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The diversification of energy resources and equipment imports in the European Union

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A R T I C L E I N F O

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A B S T R A C T

Efforts to reduce dependence on energy imports and increase domestic energy generation are often linked to imports of energy-generation equipment, which may lead to security issues. This study analyses the European Union's imports of energy and energy technologies in 2013–2023 using a common methodology based on a set of indicators. The analysis encompasses both well-established import diversification indicators and an extended version of the Herfindahl–Hirschman index (HHI), which considers the political stability of import sources. The results indicate that, while the diversification of energy imports has increased in recent years (the extended HHI for imports of the generalised group of energy and fuel products decreased from 0.16 in 2017 to 0.1 in 2022), imports of energy equipment are becoming increasingly concentrated (the extended HHI for energy technology imports into the EU increased from 0.16 in 2017 to 0.55 in 2022). This trend is particularly evident in the case of solar and energy storage technologies, which represent a significant vulnerability in the context of technology imports. Import dependency may have adverse consequences for the EU's ambitious energy transformation agenda.

1. Introduction

Energy diversification is one of the main challenges to energy security in the twenty-first century [1] and is a key tool in energy security policy-making [2]. Diversification in the energy sector can be achieved by introducing varied resources for energy production or using more diverse sources of imports. The first strategy, although seemingly more robust, usually requires significant initial investment and considerable amounts of imported equipment if domestic supply chains are insufficient. Thus, both strategic approaches to energy security deal with issues of import diversification in a globalised world. However, imports related to the energy supply are a particular source of uncertainty because of their low dependence on domestic actors and limited capacity to manage risks. Reorienting imports toward greater supply diversity and more reliable suppliers is an obvious risk mitigation measure that reduces the likelihood of energy supply disruptions but may involve higher costs for imported goods.

The European Union (EU) as a whole (and each energy-importing country within it) faces significant supply disruption risks in the global energy market, which have become particularly pronounced in recent years [3]. Recent global developments (the COVID-19 pandemic, war in Ukraine, energy price crisis, and related supply chain disruptions) vividly illustrate the roots of threats associated with import dependence. The diversification of oil import sources is one way to improve energy security [4]. Its implications go beyond energy security because dependence on oil imports from politically unstable countries can lead to political instability in importing countries [5]. Similar arguments in favour of import diversification can be made for other sources of energy.

The importance of this issue has led to strong academic focus on import vulnerability and supply risks. Previous studies have focused on the availability of individual resources and critical materials. Owing to their extremely limited substitutability, supply disruptions would have a direct impact on bottlenecks in the supply chain, putting entire supply chains at risk. For example, high concentrations of caesium supply pose potential threats to oil extraction and photovoltaic production [6], while platinum supply risks play a critical role in the fuel cell vehicle supply [7]. In China, tin, cobalt, chromium, and nickel pose the main supply

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Abbreviations

CN –	combined nomenclature
EU –	European Union (27 member states as of 2020)
HDI –	Human Development Index
HHI –	Herfindahl–Hirschman index
Extended HHI –	political stability extended Herfindahl–Hirschman index
GDP –	gross domestic product
LNG –	liquefied natural gas
PV –	photovoltaic
WGI –	Worldwide Governance Indicators

risks for the production of clean energy technologies (wind energy, solar energy, and electric vehicles) [8].

It is argued that in studying the issue of import diversification, the research should address import product diversification and geographical scope of import diversification [9]. Geographical diversification of energy imports is the focus of researchers in different countries such as India [10] and China [11]. Lambert et al. discussed natural gas import diversification challenges in EU in context of Russian-Ukrainian war. Researchers performed semi-directed interviews with the European natural gas industry executives and found that USA and Qatar may play a relevant role when diversifying gas and supplying it to EU through the LNG in the medium term (2023–2030) [12]. The study on the diversification of oil and natural gas supplies in OECD economies showed that diversification of oil supplies changed insignificantly, but diversification of natural gas supplies increased remarkably in energy-importing countries [13]. Vivoda focused on LNG import diversification and found that LNG import portfolios have become more diversified in China, Japan, India, Taiwan and South Korea from 2001 to 2017, but existed variations in diversification over time and across countries [14]. Dejonghe et al. carried out an analysis of natural gas and hydrogen import regimes. They argued that the hydrogen market has the potential to be less concentrated than the natural gas market. They concluded that policymakers should prioritize diversification of hydrogen supply routes, carriers, and storage, even if this results in higher costs [15].

Many studies have focused on oil imports [16]. Import diversification has featured prominently in the work of many scholars assessing oil supply security [17], and it has been identified as an essential tool for reducing oil supply risks in the EU and Japan [18]. Researchers have also examined imports of natural gas: a 10 % increase in the risk of natural gas imports, in the form of a price increase, would reduce China's GDP by 0.24 % [19]. However, diversifying imports by reducing the share of currently dominant suppliers and increasing imports from new potential suppliers significantly cuts the risk of gas imports [20]. Natural gas imports are highly dependent on infrastructure, which is why liquefied natural gas (LNG) import options are a key factor in ensuring diversification while increasing the security of natural gas supply [21]. Nevertheless, for exporting countries, export diversification can ensure security of demand [22].

The measurement issue of import diversification was also addressed in the research works. Researchers propose to apply various concentration indices for the purpose. Import diversification is usually measured by applying quantitative measures of concentration borrowed from the income-distribution. The most frequently used concentration indices are Herfindahl and Gini [23], other indicators such as Theil or Shannon-Wiener might be applied too. Herfindahl–Hirschman index was applied to measure energy portfolio diversification [24] and LNG import diversification in Asia [25]. The Shannon-Wiener and the Herfindahl-Hirschman indices, as well as the energy import dependence indicator, were used by de Rosa to analyse energy supply in the EU [26].

However, pure concentration indices do not reveal the qualitative characteristics of import sources and may, therefore, be misleading. Thus, the comparative aspect of different energy sources has received less attention in the scientific literature and has been limited to comparing only a few energy resources. Gamarra et al. analysed the supply chain risks of natural gas and concentrated solar power [27]. Koyamparambath et al. compared the supply risks of fossil fuels and battery raw materials using the GeoPolRisk framework [28], which is often used to assess geopolitical risks primarily related to raw material supply [29]. Vulnerability indicators have been calculated to extend the assessment of energy import risk. In addition to import diversification, they include other factors related to the impact of potential supply disruptions (share of imported energy sources in consumption, prices, etc.). For Turkey, such an analysis shows a decreasing vulnerability index for oil imports but an ongoing high vulnerability index for natural gas [30]. Generally, comparative aspect of different energy sources has received less attention in the scientific literature and has been limited to comparing only a few energy resources. Gamarra et al. analysed the supply chain risks of natural gas and concentrated solar power [27]. Koyamparambath et al. compared the supply risks of fossil fuels and battery raw materials using the GeoPolRisk framework [28], which is often used to assess geopolitical risks primarily related to raw material supply [29].

The calculation of vulnerability indicators has certain inherent limitations, which depend on the methodological approach adopted. In many cases, completely new indicators are produced that attempt to integrate contradictory characteristics, which limits the interpretability of such composite indicators. On the other hand, even if the logical relationships in the indicator structure are maintained, the comparability of the new indicators with existing indicators to which decision-makers and other users are already accustomed and familiar with how to interpret them is challenging.

On the other hand, the most general import threat benchmarks used in vulnerability assessments are versatile, allowing them to cover all commodities, not just energy imports. However, an assessment of the links between import threats and energy security must consider specific energy aspects. Some energy sources are relatively interchangeable, not only because they are suitable for use in the same generation technologies but also because it is possible to change the generation mix, even in the short term, by changing the operating time of existing technologies. However, in the longer term, it is important to consider the potential for energy system transformation. As the use of fossil fuels declines, the risks associated with fossil fuel imports decrease. At the same time, with the development of renewable energy and other capital-intensive technologies, the role of equipment and related commodities is expected to increase. The vulnerability of a country or region to import-related threats depends on the volume of imports, import diversification, import sources, and the substitutability of imported goods, but not all indicator systems are capable of covering these aspects. Therefore, it is important to comprehensively analyse the imports of both fuels and energy technologies.

The objective of this study is to address the existing gaps in the academic literature with regard to both the assessment of import diversification and the practical knowledge of the dynamics of energy-related imports in the EU. While previous research has extensively covered various aspects of energy diversification, this study focuses specifically on the diversification of energy resources and equipment imports, including different products. This new perspective aims to provide a more comprehensive understanding of how diversifying energy-related products can contribute to the EU's energy security and sustainability goals.

The novelty of the study consists of several aspects. First of all, it integrates political stability into an extended HHI that is comparable to the original HHI. This provides excellent interpretation opportunities. Second, the analysis not only covers all the EU's major energy import groups but also includes energy technologies. Finally, the period 2013–2023 is unique in that it marks a very significant change in the

EU's energy sector, the impact of which on the diversification of energy-related imports into the EU has not yet been explored in the scientific literature.

This study analyses the diversification of energy-related imports into the EU between 2013 and 2023. Therefore, the analysis covers not only different energy (fuel) sources but also energy technologies (energy equipment and other energy-related goods used in operation and maintenance processes). Unlike previous studies that focused on the supply chains of critical materials, this study focuses on the parts of the supply chain that are closer to consumption. Threrefore, this allows for an assessment of the direct links to Europe's energy self-sufficiency and energy transition ambitions. This study also fills the gaps in previous research, which lacks comparative analysis, by covering not only different types of energy but also imports of energy technologies. Integrating a political stability indicator into the import diversification calculations proposed in this study allows us to include qualitative import characteristics in a conceptual framework comparable to the classical Herfindahl–Hirschman index (HHI). Finally, as the study analyses the most recent data covering the period 2013–2023, the analysis let us to assess the impact of recent developments (e.g. COVID-19 pandemic, war in Ukraine) on the diversification of energy-related imports in the EU.

The remainder of this paper is structured as follows. The second section presents the methods used to assess import diversification. The third section analyses the diversification of imports of energy-related commodities in the EU. The fourth section concludes and offers policy recommendations.

2. Materials and methods

The prevailing methodologies for assessing supply risk are the EU Revised Methodology, Yale Methodology, and US National Science and Technology Council Methodology [6]. All three approaches include an assessment of import diversification as a measure of risk and the riskiness of the countries from which imports originate. Broad indices covering many dimensions have been developed for supply risk analyses [31]. In practice, not all elements used are equally relevant to the issue at hand, and the different dynamics of their levels may mask critical situations. The use of composite indices is most justified when all the elements used reflect the specificity of an issue (in this case, the aforementioned offsetting effects of the different elements of the index are present not only in the calculation of the index but also in reality). Thus, the index comprises indicators that reflect the specificities of the supply of a given commodity [32].

However, it is important to focus on universal factors to ensure comparability between different goods. For these reasons, it is appropriate to focus on clearly interpretable indicators rather than increasing their complexity by losing clear links to supply disruptions. Therefore, the analysis includes both simple and complex indicators.

2.1. Methods

To assess the concentration of supplier countries, either the sum of the market shares of the one to three largest suppliers or the HHI is typically used [33]. A straightforward diversification measure is the largest share of a single supplier. For import good c in period t, the largest share of a single supplier $MaxShare_{c,t}$ is

$$MaxShare_{c,t} = \max{}_{i=1}^{n} \left(\frac{Imp_{i,c,t}}{\sum_{i=1}^{n} Imp_{i,c,t}} \right), \tag{1}$$

where $Imp_{i,c,t}$ is the import of product c from import source in time period t, and n is the number of import sources.

When there is a dominant supplier, its share of total imports is key information. However, it ignores the shares and possible significant roles of other suppliers, which could cause import vulnerabilities (e.g. if they start to act as dominant suppliers) or provide alternatives to other suppliers.

By assessing the shares of both the largest and other suppliers, the HHI provides a more complete picture of the distribution of supply sources in the market. The HHI has been widely used in energy diversification assessments [14]. The HHI for commodity c is calculated as

$$HHI_{c,t} = \sum_{i=1}^{n} \left(\frac{Imp_{i,c,t}}{\sum_{i=1}^{n} Imp_{i,c,t}} \right)^2, \tag{2}$$

where $Imp_{c,i}$ is the value of imports of commodity c from i-th source in time period t, and $TImp_c$ is the total value of imports.

Although the HHI is probably the most common indicator used in the literature to measure concentration and diversification, for simplicity, even the largest share of a single supplier can provide valuable information. This is illustrated by theoretical calculations of the impact of import sources (Fig. 1).

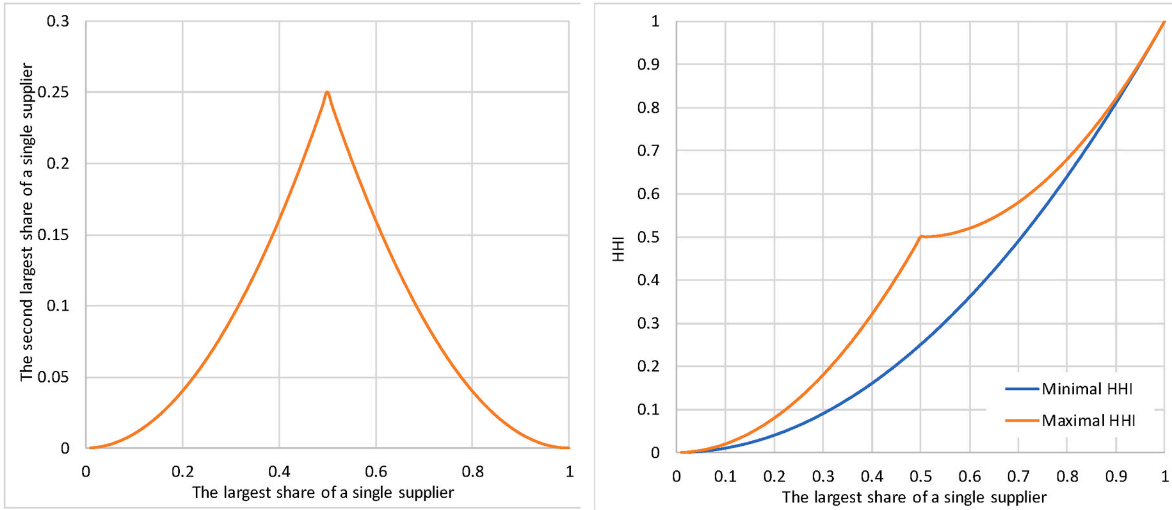
As Fig. 1 shows, the HHI is mostly determined by the source of imports with the highest share of total imports. Even the supplier with the second-largest share plays a significant role in the calculation of the index only when imports come from two sources with shares close to 50 %. In other cases, knowing the maximum share of a single supplier is sufficient to draw meaningful conclusions regarding import concentration. This is because if the largest share of imports from a single supplier is small, the second-largest share from a single supplier will not be larger, and that imports will be well diversified. However, if the largest share of imports of a single supplier is high, the second largest share of the supplier will not have a significant impact on the HHI calculation, and the high import concentration will be due to the highly concentrated imports of the first supplier.

Both the single largest share indicator and the HHI only show the concentration of imports and summarise the distribution of suppliers well, but do not consider qualitative characteristics of import sources; additional information must be used to obtain indicators that assess the specificity of import sources, particularly their level of riskiness and political stability.

Country assessments typically use integrated indicators to describe countries. Several indices summarising the risk characteristics of countries can be found in the literature. Various indicators have also been used to analyse energy imports. They range from broad indices, such as the International Country Risk Guide (ICRG) [13,34–37], Worldwide Governance Indicators (WGI) [38–40], and Human Development Index (HDI) [26], to very specific indices, such as the Piracy and Armed Robbery Index, which are used to evaluate oil supply security through specific sea areas [39]. The choice of appropriate indicators always poses a number of dilemmas, often oscillating between reflecting specific threats to the supply of specific products along specific logistical routes and the potential for universal application. In the context of the energy and energy technology import issues addressed in this study, universality is a priority, while recognising that the use of broad indicators has limitations related to the reduced ability to assess the specific import risks. In other words, while the universal indicators do not directly reflect specific aspects of import risk, they may to some extent reflect these aspects indirectly.

Other criteria for the selection of the indicator include a broad list of countries included, open access, transparency of methodology and acceptance in the scientific community. The WGI [41]published by the World Bank meet these criteria. They consist of six broad dimensions.

- Voice and accountability
- Political stability and absence of violence/terrorism
- Government effectiveness



(a) (b)

Fig. 1. The impact of market shares of import sources on the HHI calculation: (a) HHI levels depending on the maximum share held by one supplier, (b) Maximum potential contribution to the HHI of the supplier with the second highest import share.

- Regulatory quality
- Rule of law
- Control of corruption [41].

By analysing previously published work, two prevailing trends in WGI use can be identified: averaging the six dimensions [20,42,43] or selecting one of the indicators. The first strategy frees one from the choice of dimension; however, it is questionable whether the average of the six dimensions adequately reflects the risks specifically related to the import of goods. There may be some discrimination against developing countries, as is the case with the use of integrated development indicators, such as the HDI, to assess country risks, which focuses more on the level of development of the countries concerned than on specific supply related threats, limiting their applicability in assessing import risk. On the other hand, it is clear that while the WGI dimensions are related to potential import risks, the relationship of each of them to the credibility of the countries under consideration as sources of imports is not uniform.

The political stability and absence of violence indicators are considered to have a significant correlation with stable and reliable supply and are therefore often used to represent supply country risk [7,40,44–46]. This indicator was also used in the GeoPolRisk conceptual framework [28]. Therefore, a political stability indicator was chosen for this analysis.

The WGI indicators are presented on a scale from −2.5 to 2.5, where a lower number indicates poorer governance performance. Following common praxis [46], the political stability indicator was scaled to cover a range from 0 to 1, with lower values indicating lower risks:

$$PSscaled_{i,t} = -0.2 \times PSoriginal_{i,t} + 0.5, \tag{3}$$

where $PSoriginal_{i,t}$ is the original value of political stability in the absence of violence indicator in time period t as published in the WGI.

This indicator can be used to calculate the weighted average of political stability for imports, where an estimate of political stability is calculated based on the share of each import source in total imports:

$$WeightedPS_{c,t} = \sum_{i=1}^{n}\left(\left(\frac{Imp_{i,c,t}}{\sum_{i=1}^{n} Imp_{i,c,t}}\right) \times PSscaled_i\right). \tag{4}$$

This indicator is particularly useful in situations where imports are well-diversified across several countries but import diversification might not be sufficient to avoid supply disruptions if the same factor affects several countries with low stability and other common factors that may cause disruptions to supplies from those countries.

Typically, the political stability factor is incorporated into the HHI by multiplying the supplier's market share by a normalised estimate of political stability in the range of 0–1 [13].

$$HHIadjustedPS_{c,t} = \sum_{i=1}^{n}\left(\left(\frac{Imp_{i,c,t}}{\sum_{i=1}^{n} Imp_{i,c,t}}\right)^2 \times PSscaled_{i,t}\right), \tag{5}$$

However, a major drawback of this strategy is that the resulting indicator is not comparable to the original HHI. As Cappelli and Carnazza point out, the same values of the simple and political-stability-adjusted HHI can only be obtained when $PSscaled_{i,t}$ is equal to one, that is, when all import sources exhibit maximum political instability, whereas in practice, the HHI adjusted by the political-stability indicator is about half of the original HHI [40]. This is because the median of each WGI value is zero, and Equation (3) shows that the median of $PSscaled_i$ is 0.5. Thus, if imports are from sources with high or low political stability, with an estimate close to the median (0.5), the adjusted HHI is half the original value.

In this context, to ensure comparability with the original HHI, the normalised estimate of political stability is multiplied by two in the import diversification calculations. Thus, the resulting extended HHI indicator is comparable to the unadjusted (original) HHI.

$$HHIextendedPS_{c,t} = \sum_{i=1}^{n}\left(\left(\frac{Imp_{i,c,t}}{\sum_{i=1}^{n} Imp_{i,c,t}}\right)^2 \times 2 \times PSscaled_{i,t}\right), \tag{6}$$

The theoretical range of the extended HHI indicator is wider than that of the original HHI; in the extreme case of imports from a single source (HHI = 1) with a maximum level of political instability ($PSscaled_{i,t} = 1$), it reaches 2. In the other theoretical case, in which all imports reach the country in question from countries with maximum political stability, the value of the HHI extended indicator is zero, regardless of the level of import diversification. In the case of high import diversification, the extended HHI would also be close to zero, regardless of the level of political stability of the import sources, as the share of each supplier country in the total import structure would be close to zero. In this case, the calculation of the indicator reflects the assumption that political instability can be offset by the possibility of switching to alternative sources of supply in the case of an emergency thanks to import diversification. The main advantage of this methodological approach is its good comparability with the original HHI, where most of the obtained values fall within the same range between 0 and 1. Although some studies are limited to ensuring that the original and adjusted HHI are in the same direction [36], because both higher import concentration and the predominance of less reliable suppliers are considered to be higher risks, the convergence of the scales has significant added value because of good interpretability.

Compared to composite indices, the approach proposed here provides a realistic assessment of the impact of the components of the indicator, as sufficient diversification of sources of supply reduces the impact of supply volatility, and a high level of political stability of sources of supply reduces risks, even if imports are not highly diversified.

An important methodological issue is related to time in the estimation of political stability. While long-term averages of estimates of political stability are sometimes used in the evaluation of energy infrastructure projects [47], it must also be acknowledged that the situation of countries can change significantly over the long term and that a bad (or good) situation at the beginning of the period analysed may have nothing to do with the current and future situation. Therefore, it is more appropriate to focus on the most recent estimates of political stability or use estimates of political stability for each year in the assessment, thus covering both the dynamics of import diversification and the political stability of import sources. However, for practical considerations, compatible data are required. Information on direct imports is available quickly (the latest data are published with a delay of only three months), whereas the WGI is published once a year with a delay of almost one year. Thus, using the full WGI time series raises the issue of assumptions about the most recent indicators for which import data are already available, but not yet for the WGI.

To ensure comparability, all calculations in this study are based on the value of imported goods rather than on quantities. While this undermines the suppliers of larger volumes at lower prices, the value of imports better reflects the relative effects (importance of imports in the presence of quality or other differences).

2.2. Data

The main data source for the analysis is Eurostat's Comext database [48], which collects trade data for all EU Member States from 2020 onwards (excluding the UK). The selected study period 2013–2023 covers all recent changes.

While the database provides a detailed list of products (eight-digit level of the Combined Nomenclature), this study focuses on more aggregated descriptions, which often allow substitution within the same position. The level of product aggregation is also important for analysing import diversification in terms of the values of the resulting diversification indices. Although this is not a rule, in most cases, a more detailed analysis means less diversification; however, this does not necessarily mean that the aim of analysing the most detailed product groups is correct. For example, in the case of natural gas and LNG, there are indeed substitutes, so analysing each of these products separately would lead to unjustifiably high import concentrations. In reality, the possibility of substituting LNG for natural gas in the case of gas injected into the market means better diversification of imports and more protection against potential supply disruptions, rather than additional risks due to the lack of diversification of one of the individual products taken separately.

The commodities analysed and their groups are listed in Table 1. The table includes shortened descriptions of the CN codes, whereas exact descriptions are available in the regulation of the Combined Nomenclature (2658/87).

Table 1
Energy resources and energy-related products analysed.

CN 2022 code	Short name
Solid fossil fuels	
2701	Coal
2702	Lignite
2703	Peat
2704	Coke
Natural gas	
271111	Natural gas, liquefied
271121	Natural gas, gaseous
Crude oil	
2709	Crude oils
Oil products	
2710	Petroleum oils, other than crude
271112	Propane, liquefied
271113	Butanes, liquefied
Electricity	
2716	Electrical energy
Wood fuel	
4401	Fuel wood in various forms
4402	Wood charcoal
Nuclear fuel	
840130	Nuclear fuel elements (cartridges), non-irradiated
Energy technology and related commodities	
840110	Nuclear reactors
841020	Machinery and apparatus for isotopic separation
840140	Parts of nuclear reactors
8402	Steam boilers
8403	Central heating boilers
8404	Auxiliary plant for use with boilers
8406	Steam and other vapour turbines
8410	Hydraulic turbines
841181	Gas turbines of a power $\leq$5.000 kW
841182	Gas turbines of a power $>$5.000 kW
841199	Parts of gas turbines
8415	Air conditioning machines
8416	Furnace burners
841861	Heat pumps
841911	Instantaneous gas water heaters
841912	Solar water heaters
841919	Water heaters (excl. electric and gas)
841950	Heat-exchange units
8502	Electric generating sets and rotary converters
8503	Parts for use with electric motors and generators
8504	Electrical transformers, static converters
850750	Nickel-metal hydride accumulators
850760	Lithium-ion accumulators
8514	Electric furnaces and ovens
851610	Electric water heaters
851621	Electric storage heating radiators
851629	Electric heating apparatus (excl. storage heating radiators)
8541	Diodes, transistors and similar semiconductor devices, incl. photovoltaic cells

Another reason for using less detailed headings in the analysis is that some important technologies do not have or have only recently obtained separate CN headings. However, it is likely that some of these were still classified in their previous positions. Theoretically, therefore, the choice of a wider range of items reduces accuracy but allows more energy technologies to be covered and improves the quality of the analysis. Analysing import diversification, including related products, is generally not as detrimental as ignoring individual technologies.

For a more detailed analysis of the import of technologies of particular relevance to the energy transition, specific import goods have been identified, but for the purposes of the analysis they have been grouped into wind, solar and energy storage. In this case, belonging to a group does not imply substitutability (e.g. an inverter could not be used instead of a PV panel), but rather includes examples of goods that are clearly linked to a particular energy technology. The grouping of technologies is shown in Table 2.

As the table shows, the lists of technology goods vary in their level of exhaustiveness. While solar energy is represented by five items, wind

Table 2
Energy technology groups analysed.

CN 2022 code	Short name
Solar	
850171	Photovoltaic DC generators, of an output ≤50 W
850172	Photovoltaic DC generators, of an output >50 W
850180	Photovoltaic AC generators
854142	Photovoltaic cells not assembled in modules or made up into panels
854143	Photovoltaic cells assembled in modules or made up into panels
Storage	
850750	Nickel-metal hydride accumulators (excl. spent)
850760	Lithium-ion accumulators (excl. spent)
Wind	
850231	Generating sets, wind-powered

energy is represented by only one. As the table shows, the lists of goods representing each technology vary in exhaustiveness. While solar energy is represented by five items, wind energy is represented by only one. It is clear that wind energy projects require many more components than just the generating set. However, as this study focuses on import diversification issues, it only considers the goods for the energy type mentioned in Table 2, and ignores the goods available for a variety of applications. It is worth noting that the types of storage shown in the table can be used for other purposes, not necessarily for balancing RES and similar uses in the energy sector. However, they are energy storage that will be increasingly needed as the energy transformation progresses. Furthermore, the selection of goods is also limited by the granularity of the classification used. For instance, solar energy goods were not included in the combined nomenclature as a separate category until 2022. In contrast, wind-powered generating sets were distinguished much earlier, which has resulted in a relatively long time series being available.

The estimates of political stability are taken from World Bank data [41]. This dataset covers almost all of the EU's trading partners; therefore, the data gaps are not significant. However, in the absence of information on the political stability of some import sources, proxies for similar countries or the median political stability are used. As the latest available data for the Political Stability indicator cover the year 2022 and the analysis period extends to 2023, the 2022 Political Stability indicator data are also used to describe the sources of imports in 2023. Although it can be seen as a limitation of this study, this approach allows the analysis of the most recent data available, which is particularly relevant in the context of the recent disturbances.

3. Results and discussion

The period 2013–2023 was analysed to assess the dynamics of the diversification of the EU's energy imports. On the one hand, this period is long enough to capture the underlying trends. On the other hand, the latest available data include recent developments that have had a significant impact on supply chains. Finally, the latest developments also coincide with the EU's strategic energy transformation initiatives, in which the import of energy or energy technologies may play a significant role, as the risks of imports would also lead to risks in the implementation of the objectives.

3.1. An overview of energy-related imports in the EU

General trends in EU imports of goods are shown in Fig. 2 which is based on the data from Comext database [48]. Fig. 2 distinguishes between imports of energy (fuels) and other goods. Over 2013–2023, total imports of goods amounted to EUR 1.6–3 trillion, of which EUR 0.2–0.7 trillion were energy and fuel imports. The share of energy and fuel imports ranges from 12 % to 27 %. As energy demand changes relatively slowly, the share of energy imports in the total value of imports depends mainly on the dynamics of energy prices, as indicated by the highest values of this indicator during periods of high energy prices. However, the lowest share of energy imports in total imports was observed in 2020 when the COVID-19 pandemic and lockdowns led to a sharp drop in energy demand (complementary price and volume effects were observed in this case). Fig. 2 does not include energy technologies and related commodities in the value of energy and fuel imports, because the list of commodities highlighted in this study is not exhaustive. Including various additional commodities would change the overall values only slightly, as the share of energy technologies in the total value of imports is modest, at a few percent of the total import value. Imported technologies can significantly affect energy production and other energy transformation activities.

The full dynamics of the structure of imports and exports of energy-related products to the EU are shown in Fig. 3, which shows the export values of the products concerned for comparison purposes. It is important to stress that the EU is a large entity and that imports of some energy products are closely linked to infrastructure (e.g. oil and gas pipelines); therefore, the analysis at the EU level does not reflect the situation of individual countries. A near-zero import-export balance may imply that some countries are net exporters and others are net importers, which may be highly vulnerable to import dependence.

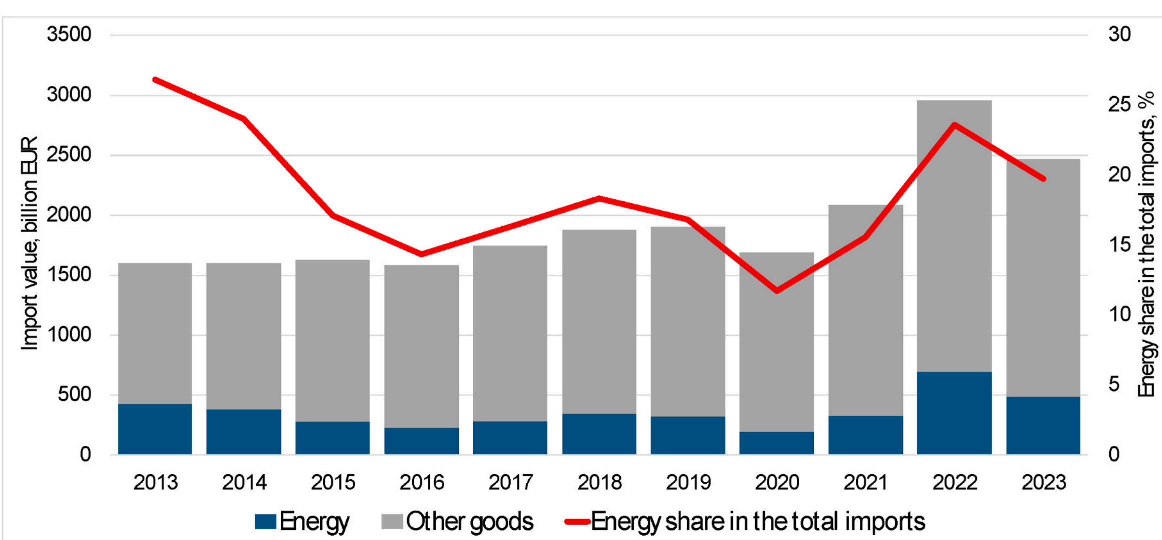


Fig. 2. Dynamics of imports to the EU in 2013–2023.

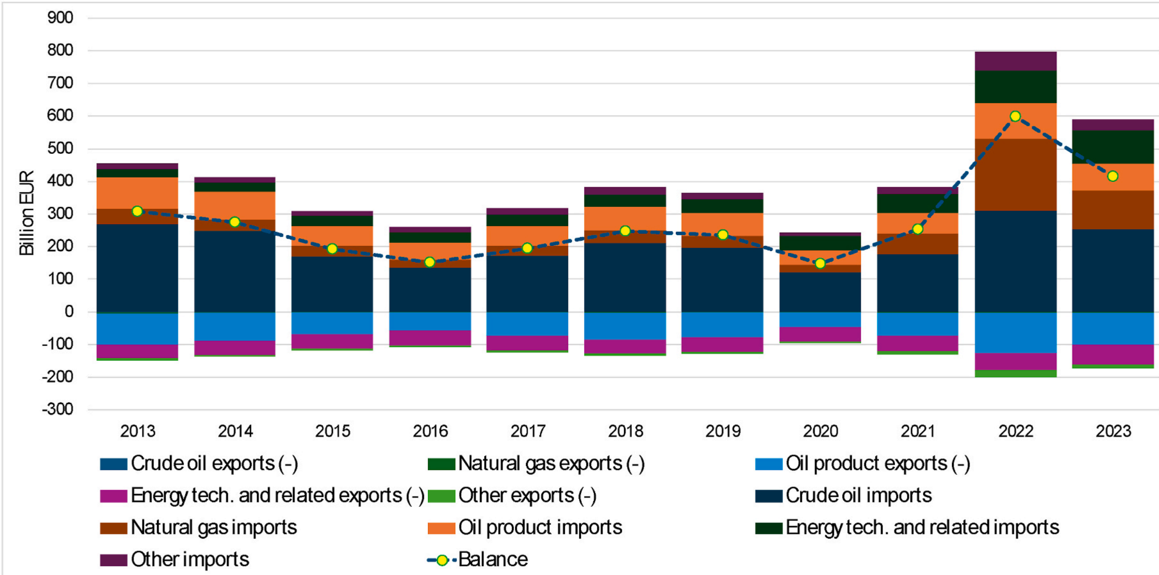


Fig. 3. Dynamics energy and related trade flows in the EU in 2013–2023.

Fig. 3 shows that the EU is a net importer of energy and related goods in all periods, with net imports ranging from EUR 147 billion in 2020 to EUR 597 billion in 2022. As the volumes of imported energy resources have not changed sharply, it can be argued that in most cases, the dynamics of the value of imports have been influenced to a large extent by the evolution of the prices of imported energy resources, which is particularly evident in the situation for 2022. In 2023, the EU's import balance showed a slight improvement, although the situation remained worse than in 2021 and previous years.

Three product groups can be distinguished by comparing the import dynamics of individual product groups.

- import values are consistently higher than export values;
- a constant import-export balance close to zero;
- reversal trade direction over the period considered.

The first group includes primary energy resources (in order of import value): crude oil, natural gas, petroleum products, and solid fossil fuels. These commodities are responsible for the fact that energy commodity imports are higher than exports. The second group of relatively neutral commodities includes electricity, for which net imports became more significant only in 2022, and nuclear and wood fuels, for which exports were slightly higher than imports each year. Finally, energy technologies and related goods reflect the changing trends. At the beginning of the period, the value of exports of these goods exceeded the value of imports by around EUR 7–16 billion; the gap started to narrow from 2018 onwards, and by 2021, the value of imports was EUR 12 billion higher than the value of exports, while in 2022, excess imports reached EUR 47 billion. In 2023, exports of energy technologies grew by 14 % and imports by only 2 %, which has led to a reduction in the negative import balance in this category to EUR 40 billion. However, it should be noted that imports and exports can be of different goods, so the role of imports at the level of a particular good may vary.

Although the total value of energy technology imports is modest compared with the value of imported energy resources, this change in trend is significant in the context of efforts to reduce energy imports and transform the European energy system. While energy import vulnerability can manifest itself as short-term supply chain disruptions, energy technology import vulnerability is potentially linked to both long-term challenges, such as the development of renewable energy, and short-term vulnerabilities, such as access to specific supplies for maintenance processes or even threats related to the technology supplier's ability to influence its performance, for example, through access to control of digital technologies.

The increase in the value of net imports of energy resources and other energy-related commodities makes it even more important to analyse the degree of import diversification and import diversification trends to minimise potential import risks.

3.2. Import diversification dynamics

The import diversification indicators were first calculated at the commodity group level, as presented in Table 1. The grouping of energy resources considers their substitutability (e.g. different forms of coal or biomass, natural gas imports by pipelines in gaseous form, or by terminals in liquid form). Energy technologies and related commodities have different levels of substitutability, but their aggregation allows for the analysis of diversification trends if meaningful groups are created.

The share of the largest supplier in imports of a given commodity – is depicted in Fig. 4, which shows that nuclear fuel imports are the most concentrated (68–89 % of imports come from Russia). While there was a downward trend in the dependence on Russian nuclear fuel imports, with the share of the largest supplier falling to 68 % in 2022, this was not a consistent trend. In fact, Russia's share of the EU's nuclear fuel imports rose again to 79 % in 2023.

Concerning nuclear fuel imports, while the overall balance between nuclear fuel imports and exports in the EU is on the export side, the dependence of individual plants on nuclear fuel imports is linked to past choices of nuclear technology. This imposes restrictions on the shift from one importing country to another.

Increasing import dependence can be expected in other energy sectors, as the share of the largest supplier in the total imports of energy technology and related goods rises sharply. While the share of the largest supplier was approximately 40 % at the beginning of the period, it exceeded 60 % by the end, with an increasing trend from approximately 2019 (even before the COVID-19 pandemic and other global trade disruptions).

China accounts for the largest total value of imports of energy technology and related goods; however, the leading countries vary for specific goods. Turkey is the leading exporter of central-heating boilers to the EU, the UK has a strong position in auxiliary equipment for boiler use, and the US is the main foreign supplier of nuclear reactor parts. The supply of steam turbines is fairly well diversified, with leadership changing every year Most other energy technologies and energy-related

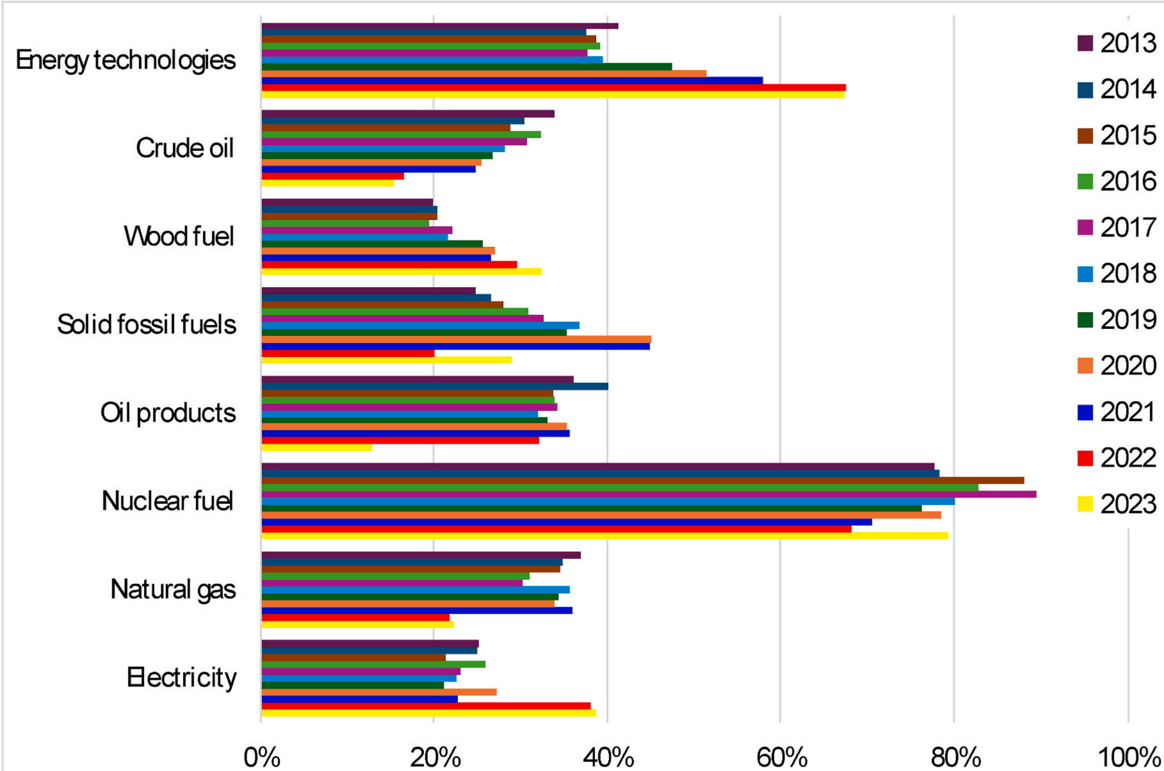


Fig. 4. Percentage share of the most significant foreign supplier to the EU.

goods, including parts for electric motors and generators, electric transformers, static converters, electric generating sets, rotary converters, diodes, transistors, and semiconductor devices, are dominated by imports from China. The dominance of one country among import sources does not necessarily imply import dependence, as some technological goods, such as burners, steam boilers, steam turbines, and power-generating sets, are heavily produced in the EU. Their exports exceed their imports; however, the value of semiconductor imports is

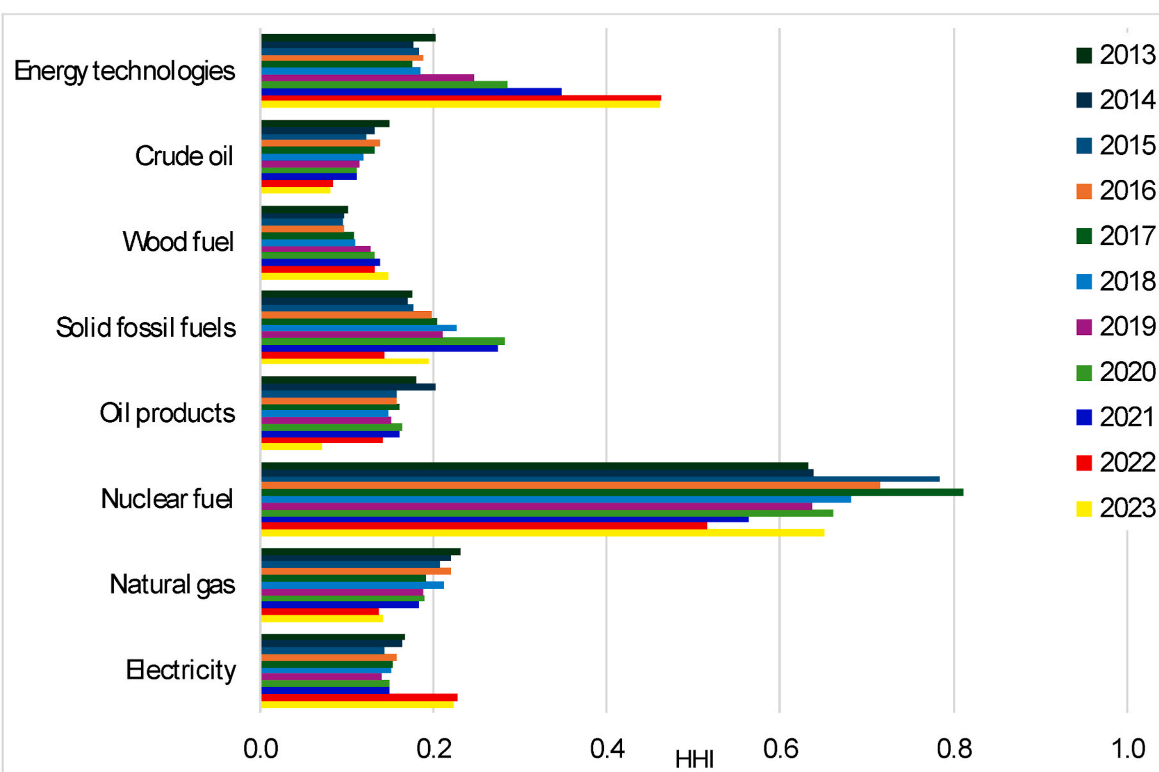


Fig. 5. Herfindahl–Hirschman index for imports to the EU by commodity group (with a range from 0 to 1, with a larger number showing greater concentration).

several times higher than that of exports, indicating a high degree of import dependence.

The other commodity groups studied do not show such a strong dominance of a single source of import. In the case of natural gas, crude oil and petroleum products, and solid fossil fuels, the decline in the share of the largest supplier in 2022 is mainly due to the declining role of imports from Russia following the war in Ukraine and the imposition of increasingly stringent sanctions. It is perhaps most evident in the import of petroleum products, where the share of the largest supplier has fallen from 35 % in 2021 to 32 % in 2022 and to 13 % in 2023, with Saudi Arabia taking over the leading position from Russia.

In crude oil imports, Russia's slowly declining import concentration has been steadily observed, but already in 2022 its share as a major supplier has fallen to 17 %, and in 2023 the US has become the EU's largest oil supplier with a 15 % share of imports.

In contrast to the share of the largest supplier, the HHI provides an indication of the distribution of all suppliers. The calculated HHI values are shown in Fig. 5.

In terms of HHI, the level of import diversification shows similar trends for the commodity groups considered. This is not surprising given the nuances of the HHI calculation discussed above and its dependence on the indicator of the largest share of one supplier. The peculiarities of the HHI calculation lead to a greater dispersion of the index values. In this case, the concentration of nuclear fuel imports with values above 0.8 stands out even more. The concentration of imports of energy technology and related goods increased sharply in the second half of the period considered. This is purely due to an increase in the share of the largest supplier, as the shares of suppliers ranked 2–5 in the EU import structure decreased from 2018 onwards. The situation is different for natural gas, where the drastic decrease in natural gas imports from Russia in 2022 is followed by increased imports from the US and the UK. It is also worth noting that in the wake of the Russia-Ukraine war, the prevailing view among experts was that reducing the consumption of Russian gas would be a complicated process [12].In the case of solid fossil fuels, the decline in imports from Russia was partly offset by increased imports from Colombia and South Africa, but the diversification of imports improved significantly more than that of natural gas owing to the increased share of small suppliers. In 2022, the imports of crude oil and petroleum products were the most diversified in terms of the HHI, although imports from Russia accounted for a significant share (16.5 % crude oil and 25.1 % petroleum products).

The assessment of imports differs considerably when focusing on the political stability of the import sources. Fig. 6 shows the average political stability index by import commodity group, considering the import value shares from different countries. The index is normalised such that 0 represents the best situation, and 1 represents the highest probability of instability.

The context of the political stability indicator is well illustrated by the fact that the average (unweighted) political stability indicator for EU countries in the period 2013–2022 ranges between 0.341 in 2013 and 0.376 in 2022 (among other factors, Russia's war against Ukraine has affected the score of political stability of EU countries). As can be seen from the figure, for all the product groups considered, the predominant sources of imports have been countries with lower political stability than the EU average., The most sensitive situation is that of crude oil and nuclear fuel imports. The situation for electricity imports is the best, as a large portion of the electricity reaches the EU from Switzerland, Norway, and the UK, which are considered politically stable (they rank high in political stability).

The improvement in the political stability indicator for most commodities is not due to political stability changes in the supplier countries, but because of the changing structure of imports.

Fig. 7 shows the relationship between the political stability of supplier countries and the diversification of imports by product group.

Several cases can be identified based on Fig. 7.

- Well-diversified imports, but dominated by countries considered politically unstable (e.g. crude oil, whose import diversification has

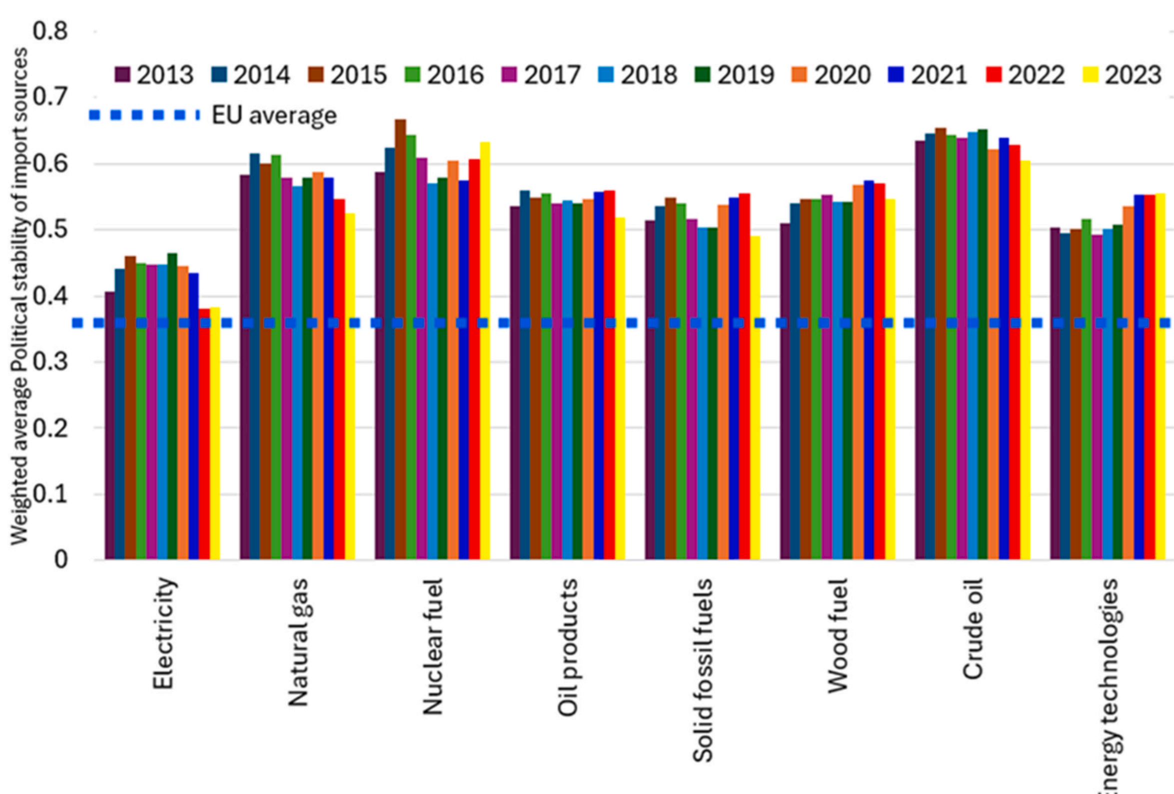


Fig. 6. Weighted average of political stability index for imports to the EU by commodity group (a higher number represents a higher probability of instability).

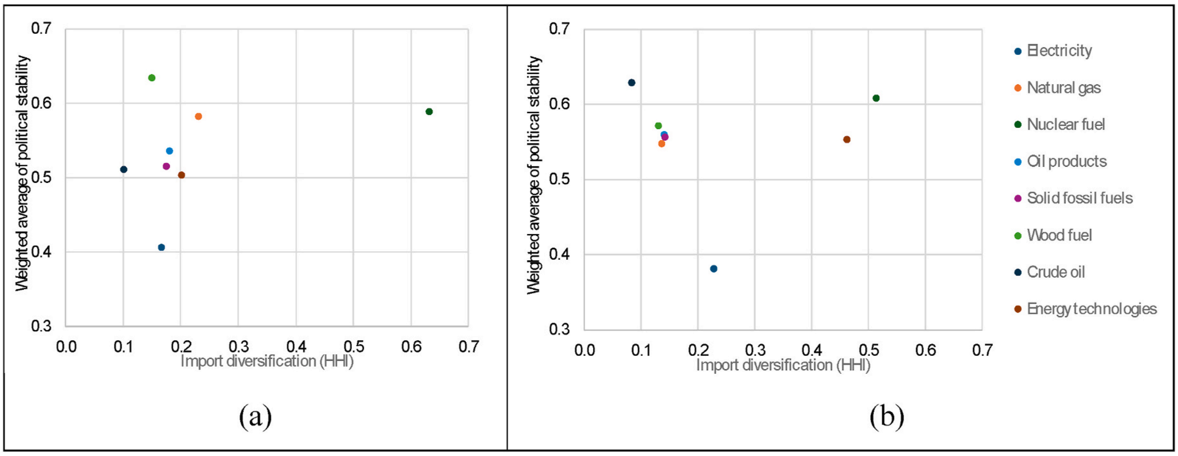


Fig. 7. Relationship between political stability in supply countries and import diversification by product group: (a) 2013, (b) 2022.

been improved significantly, but imports from countries considered by WGI as less politically credible have remained).

- Well-diversified imports with moderate political stability (most commodities by 2022; higher dispersion by 2013).
- High concentration of imports from countries with moderate political stability (nuclear fuel in all periods, energy technology, and related goods in 2022).
- Relatively well-diversified imports and politically stable countries of origin (electricity).

Comparing the 2013 and 2022 states, for most commodities, both the diversification and stability indicators of the supplier countries have improved, leading to the formation of a tight cluster in 2022. In this cluster, consisting of natural gas, petroleum products, wood fuels, and solid fossil fuels, the HHI is around 0.135 (on a scale of 0–10,000, this would be equivalent to 1350), and the Political Stability Index is around 0.537 (on a scale of −2.5 to 2.5, this would be equivalent to −0.185, which is a bit worse than the median value of zero). The diversification of electricity imports decreased but political stability increased, while in technology imports, both diversification and the political stability index deteriorated.

The extended HHI (*HHIextendedPS*) estimates, calculated by combining import diversification and political stability assessments, are presented in Fig. 8.

These estimates suggest that the import risks of most commodities, except energy technology, have decreased significantly in recent years. The most potentially vulnerable imports remain those of nuclear fuels, energy technology, and related goods, for which this indicator exceeds 0.5.

In the case of nuclear fuel, good storage capabilities and a relatively

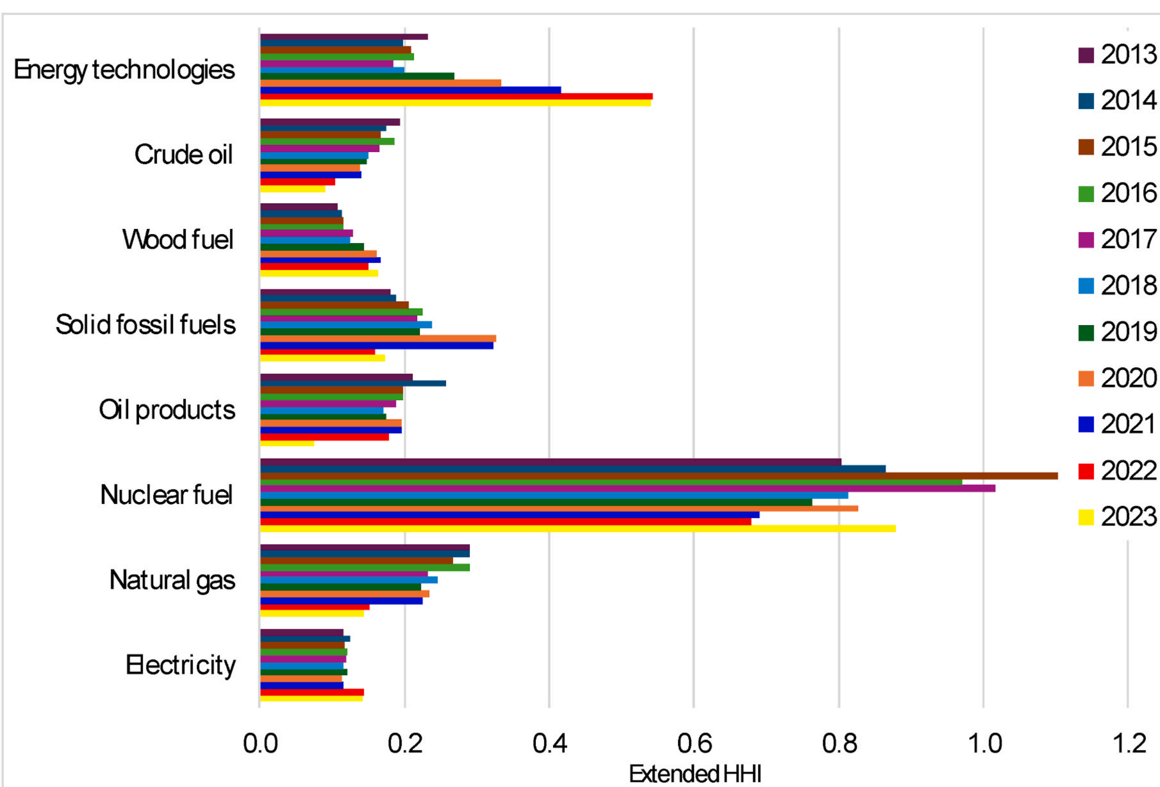


Fig. 8. Political stability extended Herfindahl–Hirschman index for imports to the EU by commodity group.

small fuel component in the cost structure of nuclear power generation help manage risks. The situation is somewhat different for technology imports, where potential import disruptions can have a significant impact not only on long-term energy projects, but also on day-to-day operations as the technologies analysed here consist not only of goods related to investment, but also to maintenance processes. Finally, the reliance on technology imports includes integrated information and communication technologies, which have a major impact on the operation of increasingly complex energy systems.

Fig. 9 presents a summary comparison of the vulnerability of fuel and energy imports, as measured by the extended HHI, with the vulnerability of imports of energy technology and related commodities.

Until 2018, the diversification indicators for both energy technology and related imports and energy/fuel imports were relatively stable, while technology imports were only slightly less diversified. Thereafter, the concentration of technology imports begins to increase rapidly, reaching 0.55 in 2022, as measured by the extended HHI. Because this trend began before 2020, it cannot be assumed that it was a short-term development due to recent global shocks. The growing divergence between technology and energy import diversification has also been reinforced by the significant increase in the EU's energy import diversification which started in 2022 and which was partially a result of increasing energy prices and trade sanctions gradually imposed on Russia. Finally, the change in the configuration of import markets has led to a widening gap between the original HHI and extended HHI in the case of technology and the convergence of the two indices in the case of energy.

This demonstrates the merits of the methodological approach proposed in this study for an integrated assessment of import diversification in uncovering import-related threats. Although the weighted indicator of the political stability of sources of fuel and energy imports is worse than that of technology imports, the lower diversification of technology imports leads to a multiplier effect, whereby the extended HHI of technology imports at the end of the period under consideration is significantly higher than the original HHI. In the case of energy imports, the weaker political stability of import sources is counteracted by an increase in the diversification of import sources, since, assuming no global coalitions are formed, the dispersion of imports, even in the presence of less reliable sources of supply, allows for the possibility of securing security of supply through alternative sources.

Fig. 10 presents an assessment of the import diversification of technologies essential for the energy transition using extended HHI.

Although data on imports of solar technologies are only available from 2022 onwards, it is clear that imports into the EU are very poorly diversified. This situation is primarily due to the fact that the share of imports of the solar technologies under consideration from a single source of supply, China, was 96 % in 2021 and 97 % in 2022. Since the political stability indicator of China in WGI in 2022 was −0.44 (in the original WGI range of −2.5 to 2.5), this results in an extended HHI value above 1.

The extended HHI for wind technology imports into the EU fluctuates significantly over the whole period, in no small part due to the relatively low import volumes of the good considered (It is the only one of the three energy technologies considered here whose production in the EU and exports to third countries exceeds imports). Meanwhile, energy storage imports have grown strongly in recent years. From less than EUR 2 billion per year in 2013–2014, they have already reached almost EUR 7 billion in 2020 and exceeded EUR 26 billion in 2023. Together with imports of solar energy technologies (almost EUR 20 billion in 2023), they account for a significant share of the total EU imports of energy technologies. This growth trajectory was mirrored by a rising extended HHI, which reached 0.9 in 2023. Similarly to solar PV, China was the primary source of imports, accounting for 87 % of total EU imports in 2023.

Despite the lack of research on imports of energy and energy technologies, the results of this study clearly demonstrate the EU's dependence on imports. This is in line with the findings of other authors, such as De Rosa et al. [26].

The findings of this study to some extent continue the work of Yang et al., who looked at the period up to 2010 and obtained similar HHI estimates (approximately 0.17) at the end of their analysed period [36] as were found for the beginning of the period of the present study. Koyamparambath et al. examined the risks of supplying raw materials and fossil fuels for battery production in OECD countries, and found that the risks of supplying raw materials were significantly higher [28]. Although this study focused on a different segment of the supply chain when examining critical materials, the results are in line with the findings of the present study. From a policy perspective, the declining diversification of technology imports and increasing dependence on technology imports generally signal even greater threats. Nevertheless, increasing import diversification and promoting domestic production are not necessarily the most effective solutions. Import diversification is

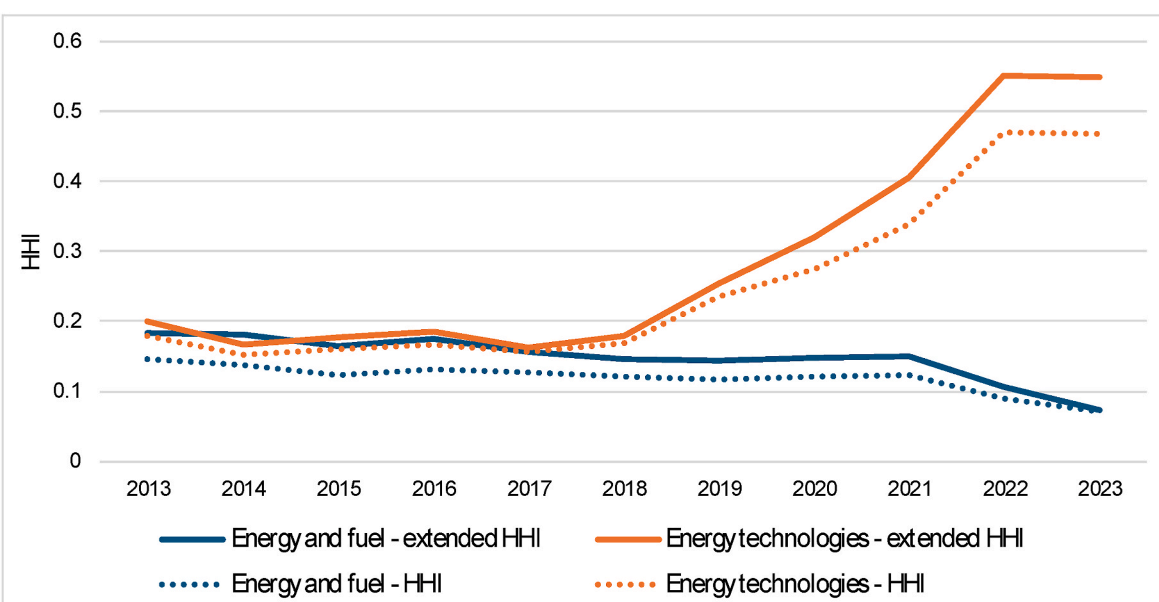


Fig. 9. Diversification dynamics of energy (fuel) and technology imports into the EU 2013–2023.

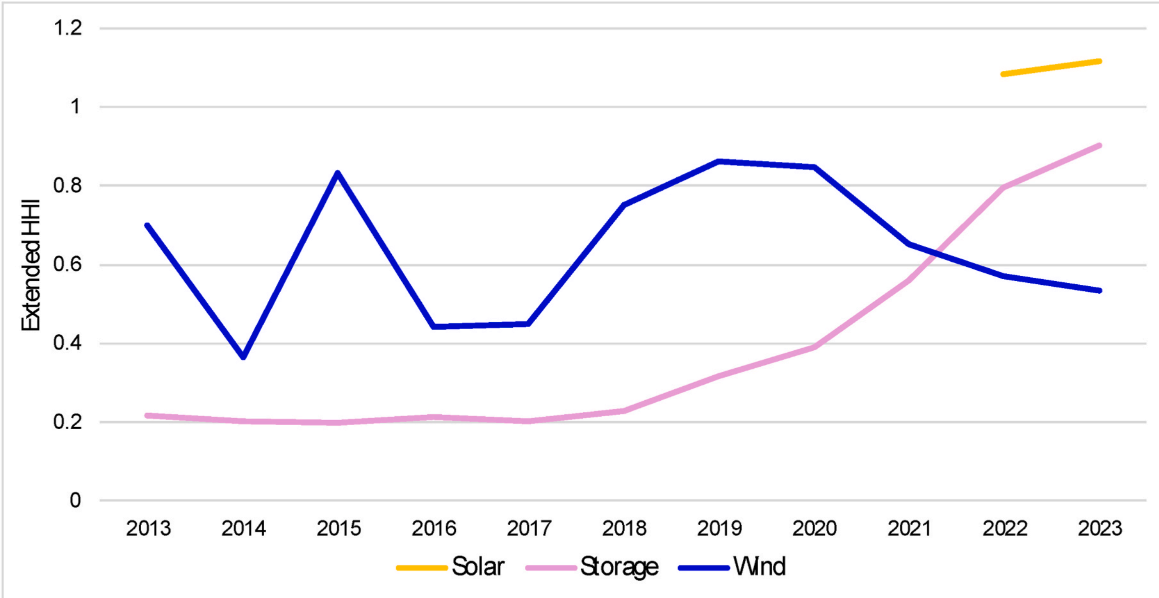


Fig. 10. Diversification dynamics of solar, wind and storage technology imports.

constrained by geographical, political, infrastructural, and technological factors as well as the simple availability of certain materials [4]. Depending on the situation, diversification can lead to significant cost increases that could affect the entire economy. As Gozgor and Paramati show, primary energy diversification has heterogeneous effects depending on the time horizon and specificities of the countries concerned [24]. Increasing import diversification is likely to lead to a similar conclusion, as suboptimal diversification in the short term avoids supply disruptions. It would be prudent to view the analysis of import diversification as a tool to identify risks, rather than as an end in itself. Diversification of energy import sources is only one part of a broader energy security package that also includes energy efficiency and international policy [11].

The analysis of the diversification of imports of solar and energy storage technologies using the extended HHI clearly highlights the challenges of the energy transformation due to the EU's dependence on imports from a single source. As the academic literature shows, ensuring the competitiveness of local producers requires both significant resources and a wise choice of instruments [49] that need to be precisely used [50]. On the other hand, the example of wind energy technologies analysed in this study shows that it is possible to counteract the threats posed by dependence on import sources by developing and maintaining local production. However, this requires a targeted strategy, involving a broad process from research to industrial policy to energy development itself, focusing not only on environmental and energy objectives but also on the potential of local industry. It is necessary to ensure an appropriate balance between import diversification and economic efficiency, considering the risks of supply disruptions and their potential economic impacts. The development of energy technologies and the relocation of energy equipment production to the EU would reduce import risks; however, cost efficiency must be ensured to increase competitiveness.

The range of supply risks is much wider than that covered by the political stability assessment and that risks such as extreme weather events due to climate change [51] may affect energy supply but are unrelated to changes in the political stability of the countries from which imports originate. Therefore, the political stability indicator used in this study should be interpreted as a possible qualitative characteristic for assessing import sources, and the choice of indicator should depend on broader policy objectives and the nature of potential risks. Another potential limitation of the present study is that imported electricity is considered a homogeneous product, whereas in terms of supply risks, it is important to consider not only the political stability of the exporting countries but also their energy mix, which may change the nature of the risks associated with electricity exports. For consistency, all imports in this study have been analysed using the same underlying methodological principles, but in some cases, it may be useful to look at import sources in an aggregated way. A good case in point is oil imports, where OPEC members can be considered a single supplier because of their cartel behaviour [35]. Finally, this study looked at the dynamics of import diversification, interpreting a wider diversification of import sources and their greater political stability as positive aspects of Europe's energy security in the energy transition. However, this approach does not take into account the costs associated with the transition to more threat-resilient energy supplies. As Zhu shows, rising energy prices can have a negative impact not only on the overall economic situation, but also on green innovation [52], which is one of the key factors in both the energy transformation and the reduction of dependence on technology imports.

4. Conclusions

Energy imports account for a significant share of the EU's total imports, particularly in 2022 when energy prices rose sharply, and energy goods accounted for almost 20 % of total EU imports. While the EU was a net importer of crude oil, natural gas, petroleum products, and solid fossil fuels throughout the period considered, the import situation for the equipment and technology covered in this study started to change from a net exporter to a net importer and no significant signs of improvement have been detected over the period analysed.

The incorporation of WGI political stability indicator into import diversification calculations using HHI proposed in this article enables the quantitative and qualitative characteristics of import diversification and import sources to be evaluated within a unified conceptual framework, thereby ensuring comparability to the original HHI. Assessments of the diversification of energy and energy technology imports can provide the necessary signals for policy measures to reduce the EU's vulnerability. Extending the HHI to include estimates of political stability demonstrates that the riskiness of imports for most of the commodity groups analysed has increased, with the exception of electricity, which is mainly imported from countries considered to be relatively more politically stable.

The European Union's energy-related imports have undergone significant changes in recent years, most notably the decline in Russia's role as a source of imports. As a result, the EU's energy imports have become more diversified, especially since 2022, when sanctions were started to be imposed on Russia. However, nuclear fuel imports stand out as the most concentrated of all energy types in terms of a single source of imports.

Since 2018, there has been a notable decline in the diversification of energy technology imports. This has led to an increase in import risks, particularly in light of estimates regarding the political stability of import sources. The extended Herfindahl-Hirschman Index (HHI) for energy technology imports into the EU increased from 0.16 in 2017 to 0.55 in 2022, while the extended HHI for imports of the generalised group of energy and fuel products decreased from 0.16 in 2017 to 0.1 in 2022. The European Union's dependence on China for solar and energy storage technology imports, which are crucial for energy transformation, represents a significant vulnerability in the context of technology imports.

Improving the EU's import situation requires a wide range of measures in which import diversification does not necessarily play a key role. The development of energy technologies for the production of energy equipment in the EU can be seen as a promising strategy to address import risks while ensuring that the energy transition process is less vulnerable to import threats; however, cost-efficiency and competitiveness challenges need to be considered.

CRediT authorship contribution statement

Vidas Lekavičius: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rimantė Balsiūnaitė:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Viktorija Bobinaitė:** Writing – original draft, Methodology, Formal analysis. **Inga Konstantinavičiūtė:** Writing – original draft. **Kristina Rimkūnaitė:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dalia Štreimikienė:** Writing – original draft, Validation, Methodology. **Dalius Tarvydas:** Writing – original draft, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vidas Lekavičius reports financial support was provided by Lithuanian Research Council (LMTLT). Viktorija Bobinaitė reports financial support was provided by Lithuanian Research Council (LMTLT). Kristina Rimkunaitė reports financial support was provided by Lithuanian Research Council (LMTLT). Dalia Štreimikienė reports financial support was provided by Lithuanian Research Council (LMTLT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

data sources are publicly available and listed in the article

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