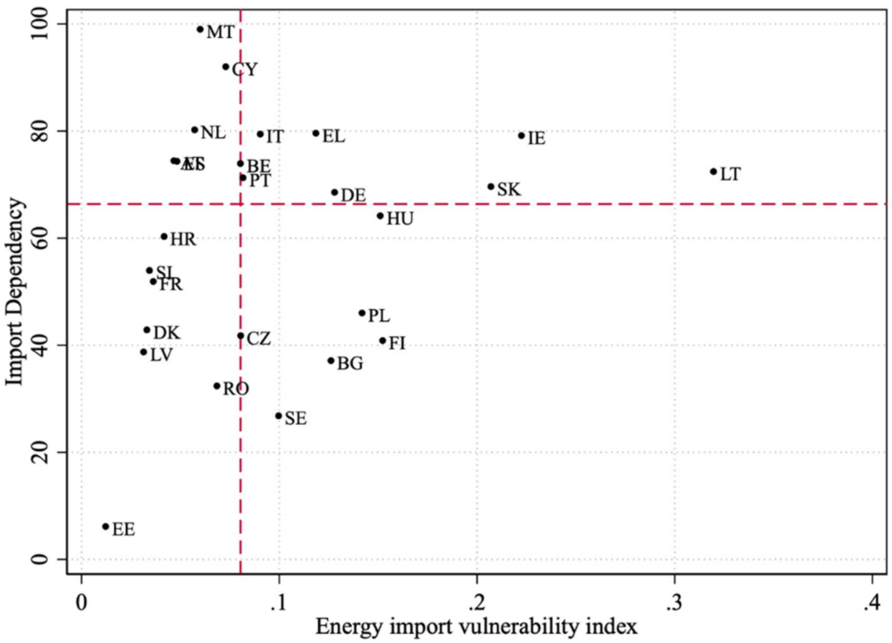

Fig. 7 Import dependency and import vulnerability, 2022. Source: Own elaboration based on Eurostat data. Notes: Dashed red lines denote median values. The Energy Import Vulnerability (EIV) measures a country's reliance on non-EU energy imports and the concentration of import origins. A higher EIV value means greater vulnerability, while a lower value indicates a more secure and diversified energy import structure. It is a composite indicator calculated as follows: $EIV = ImpDep^{non-EU} * Imp^{HHI}$. Where, $ImpDep^{non-EU}$ is the share of energy imported from outside the EU, reflecting a country's dependency on non-EU energy sources. Imp^{HHI} is the Energy Import Origin Concentration Index, based on the Herfindahl-Hirschman Index (HHI). It measures the diversification of a country's energy import sources and ranges between 0 and 1, where lower values indicate more diversified energy import origins and vice versa (i.e., higher values indicate more concentrated import origins)

member states urgently need to diversify their energy sources and enhance renewable energy production.

Finally, price developments are also paramount in determining private sector vulnerability to energy shocks. All other things being equal, a higher price of electricity, or higher taxes on energy, increase costs and reduce incomes for both households and firms, reducing their resilience to price swings. Figure 8 shows the average electricity prices faced by household consumers between 2010 and 2022, along with the prices net of taxes. Among large countries, households in Spain, Portugal, Germany and Italy face the highest costs.

Figure 9 looks instead at the relation between energy price volatility—measured as the variance in electricity price for household consumers between 2010 and 2022—and the share of vulnerable households—measured as those below 60% of median equivalised income with arrears on energy bills (left panel), and those unable to keep their house adequately warm (right panel). Again, countries in the top-right quadrant of the scatter plot—such as Greece, which has the highest share of vulnerable population, or Italy, Ireland or Spain, which record the highest price volatility—are the

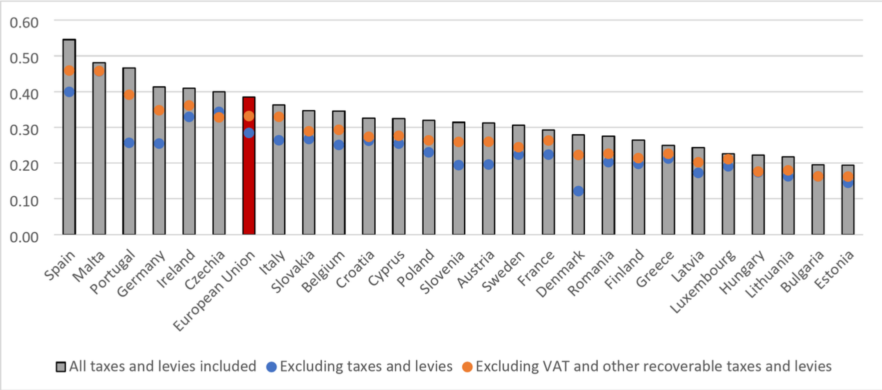

Fig. 8 Electricity prices for household consumers. Mean 2010s1–2022s2. Source: Own elaboration based on Eurostat data.

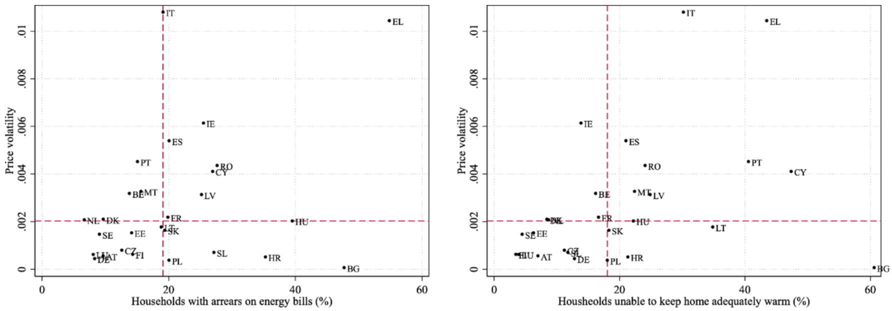

Fig. 9 Household vulnerability to energy price shocks. Source: own elaboration based on Eurostat data. Notes: Dashed red lines denote median values. Variance in electricity prices in computed for the period 2010–2022, Vulnerable households are defined as the percent of households, below 60% of median equivalised income, with arrears on energy bills or who are unable to keep their home adequately warm.

most vulnerable, since shocks affecting electricity prices are likely to translate into an increase in energy poverty, putting additional burden on public finances to curtain its effects. Also, firms in the eastern periphery—both small and large—experience higher than average electricity prices. Hungary is a clear outlier in this respect, with a price for KwH ten times larger than most EU countries, followed by Czechia, Poland and Romania (Fig. 18).

3.3 Other dimensions of energy vulnerability and resilience

So far, we have documented how European countries are characterised by different degrees of energy import dependency and vulnerability. We now turn our attention to the intertwined supply, demand, and policy ‘drivers’ that may influence these dependencies. Recognizing that these elements are deeply interconnected, meaning that there are no truly ‘exogenous’ factors at play (for a discussion, see Sect. 2 and Boneva, 2018).

The scatter plots presented in Fig. 10 provide a visual representation of the challenges facing different EU countries with regard to not only energy import dependency but also other associated economic and technological factors. In what follows, we report a brief assessment of each dimension.

- *Energy Intensity.* Countries to the right of the median are characterised by less efficient energy use, rendering them more vulnerable as they require more energy inputs for the same output. Finland and many Eastern European countries are pertinent examples. Those in the top-right quadrant are particularly at risk; their high import dependency, combined with energy inefficiencies, can amplify economic vulnerabilities during fluctuations in energy prices or supply disruptions. Such countries should prioritise policies that enhance energy efficiency.

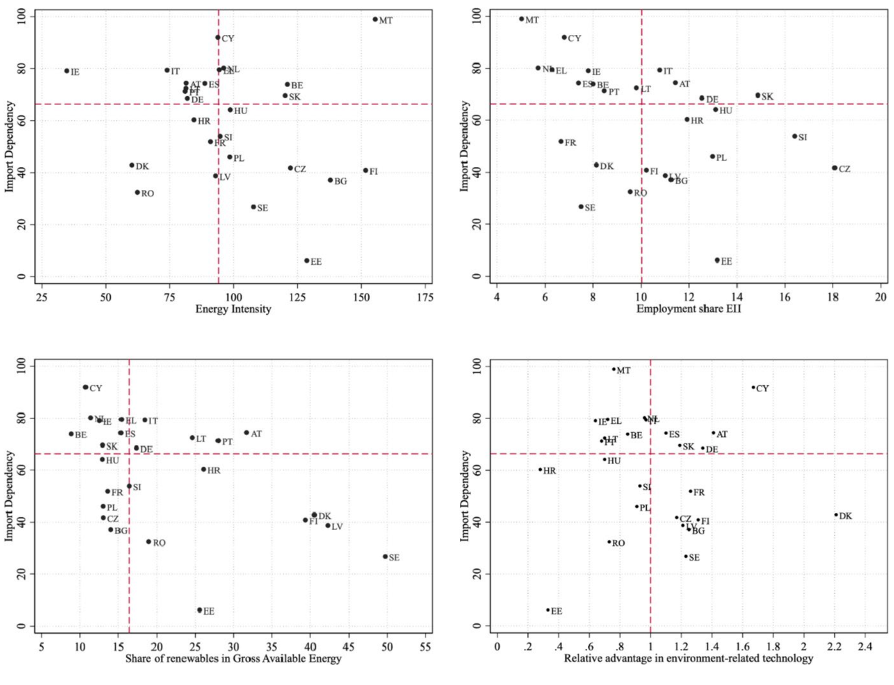

Fig. 10 Different dimensions of energy resilience, 2022. Source: Own elaboration based on Eurostat and JRC SETIS data. Notes: Dashed red lines denote median values. (i) Energy intensity is defined as Gross Available Energy (GAE), expressed in kilograms of oil equivalent (KGOE), per thousand euro of GDP, expressed in purchasing power standards (PPS). (ii) Employment in energy intensive industries (EII) is the share of those aged 15–64 employed in manufacturing sectors with above the median share of final energy consumption in total manufacturing final energy consumption. (iii) The share of RES in GAE is computed from energy balances. (iv) Relative advantage in environment-related technology is computed using patents in environment-related technologies. Countries positioned above the horizontal line—representing a relative specialization index greater than 1—exhibit specialization in these technologies. This indicates that their share of environment-related patents in total patents (across all technologies) exceeds the world average, reflecting a relative advantage in green innovation

- *Employment Share in Energy-Intensive Industries (EII)*.[13] Countries with a large segment of their workforce employed in EII are not only more vulnerable to energy supply shocks but may also 'resist' transitioning to greener alternatives. This resistance stems from the high costs of restructuring and the potential negative impacts on employment and local economies. Eastern European nations and Germany serve as notable examples. Moreover, countries situated in the upper-right quadrant are doubly burdened by high energy dependency, amplifying their vulnerability. Targeted public interventions are essential in addressing these challenges. These should include incentives for adopting green technologies, enhancing productive and technological capacities in this domain (Barbieri et al., 2023; Fischer & Newell, 2008) and implementing social safety nets and retraining programs for affected workers. Countries such as Germany, Austria, Slovakia and Italy are particularly illustrative of these issues, with Italy additionally hampered by its relatively limited fiscal space (Guarascio & Zezza, 2023).[14] Nevertheless, it should be also noted that the relative weight of EII sectors has been diminishing since 2000 in most countries, coherently with a general shift towards more service-oriented economies.
- *Share of renewables in gross available energy.* The observed negative correlation between energy import dependency and the share of renewables is telling. Countries such as Hungary and Poland, which are positioned to the left of the median, are noticeably behind in deploying renewable technologies compared to their EU peers. Encouraging the adoption of renewable energy is critical not only for reducing import dependency but also for achieving ambitious decarbonization targets. Although countries below the horizontal line tend to be less import-dependent, often because they rely heavily on domestic energy sources such as nuclear energy (France), solid fuels (Poland) or both (Czechia and Bulgaria), transitioning away from these solid fuels is crucial to achieve net-zero emissions goals. This transition poses a challenge: if these countries do not increase their share of renewables, they might face rising energy import dependency.
- *Relative advantage in environment-related technologies.* While the deployment of renewables is a clear indicator of progress towards net-zero, it represents only one side of the story. Understanding how countries perform in terms of green

[13] EIIs include manufacturing sectors with above-the-median energy consumption, as defined in Celi et al. (2022): chemicals and petrochemicals; iron, steel, and non-ferrous metals; non-metallic minerals; paper, pulp, and printing; food, beverages, and tobacco; and machinery. Relying on energy balance data, this taxonomy aims to identify the sectors most vulnerable to energy shocks and facing significant restructuring costs in the context of the green transition. Although it is not based on CO_2 emissions, our taxonomy partially overlaps with the list of energy-intensive sectors covered in the EU Emissions Trading System (ETS). Specifically, industries such as iron and steel, chemicals, non-metallic minerals, pulp and paper, and certain food and beverage sectors appear in both classifications. However, the EU ETS provides a more granular classification, detailing sectors at a higher level of disaggregation compared to our more aggregated categories.

[14] Fiscal space refers to a government's capacity to increase public spending without compromising fiscal sustainability. In the European context, existing fiscal rules tend to asymmetrically constraint fiscal space in relation to the size of Member States public debt/GDP. This element, as largely documented (e.g., Heimberger et al., 2024), has contributed to increase the divergence between core (characterized by lower debt/GDP levels) and peripheral countries (higher debt/GDP levels and smaller fiscal space), also concerning the availability of resources needed to pursue green industrial policies.

technological capabilities is equally relevant. Countries scoring lower in this metric often lack the domestic technological capabilities needed to transition towards more sustainable energy solutions, which not only impacts their potential in green industries but also likely reflects continued reliance on traditional energy sources or foreign green technology. Northern and some core countries, like Denmark, Austria and Germany, display a relative advantage in environmental technology, while eastern European countries generally score lower. The southern periphery, with Spain as an exception, is lagging behind.

As illustrated in Fig. 11, countries that have committed more public resources to green R&D from 2011 to 2020 are those that, by 2021, had a relative advantage (greater than 1) in environment-related technologies, with green technologies forming a substantial part of this. Notably, Scandinavian countries and Austria are leaders in this area, illustrating the positive impact of sustained public investment in green R&D.

Finally, we delve into the green manufacturing capabilities within the EU, identifying both the front-runners and those lagging behind. This exploration is crucial for reducing dependency on imported energy and underscores the significance of building domestic capabilities. We extend our analysis from the current deployment of renewables (in Fig. 10) to a broader examination of the green energy production potential across the EU, aiming to pinpoint significant investment gaps.

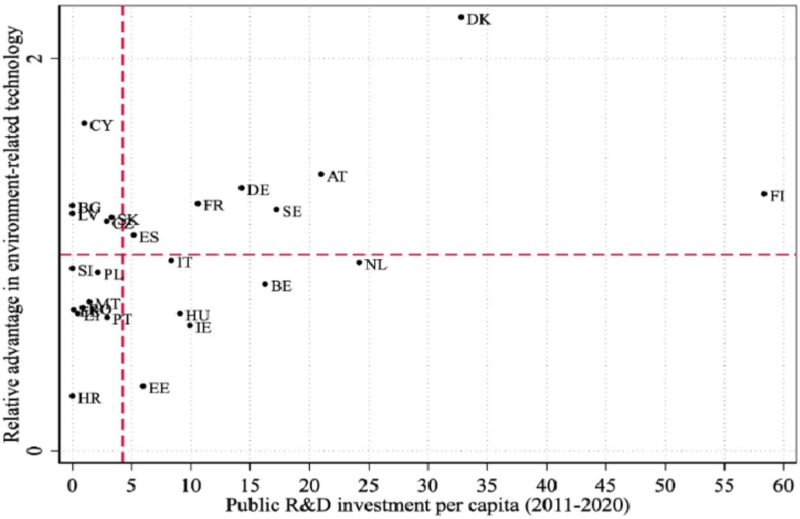

Fig. 11 Specialization in environment-related technologies and Public R&D in renewables, 2022. Source: Own elaboration based on JRC SETIS, and Eurostat data. Notes: Dashed red lines denote median values. Relative advantage in environment-related technology is computed using patents in environment-related technologies. Countries positioned above the horizontal line—representing a relative specialization index greater than 1—exhibit specialization in these technologies. This indicates that their share of environment-related patents in total patents (across all technologies) exceeds the world average, reflecting a relative advantage in green innovation. Public R&D investment data represent the cumulative per capita value for the period 2011–2020

Before moving to Sect. 4, which will evaluate whether EU policies are steering the region towards greater energy autonomy or simply shifting its strategic dependencies, we analyse the evolution of EU's imports of solar panels and wind turbines. A critical question arises: Is the EU at risk of replacing its dependency on Russian fossil fuels with reliance on Chinese-manufactured green technologies?

Figure 12 shows the distribution of green manufacturing plants in four key technologies: batteries, heat pumps, solar and wind across the EU. Germany has by far the highest number of 'green' manufacturing plants, particularly in wind and solar. It is followed by Italy, where heat pump production prevails, and Spain, which appears to specialise mostly in wind technology. Some smaller EU countries also show distinct specialisation patterns: Hungary, for instance, has relatively higher number of battery manufacturing plants, while Denmark is the leading wind turbine manufacturer. The production of solar, wind and heat pumps exhibit a broader geographical distribution, while battery production is more asymmetrically concentrated in just six EU countries. An important caveat to consider when interpreting this data is that the number of manufacturing facilities does not necessarily correlate with actual production capacity. Hence, the figures should be interpreted with caution. Although, the number of workers employed directly and indirectly in the renewable sectors does provide some corroboration for the ranking of countries in terms of their manufacturing capabilities.

Concerning the solar industry, most of EU employment is concentrated in the deployment of photovoltaic panels, accounting for 84% of jobs, while manufacturing itself employs only 8% (i.e., less than 50 thousand employees in the EU) (Fig. 13). This sharply contrasts with China, a global factory of solar panels, which gives employment to more than 2,7 million persons mostly in manufacturing (Tagliapietra et al., 2024).

Similar evidence can be found in trade data (see Fig. 14). The imports of solar panels have sharply increased since 2019, reflecting a booming EU demand. This increase is driven by commitments to renewable energy targets—given the crucial role of the solar PV for the clean energy transition, reduction of prices and governmental incentives subsidising deployment. In this respect, the EU's position as

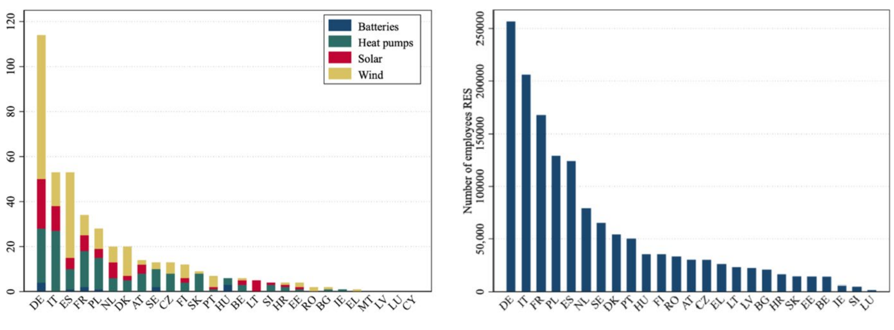

Fig. 12 Green manufacturing plants and employment in renewable energy sectors (RES), 2022. Source: Own elaboration based on Bruegel, EurObserv'ER and JRC SETIS data. Notes: "Direct employment includes RES equipment manufacturing, RES plant construction, engineering and management, operation and maintenance, biomass supply and exploitation. Indirect employment refers to secondary activities, such as transport and other services" (source: EurObserv'ER Employment and Turnover Report)

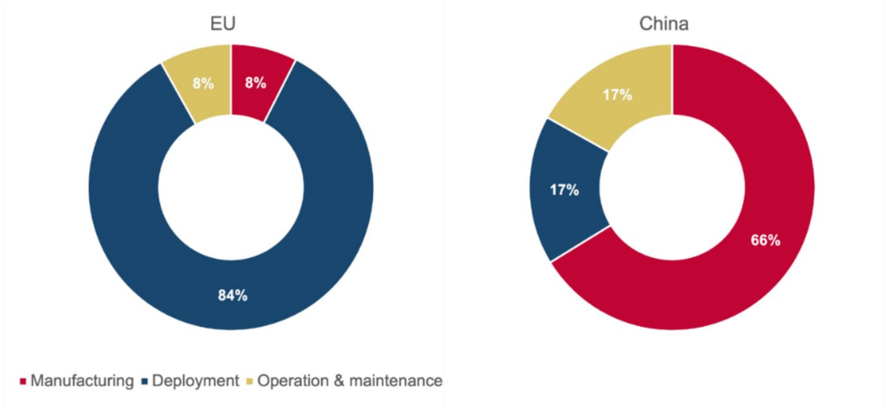

Fig. 13 Employment in solar sector, 2022. Source: Own elaboration based on Bruegel data

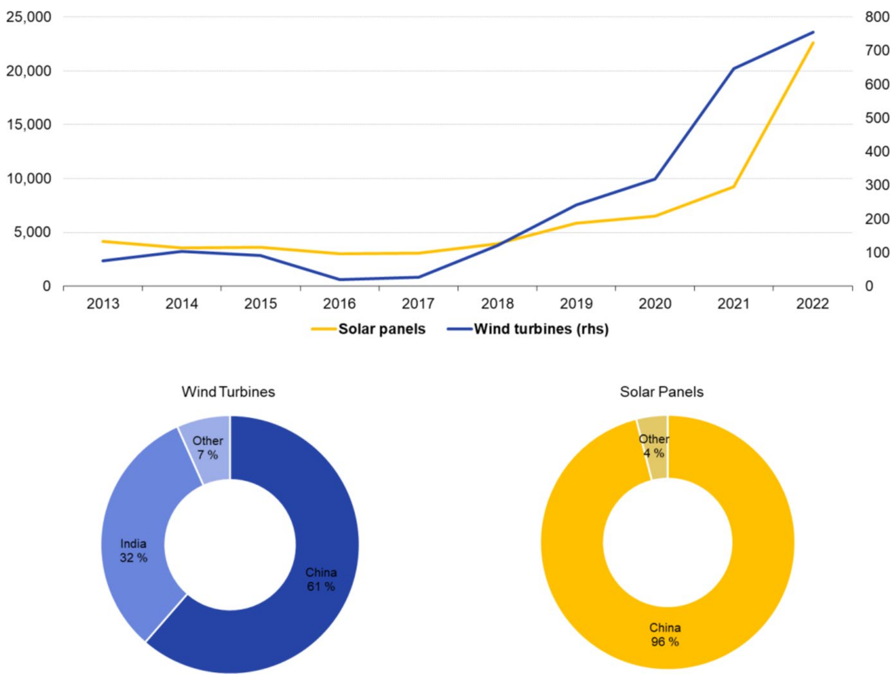

Fig. 14 Extra-EU imports of green energy products, 2012–2020 (million EUR). Source: Own elaboration based on Eurostat data. Notes: the upper panel of the figure shows the extra-EU imports of green energy products, in million euros. Solar panels are reported on the left-hand side, wind turbines on the right-hand side. The lower panel shows instead the import origin

a net importer of photovoltaic panels, coupled with such high import concentration from China (i.e. 96% of imported panels from China), highlights a critical strategic dependency (Caravella et al., 2024). This dependency exposes the EU to significant economic and geopolitical risks, highlighting the urgent need to strengthen domestic production to mitigate these vulnerabilities. Heavy reliance on a single supplier increases exposure to supply chain disruptions, price volatility and potential export restrictions, particularly in the context of global geopolitical tensions. Yet, diversification of supply sources is challenging due to China's dominance in the global solar panel value chain. Investing in domestic manufacturing capacity through public and private initiatives could reduce import dependency, enhance supply chain resilience and provide greater control over critical green technologies. Moreover, this approach would stimulate local economies, create jobs, and support the EU's long-term sustainability goals.

For wind turbines, the import dynamics tells a similar story, with significant increases from 2017 onwards. The less concentrated nature of wind turbine imports, with China accounting for 61% and India for 32%, might offer slightly more resilience against supply chain disruptions, especially given the strong domestic manufacturing capabilities. However, the EU's worsening net trade position in wind turbines, despite being a net exporter, indicates that internal demand is exceeding domestic production capacity.

Strengthening the EU's green production capacity requires efforts at both the national and EU levels. Current EU state aid rules, which are primarily concerned with preventing 'distortion of competition', restrict Member States from fully engaging in green industrial policies unless they address specific market failures (European Commission, 2023). The level of state aid dedicated to environmental protection reflects countries' commitment to green industrial policies. Higher investment reflects a more 'proactive' approach—in line with EU competition rules—towards achieving net-zero transition. Figure 15 shows how a country's energy import dependency cor-

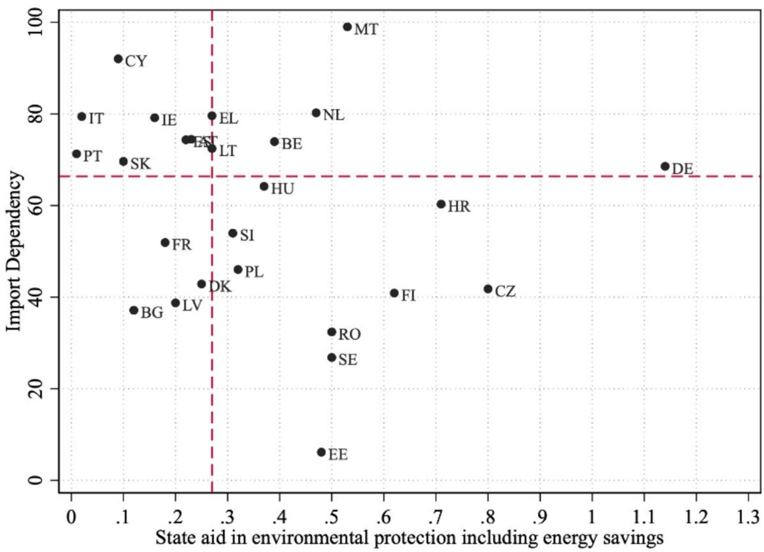

Fig. 15 Energy import dependency vis-à-vis state aid in environmental protection (% of GDP), 2022. Source: Own elaboration based on Eurostat data

relates with its level of 'green' state aid, shedding light on the scope of national green industrial policies and identifying countries where intensified efforts are necessary.

Germany stands out with the highest state aid allocation exceeding 1.1% of GDP, underlining both its proactive approach in fostering green capabilities and its substantial fiscal capacity to support such a transition. In contrast, peripheral countries like Italy and Portugal, with high energy import dependency and limited state aid, face increased vulnerability. Their constrained fiscal capacities hinder not only their own transitions but also the broader EU's green ambitions. The Eastern Periphery shows relatively higher levels of state aid in environmental protection, suggesting perhaps a greater fiscal leeway for investing in green technologies.

However, the asymmetric distribution of fiscal capacity among EU countries allows only some to push forward more ambitious green agendas (Darvas et al., 2023; Heimberger et al., 2024), potentially exacerbating technological and economic gaps, especially in the absence of a cohesive EU-level industrial policy and a coordinated policy framework (e.g., 'easing' in state aid rules alongside fiscal rules). This scenario may hamper the collective achievement of the EU's climate objectives and risks widening the gap vis-a-vis China and the US, which face fewer constraints and, in turn, pursue more interventionist and protectionist industrial strategies (Barbieri et al., 2019; Guarascio et al., 2025). Achieving climate objectives requires the involvement of all member states, not just a handful. Peripheral regions may need more targeted support from the EU level to create 'green' capabilities and capitalise on their natural advantages for renewable energy production, as illustrated in Fig. 16. Despite their geographical advantages in terms of solar and wind potential, these countries might be underutilising these resources due to financial constraints, thereby risking under-delivering on ambitious climate goals (Kakoulaki et al., 2021).

In what follows, we analyse to what extent existing EU policies are sufficient to reduce these regional disparities and ensure a green transition toward a more sustainable and resilient energy future for all member states, without leaving anyone behind.

4 Mapping policy actions aimed at reducing energy-dependency and contrasting its economic implications

This section offers a brief review of the policy actions undertaken at the EU-level as well as by selected EU member states to reduce energy vulnerability and contrast its economic implications. Beyond analysing similarities and differences, we will discuss the relative coherence of EU member states policy set-up in the light of the mapping provided in Sect. 4.

Different energy and climate packages emerged over the last years, as comprehensive policy strategies encompassing states, corporations, and civil society in the fight against climate change. Around the world, 'green' Keynesian approaches—which usually involve large public investment and focus predominantly on 'green jobs'[15] and dignified living conditions—have been advanced by both policy makers

[15] Using data on United States for the period 2011–12, Consoli et al. (2016) compare green and non-green occupations to detect differences in terms of skill content and of human capital. They find that, compared

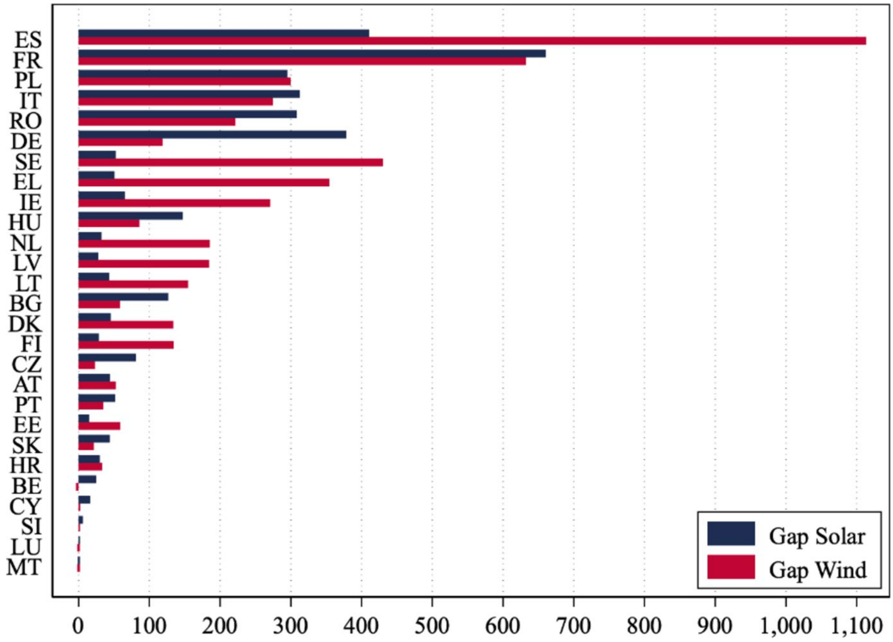

Fig. 16 Gaps in Green Energy Potential, wind and solar sector, 2022. Source: Own elaboration based on Kakoulaki et al. (2021) and Eurostat data. Notes: the Gaps in Green Energy Potential is estimated as the difference between green electricity production potential and current use of renewables for electricity. The former is sourced from the study by Kakoulaki et al. (2021), which provides the technical potential for electricity generation from renewable energy sources—including solar PV, onshore and offshore wind and hydropower—for each EU country, taking into account environmental constraints, land use limitations, and various techno-economic parameters. The latter, current use of renewables for electricity, is sourced from Eurostat

and environmental groups, with contents being adapted to political contingencies and pressures (Ajl, 2021; Aronoff et al., 2019; Mastini et al., 2021; Tienhaara & Robinson, 2022). Notably, these proposals have been discussed both in the Global North—with the EU, US, UK, and Canada at the forefront of 'green recovery' policies—as well as in China and South Korea (Leonard et al., 2021; Yoon, 2021).

In December 2019, the European Commission introduced the European Green Deal (EGD), an ambitious policy package intended to make the EU's economy environmentally sustainable. Presented as the first public state-led commitment to climate neutrality, the plan aims at reducing EU net domestic production of greenhouse gas (GHG) emissions by at least 55% by 2030 and attain climate neutrality by 2050.[16] This multi-pronged plan covers a wide array of policies, premised on the common

to non-green jobs, green occupations exhibit a stronger intensity of high-level cognitive skills. Moreover, occupations that are changing in terms of their skill content, have more formal education, work experience and on-the-job training relative to non-green jobs. An alternative taxonomy is proposed in Bohnenberger (2022), who distinguishes between green, brown and mixed-jobs by looking at the output type, occupation, work-lifestyles and outcome efficiency.

[16] For further information, see https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

goal of boosting ‘green growth’ while decarbonizing, dematerializing and decoupling growth from emissions and other ecological impacts.

The Covid-19 pandemic first, and the Russia–Ukraine conflict later, urged the European Union to double-down its efforts. Since 2021, the EU has issued other dozens of energy policy measures, regulations, and plans to foster the transition among Member States.

Table 2 lists all 45 policy actions taken at the EU level between 2021 and 2023, assigning them across the five dimensions highlighted in Sect. 2, focusing on enforced measures (i.e., measures which are only ‘announced’ are excluded from the analysis). Policies addressing Energy Intensity, Environmental sustainability and Technological Efficiency dominate the landscape, appearing over thirty times, followed by Energy Affordability (25 times) and Energy Availability (21 times).

The policies listed encompass a wide array of initiatives aimed at addressing various aspects of sustainability and energy transition within the EU. It is not surprising, therefore, that a large share of the multiannual budget for 2021–2027 is devoted to the transition to a greener economy, with 25% of the 750Bn euro NGEU allocated to climate action.

A notable emphasis across many of these policies is the focus on promoting renewable energy and energy efficiency. This is evident in initiatives such as the EC’s Social Climate Fund, which aims to alleviate the social and economic burdens of transitioning to cleaner energy sources, and the Sustainable Finance EU Taxonomy, which seeks to support sustainable investment by defining environmentally sustainable activities. Moreover, the Regulation guidance to climate-proof future infrastructure projects underscores the importance of integrating climate considerations into future developments, reflecting a broader commitment to climate resilience.

In 2022, the Commission presented the RePowerEU Plan, specifically designed to phase out the Union’s dependency on Russian fossil fuels through the diversification of energy suppliers, energy-saving practices and ‘smart’ investment and reforms. It includes three Joint European Action, for ‘Renewable Energy and Energy efficiency’, ‘Gas supply security’, and ‘Energy prices’, which encompass measures to: accelerate the switch to renewables, in particular towards solar and hydrogen; strengthening the role of the EU Energy Platform; diversify suppliers through new partnerships; limit price volatility through new legislations on minimum gas storage and support for refilling operations; the building of a new Hydrogen Accelerator.

Batteries are another focal point of action, with several dedicated programs and regulations. On the one hand, the EU signed several Strategic Partnerships programs with extra-EU countries supplying critical minerals and generally raw materials (Ukraine, Canada, Namibia, Kazakhstan, Zambia, DRC, Chile), with the aim of diversifying, strengthening, and securing the entire value chain of both primary and secondary critical raw materials and batteries. On the other hand, the EC has undertaken significant efforts to bolster the EU’s position in battery technology through the European Battery Innovation project. This Important Project of Common European Interest (IPCEI), jointly supported by several member states, allocates substantial funding to research and innovation along the entire battery value chain, from raw material extraction to recycling. Overall, these programs and policies underscore the EU’s concerted efforts to foster innovation, sustainability, and self-sufficiency in battery technology, thereby advancing the region's transition to a greener and more resilient energy future.

Another common thread among these policies is the emphasis on inclusive transitions and social equity. Policies such as the Just Transition Fund and the EU Strategy on Adaptation to Climate Change prioritize supporting regions and communities facing socio-economic challenges from the transition to cleaner energy sources. Additionally, initiatives like the EU Youth for a Just Transition toolkit aim to engage and empower youth in shaping and implementing climate policies. However, there is a need for greater clarity and uniformity in the implementation and monitoring of these initiatives to ensure that the benefits are equitably distributed and reach those most in need.

However, one weakness apparent in some of these policies is the lack of specificity and enforceability. While there is a clear intent to drive sustainable practices and investments, the effectiveness of these policies may be hindered by vague objectives and limited enforcement mechanisms. For instance, the EU Regulation on Supply chain due diligence, i.e., 'Corporate Sustainability Due Diligence Directive' (CS3D), outlines obligations for mineral importers but may lack teeth in ensuring compliance and accountability throughout the supply chain.[17] Additionally, the sheer number of policies and initiatives could lead to fragmentation and duplication of efforts, necessitating streamlining and coordination to maximize impact and avoid overlap (Consoli et al., 2023; Costantini et al., 2015, 2017; Greco et al., 2022).

Finally, the speed of implementation for most of these policies is highly heterogenous among Member States. This is shown in Table 2, which displays the share of Milestone and Targets (M&T) fulfilled in national RRF programs—focusing specifically on the "Green Transition" Policy Pillar—for all EU Member States, along with total RRF allocations, distinguishing between grants and loans.

When looking at the share of M&T fulfilled as of June 2024, figures range from the 66% of France to the 0% of Belgium, Hungary, Ireland, Netherlands and Sweden. Among the countries with the largest programs (in terms of allocation as % of GDP), Croatia and Italy stand out, with over 25% of fulfilled investment and reforms, followed by Greece (20.9%) and Spain (15.5%). However, it must be underlined that both Spain and Italy face additional challenges, as they feature the largest programs in terms of total allocations (€194.4 billion for Italy, and 163 for Spain), and that most of the fulfilled M&T to date refers to preliminary actions (i.e., setting the regulations for public procurement, publication of dedicated web-pages on ministerial websites, etc.), while most 'demanding' actions still need to be enacted.

Alongside EU programs, Member States also tried to counteract the effects of the energy crisis at the national level. Since September 2021, €651 billion have been allocated across European countries to shield private sector from rising energy costs (Sgaravatti et al., 2023). Thanks to the suspension of the Stability Pact, the support was unprecedented for EU standards, nearly 3.4% of EU GDP. Also peripheral countries, which previously suffered more from their little fiscal capacity, were able to put forth large support packages. Germany alone spent close to €160 Bn, followed by

[17] As it often happens with EU regulations, in spite of rather ambitious initial targets, the CS3D has been reformulated postponing relevant compliance targets and deadlines.

Table 2 European union energy policy measures, 2021–2023

Policy	Year	Description	Energy Availability	Energy Affordability	Techno-logical efficiency	Energy Intensity	Environ-mental sus-tainability
EU Strategic Partnership on Raw Materials	2021–2023	Includes activities along the entire value chain of critical raw materials	X		X	X	
The European Commission's Social Climate Fund	2021	Helps citizens meet social and economic costs of climate transition	X	X	X		X
The EU's "Equality platform for the energy sector"	2021	Promotes inclusion and equality in the energy sector		X			X
Temporary Framework for State aid measures	2021	Provides flexibility for supporting industries during COVID-19	X	X			
Sustainable Finance EU Taxonomy	2021	Supports sustainable investment by defining environmentally sustainable activities	X		X	X	X
Sustainable Finance Disclosure Regulation (SFDR)	2021	Introduces sustainability-related disclosure obligations in financial services	X		X		
Smart Mobility Strategy—Alternative Fuel Infrastructure	2021	Aims to increase use of sustainable alternative fuels in shipping	X		X	X	
Regulation guidance to climate-proof future infrastructure projects	2021	Includes climate considerations in infrastructure projects			X	X	X
Recovery and Resilience Facility (RRF)	2021	Supports EU member countries with funds for climate expenditures	X	X	X		X
Modernisation Fund	2021	Supports energy transition in lower-income EU member states	X	X	X	X	X
Just Transition Fund	2021	Provides financial support for regions transitioning to cleaner energy		X		X	
InvestEU- European Local Energy Assistance (ELENA)	2021	Supports sustainable energy and transportation projects	X	X	X	X	X
Innovation Fund—Investments in Innovative Clean Technology Projects	2021	Funds breakthrough technologies for clean energy			X	X	X
European Raw Materials Alliance (ERMA)	2021	Supports Europe's raw materials industry	X	X		X	

Table 2 (continued)

Policy	Year	Description	Energy Availability	Energy Affordability	Techno-logical efficiency	Energy Intensity	Environ-mental sus-tainability
European Commission Recommendation on Environmental Footprint methods	2021	Recommends methods to assess and communicate environmental performance	X	X		X	X
European Climate Law	2021	Proposes legally binding target of net zero emissions by 2050	X	X		X	X
Euratom—EU financing of ITER	2021	Secures financing for ITER project			X	X	
Energy communities in the EU	2021	Supports citizen-driven energy actions		X			X
Energy Projects of Common Interest	2021	Supports renewable energy transition	X	X		X	X
EU Youth for a Just Transition toolkit	2021	Engages youth in the Just Transition Fund		X			
EU Strategy on Adaptation to Climate Change	2021	Increases climate resilience			X	X	X
EU Regulation on Supply chain due diligence	2021	Outlines due diligence obligations for minerals			X	X	X
EU 2021–2027 Multiannual Financial Framework	2021	Allocates funds for energy and climate plans				X	X
EU Long-term budget (2021-27)—Next Generation EU		Allocates funds for climate action	X	X	X	X	X
EU Long-term budget (2021-27)—LIFE		Facilitates clean energy transition	X	X	X	X	X
EU Long-term budget (2021-27)—Just Transition Mechanism		Supports regions transitioning to a climate-neutral economy	X	X	X	X	X
EU Corporate Sustainability Reporting Directive	2021	Strengthens rules on corporate sustainability reporting	X	X	X	X	X
EU Cohesion Policy (2021-27)	2021	Aims to strengthen economic and social cohesion	X	X	X	X	X
EIB investments for climate action	2021	Backs climate action and clean energy				X	X
Cross-border energy infrastructure	2021	Modernizes EU's energy infrastructure			X	X	X
Connecting Europe Facility	2021	Funds projects in transport, digital, and energy		X	X	X	

Table 2 (continued)

Policy	Year	Description	Energy Availability	Energy Affordability	Techno-logical efficiency	Energy Intensity	Environ-mental sus-tainability
Blockchain based Circular System for Assessing Rare Earth Sustainability	2021	Develops sustainability tracking tool for critical minerals		X	X	X	X
€2.9 billion fund for research and innovation in battery technology	2021	Funds battery technology research		X	X	X	X
European Partnership for Clean Aviation	2021	Minimizes aviation sector's environmental impact				X	X
REPoweEU Plan	2022	Reduces dependence on Russian fossil fuels	X	X	X		X
Joint European action on energy prices		Specific actions in response to surge in energy prices		X			X
Joint European action on gas supply security		Measures related to gas supply security	X	X			
Joint European action on renewable energy and energy efficiency		Measures related to renewable energy and energy efficiency	X	X		X	
Minerals Security Partnership	2022	Ensures sustainable production and recycling of critical minerals			X	X	X
Joint Declaration on Reducing Greenhouse Gas Emissions from Fossil Fuels	2022	Accelerates GHG emissions reduction from fossil fuels			X	X	X
EU Methane Action Plan	2022	Supports Global Methane Pledge to reduce emissions			X	X	X
Approval of the IPCEI project Hy2Use	2022	Funds hydrogen projects			X	X	X
Joint Statement on Accelerating Methane Mitigation	2023	Accelerates methane mitigation from the LNG value chain			X	X	X
International Working Group for GHG Supply Chain Emissions	2023	Develops framework for measuring GHG emissions			X	X	X
EU Sustainable Batteries Regulation	2023	Promotes sustainable batteries			X	X	X

Source: Own elaboration based on IEA policy database

Table 3 Implementation of recovery and resilience facility (RRF) national programs, as of June 2024

	RRF (billion euro)			RRF % GDP	RRF milestone and target—green transition		
	Grants (a)	Loans (b)	Total (a+b)		Not fulfilled	Fulfilled	Fullfilled (%)
EU	356.76	291.92	648.69	3.82	2649	544	17.00
Austria	3.96	0.00	3.96	0.83	67	19	22.10
Belgium	5.03	0.26	5.29	0.91	134	0	0.00
Bulgaria	5.69	0.00	5.69	6.06	135	4	2.90
Croatia	5.79	4.25	10.04	13.13	127	43	25.30
Cyprus	1.02	0.20	1.22	4.09	112	6	5.10
Czechia	8.41	0.81	9.22	3.02	127	30	19.10
Denmark	1.63	0.00	1.63	0.44	42	31	42.50
Estonia	0.95	0.00	0.95	2.53	46	22	32.40
Finalnd	1.95	0.00	1.95	0.70	66	14	17.50
France	40.27	0.00	40.27	1.44	32	62	66.00
Germany	28.02	0.00	28.02	0.68	45	18	28.60
Greece	18.22	17.73	35.95	16.32	136	36	20.90
Hungary	6.51	3.92	10.43	5.31	194	0	0.00
Ireland	0.91	0.00	0.91	0.18	56	0	0.00
Italy	71.78	122.60	194.38	9.32	197	66	25.10
Latvia	1.97	0.00	1.97	4.88	42	6	12.50
Lithuania	2.30	1.55	3.85	5.35	56	10	15.20
Luxembourg	0.08	0.00	0.08	0.10	11	3	21.40
Malta	0.33	0.00	0.33	1.69	31	18	36.70
Netherlands	5.44	0.00	5.44	0.53	63	0	0.00
Poland	25.28	35.54	60.82	7.97	126	15	10.60
Portugal	16.33	5.89	22.22	8.37	208	40	16.10
Romania	13.57	14.94	28.51	8.78	178	18	9.20
Slovakia	6.41	0.00	6.41	5.22	79	17	17.70
Slovenia	1.61	1.07	2.68	4.26	94	25	21.00
Spain	79.85	83.16	163.01	11.15	224	41	15.50
Sweden	3.45	0.00	3.45	0.63	21	0	0.00

Source: Own elaboration based on European Commission. See https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/milestones_and_targets.html. Notes: Table displays the RRF allocations by country (grants, loans, total, and as a share of 2023 GDP), and the share of satisfactorily fulfilled milestones and targets, focusing on measures under the Policy Pillar "Green Transition". A milestone or target is fulfilled once a Member State has provided the evidence to the Commission by submitting a payment request (maximum twice a year) that it has completed the milestone or target in a satisfactory manner and the Commission has assessed it positively in an implementing decision

Italy (92.7) and France (92.2). Also, Malta, Austria, Greece, Bulgaria, Lithuania and the Netherlands spent more than 4% of GDP, whereas only three countries (Denmark, Finland and Cyprus) reported measures for less than 1% of GDP. Most governments in the EU opted for un-targeted price-distorting measures—e.g., cuts to excise duties and VAT, as in Italy—compared to income-support measures, with some exceptions. Denmark and Sweden favored to support income of vulnerable groups (financially vulnerable families, families with children, students) and pensioners. Other countries

(Austria, Belgium, Bulgaria, Germany) chose a mixed strategy, using both targeted and untargeted income support measures (Table 3).

Despite the enthusiastic engagement by EU bodies, national governments, and the media, the EGD—and more in general the EU strategy toward the Energy Transition—has been criticized by many scholars on different grounds. On the one hand, the 'green' narrative is just the last of many narratives used by the capitalist centers aimed at ensuring its continued leading economic and political role and maintaining the status quo (Vela Almeida et al., 2023).[18] On the other, the creation of 'eco-conscious' economies in the Global North risks generating 'green sacrifice zones' located beyond its boundaries (Zografos & Robbins, 2020).

Moreover, the huge financing needs of the Transition open a new frontier for private finance, further increasing the financialization of the European economy, which may possibly lead to higher financial instability (Cerrato & Ferrando, 2020; Perry, 2021). The EU 'blended finance' approach to pay for the Transition is in fact still enshrined in the neoliberal ideology for which (i) there are insufficient public funds available and (ii) that the role of the State is limited to facilitating private enterprise (Mazzucato, 2016), shifting the political question of whether and how private financing is needed to the technical question of how to optimize private finance to shape the economic prospects of the EU (Amoore, 2014).

These developments stand out quite clearly if one looks at the latest actions taken at the EU level. In March 2023, the European Commission proposed the Net-Zero Industry Act (NZIA).[19] As part of Europe's Green Deal Industrial Plan, the NZIA aims at creating a simpler and more predictable legal framework for net-zero industries in the EU, to help strengthen the manufacturing capacity of green technologies, overcome barriers to scaling up the manufacturing capacity, and improve the EU's energy resilience. In particular, the Act supports strategic net-zero technologies and projects that are either commercially available or ready-to-enter the market, and have significant potential for rapid scale-up to contribute to the EU's decarbonisation targets.[20] Still, the NZIA continues to follow the path laid out by past EU policy strategies, where the role of the public institution is, solely, to foster market development for the private sector, possibly attracting foreign capital. Most importantly, as we discussed, the EU is overly import-dependent for many net-zero technologies. In fact, more than 90% of solar photovoltaic (PV) wafers, as well as certain other PV technology components—are imported from China, along with more than one-fourth of EV cars and batteries.[21]

[18] This happens through four different registers: (1) turning ecological crises into profitable opportunities; (2) portraying the EU as a 'moral' intervener; (3) building on a 'green' 'will to improve'; and (4) securitizing and consolidating the empire.

[19] https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en.

[20] The list includes the following technologies: (i) Solar photovoltaic and solar thermal technologies; (ii) Onshore and offshore renewable technologies; (iii) Battery/storage technologies; (iv) Heat pumps and geothermal energy technologies; (v) Electrolysers and fuel cells; (vi) Sustainable Biogas/Biomethane technologies; (vii) Carbon Capture and Storage (CCS) technologies; (viii) Grid technologies.

[21] It is worth noting that China alone accounts for almost 90% of global investment in net-zero technology manufacturing facilities.

5 Conclusions

This article has provided a comprehensive mapping of energy vulnerability and resilience in the EU. We started from a brief review of the relevant literature, discussing key concepts and indicators used to assess countries' relative positioning. The main outcomes of the analysis are the following. Regarding import dependency, taking into consideration also the degree of market concentration (HHI), a non-negligible share of the EU economy, including countries such as Lithuania, Slovakia, Germany, Spain, Italy, Portugal, Belgium and Ireland, displays a quite strong vulnerability—i.e., high exposure to geopolitical risks and supply chain disruptions. Among those countries, Slovakia, Germany, Austria and Italy face further challenges given their relatively high share of energy-intensive industries. This may increase restructuring costs, rising the risk of negative socio-economic implications of the energy transition. Another relevant divide emerges concerning the share of renewables in gross available energy. Nordic countries, such as Denmark, Finland, Latvia and Sweden, leave most of the other member states behind, especially the Eastern periphery (e.g., Hungary and Poland). Similarly, Denmark, Austria and Germany display a relative advantage in environmental technology, while eastern European countries generally score lower levels. Likewise, the southern periphery, with Spain as an exception, lags behind. Such an heterogeneous positioning partly reflects the uneven national efforts concerning environmental policies. In fact, a considerable polarization regarding environmental state aid has been documented. Again, Germany stands out while the Southern periphery, in particular countries like Italy and Portugal, report significantly lower state aid levels.

The policy dimension is also paramount in determining countries' relative vulnerability and resilience toward energy shocks. Over the last few years, and with an acceleration following the Pandemic and the Russia-Ukraine conflict, the EU has doubled down its efforts to sustain the transition to a greener economy, reinforcing key value chains, and decouple from geopolitical risks. In the long list of policies put forth at the EU level, those aimed at increasing energy production from renewables dominate the landscape, alongside policies aimed at improving efficiency, secure the supply of critical minerals, enhance security, and foster innovation and R&D in both private and public sectors. However, an apparent weakness relates to the lack of specificity and enforceability. While the intent to drive sustainable practices and investments is clear, vague objectives and limited enforcement mechanisms may hinder the effectiveness of these policies. This is especially true for regulations and policies aimed at strengthening the supply chain of renewables, concerning both Critical Raw Materials (CRMs) and technologies. Although quite ambitious on paper, the EU green policy commitments seem to be difficult to be comprehensively enforced, as they may lack teeth in ensuring compliance and accountability throughout the supply chain. Analogously, the large number of policies and initiatives, could lead to fragmentation and duplication of efforts, whereas streamlining and coordination would maximize impact and avoid overlaps.

At the national level, helped by the suspension of fiscal rules, also those Southern Periphery countries—notably Italy and Portugal—which have in previous occasion suffered more from the lower fiscal space, put in place large support packages. However, to shield households and firms from the effects of the energy crisis, countries opted for different strategies, with Nordic countries preferring income support measures for vulnerable groups, while a large and heterogenous group of countries opted for mostly un-targeted price-distorting measures.

However, the asymmetric distribution of fiscal capacity among EU countries, further exacerbated by the new fiscal rules, risks allowing only some member states to push forward with ambitious green agendas. This may widen technological and economic gaps, especially in the absence, as we have seen, of a cohesive EU-level industrial policy and a coordinated policy framework. As the latest news from Brussels clarified once more—e.g., the Net Zero Industry Act or the recent report from the former Italian Prime Minister Letta—the EU 'blended finance' approach to *pay for* the Transition is in fact still enshrined in the neoliberal ideology—with the role of the State limited to facilitating market forces, leaving private finance to shape the economic prospects of the EU, with the risk of increasing both polarization and financial instability.

This scenario risks jeopardising the collective achievement of the EU's climate goals, contradicting the bold objectives put forth by the recent Report on EU competitiveness (Draghi, 2024). As a result, the technological and productive gap vis-à-vis the US and China—two countries facing fewer constraints and pursuing more interventionist and protectionist industrial policies—may increase. On the other hand, given their geographical advantages in terms of solar and wind potential, peripheral regions should be targeted with more support from the EU level, in order to create 'green' capabilities and capitalise on their natural advantages for renewable energy production. In this respect, the need of core countries and their key industries—especially Germany and its automotive sector—shall not be the driving force of EU industrial and energy policies. Conversely, investment decisions should be aimed at strengthening technological capabilities and generating cross-country spillovers. In the same way, the network of relevant infrastructures and the distribution of productive capacity must magnify the potential for economies of scale, scope and integration, in line with other Cohesion Policy objectives, and in tandem with existing programs aimed at reducing country and regional divergence.

This study provides an extensive mapping of energy vulnerability and resilience across EU member states, elucidating key indicators and policy responses. Nevertheless, the analysis relies on descriptive statistics and mapping, which, while valuable, do not allow for the identification of causal relationships or the control of confounding variables. Moreover, the use of national-level data may mask significant regional heterogeneities within countries, whereas disparities in energy infrastructure, industrial composition, and policy implementation could be critical in understanding localized energy vulnerabilities and resilience.

Future research could address these limitations in several ways. First, econometric techniques should be employed to test the robustness of the findings and control for confounding variables such as regional economic structures, technological capacities, and fiscal space. Second, constructing composite indices for energy vulnerability and resilience would provide a more holistic and comparable framework to assess country and regional performances. These indices could incorporate weights derived from statistical methods to reflect the relative importance of different dimensions.

Third, future studies could explore the impacts of energy vulnerability and resilience on broader macroeconomic outcomes, such as growth, productivity, and inequality, shedding light on the socio-economic implications of energy transitions. Finally, extending the analysis to the regional level, where data availability permits, would provide more granular insights into within-country disparities, informing targeted policy interventions. These advancements would significantly enhance the analytical depth and policy relevance of the research, guiding both national and EU-level strategies toward a more equitable and resilient energy future.

6 Appendix

See Figs. 17, 18 and 19 and Tables 4 and 5.

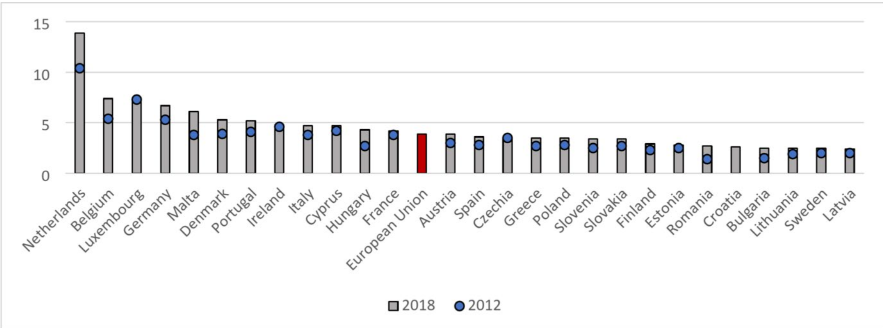

Fig. 17 Land use with heavy environmental impact (%). Source: Own elaboration based on Eurostat data

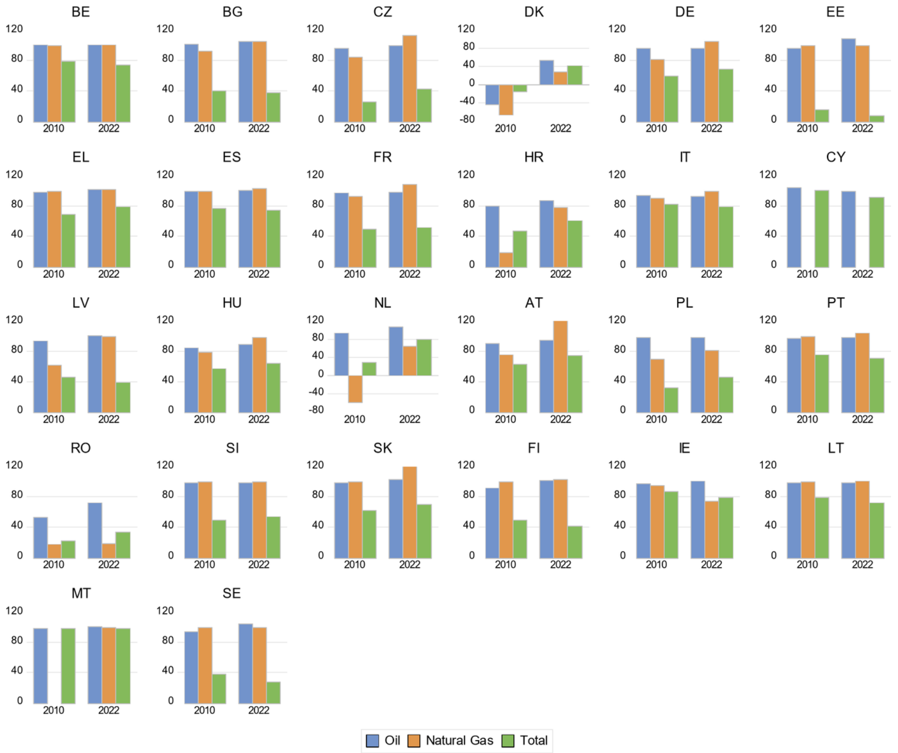

Fig. 18 Import Dependency Rate by energy source, 2010 vs. 2022. Source: Own elaboration based on Eurostat data

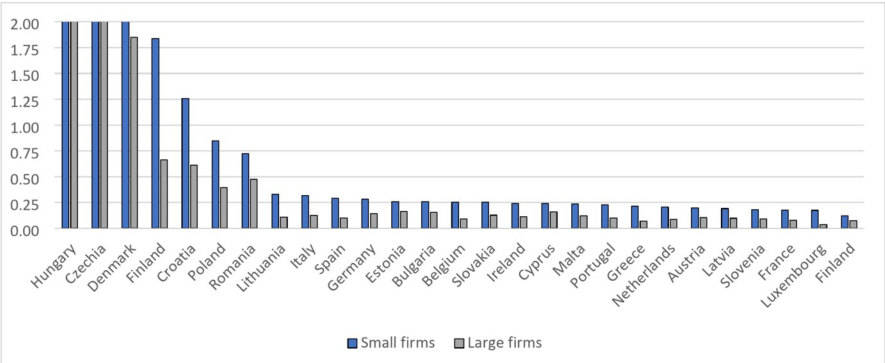

Fig. 19 After-tax electricity prices for businesses. Mean 2010s1-2022s2. Source: Own elaboration based on Eurostat data. Notes: small firms are defined as firms with consumption of less than 20 MWh; large firms are those with consumption of more than 70,000 MWh. Prices include all taxes and levies and are expressed in Purchasing Power Standard (PPS)

Table 4 Top 3 oil import partner share in total import, EU27, 2022 (%)

	Partner 1		Partner 2		Partner 3	
	%	Country	%	Country	%	Country
European Union	15.7	Russia	7.8	USA	7.1	Norway
Euro area	13.9	Russia	8.0	USA	5.2	Norway
Belgium	16.3	Russia	10.3	USA	7.2	UK
Bulgaria	8.7	Russia	3.3	USA	1.0	Kazakhstan
Czechia	36.6	Russia	15.2	Azerbaijan	6.4	Kazakhstan
Denmark	25.8	USA	18.3	Norway	7.2	UK
Germany	22.9	Russia	11.1	Norway	10.3	USA
Estonia	19.8	Russia	3.5	Kazakhstan	–	–
Ireland	52.0	UK	23.7	USA	7.1	Azerbaijan
Greece	32.2	Iraq	18.4	Russia	10.3	Kazakhstan
Spain	9.8	Nigeria	9.7	USA	7.4	Mexico
France	11.0	USA	10.7	Russia	9.6	Saudi Arabia
Croatia	29.7	Azerbaijan	23.2	Switzerland	7.2	Russia
Italy	18.2	Russia	12.3	Libya	11.6	Azerbaijan
Cyprus	32.5	Israel	7.7	Russia	1.8	Türkiye
Latvia	17.4	Russia	9.3	Switzerland	0.3	China
Lithuania	30.7	Saudi Arabia	17.6	Russia	14.3	UK
Luxembourg	–	–	–	–	–	–
Hungary	57.2	Russia	5.2	Kazakhstan	1.4	Saudi Arabia
Malta	9.6	Israel	5.9	Kazakhstan	4.0	UK
Netherlands	13.6	Russia	9.7	UK	7.9	USA
Austria	17.0	Kazakhstan	8.6	Libya	6.9	Iraq
Poland	40.5	Russia	22.6	Saudi Arabia	10.1	Norway
Portugal	25.4	Brazil	9.1	Nigeria	7.5	Algeria
Romania	37.0	Kazakhstan	29.9	Russia	5.7	Azerbaijan
Slovenia	17.6	Egypt	9.7	Russia	4.8	Saudi Arabia
Slovakia	73.3	Russia	0.1	UK	0.1	Serbia
Finland	43.3	Norway	20.7	Russia	9.4	USA
Sweden	54.1	Norway	11.7	USA	6.7	UK

Source: Own elaboration based on Eurostat data

Notes: darker shades indicate the countries appearing the most (Russia, dark grey, 21 times), USA (grey, 12 times), Kazakhstan and UK (light grey, 8 times)

Table 5 Top 3 Natural Gas import partner share in total import, EU27, 2022 (%)

	Partner 1		Partner 2		Partner 3	
	%	Country	%	Country	%	Country
European Union	21.0	Russia	15.8	Norway	12.6	USA
Euro area	18.6	Russia	17.2	Norway	13.0	USA
Belgium	24.0	Qatar	21.1	Norway	15.6	UK
Bulgaria	41.4	Russia	18.9	Azerbaijan	13.3	USA
Czechia	59.8	Russia	12.4	Norway	–	–
Denmark	28.4	Norway	–	–	–	–
Germany	31.6	Norway	29.6	Russia	–	–
Estonia	–	–	–	–	–	–
Ireland	100.0	UK	–	–	–	–
Greece	32.5	USA	19.8	Azerbaijan	17.5	Russia
Spain	28.9	USA	23.6	Algeria	14.3	Nigeria
France	24.8	USA	22.4	Norway	15.2	Russia
Croatia	70.2	USA	9.4	Egypt	3.0	Qatar
Italy	35.8	Algeria	19.3	Russia	14.2	Azerbaijan
Cyprus	–	–	–	–	–	–
Latvia	22.6	Russia	–	–	–	–
Lithuania	66.9	USA	25.2	Norway	7.9	Russia
Luxembourg	35.4	Norway	25.1	UK	0.0	Russia
Hungary	82.4	Russia	–	–	–	–
Malta	67.8	Trinidad and Tobago	32.2	USA	–	–
Netherlands	23.9	Norway	22.0	USA	16.3	Russia
Austria	80.0	Russia	–	–	–	–
Poland	22.6	USA	19.6	Russia	15.1	Qatar
Portugal	50.3	Nigeria	34.5	USA	6.6	Trinidad and Tobago
Romania	12.8	Russia	0.7	Moldova	0.7	Ukraine
Slovenia	8.6	Russia	3.8	Algeria	–	–
Slovakia	38.6	Russia	–	–	–	–
Finland	49.5	Russia	1.5	Egypt	–	–
Sweden	7.6	Russia	7.2	Norway	0.5	USA

Source: Own elaboration based on Eurostat data. Data for Austria are retrieved from Austrian Energy Agency

Notes: darker shades indicate the countries appearing the most (Russia, dark grey, 20 times), USA (grey, 13 times), and Norway (light grey, 11 times)

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Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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