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Diversification, concentration and renewability of the energy supply in the European Union

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ABSTRACT

Energy security assessment quantifies the energy supply to a population and the likelihood, or risk, of an energy disruption or shortage and represents an important aspect of national security, economic stability and prosperity. The quantification of the state of energy supply is context-dependent and involves multiple perspectives: infrastructural, technological, environmental, market, social and geopolitical. Among all the different and relevant aspects involved, diversity and dependence of the energy fuel mix are two of the main energy security dimensions. The present paper investigates the diversification of the energy supply in Europe, by analysing import dependence, market concentration and renewable energy resource deployment in the European Union over the last decade. The analysis utilises a set of indicators aimed at measuring the fuel mix diversity, market concentration, geopolitical stability, renewable energy share and stochasticity - both at single country and at aggregated European levels. Results show a stable evolution of the diversity of the fuel mix and a relatively low market concentration of the period examined. However, the import dependency reduces the energy security by approximately 30% due to the high proportion of imports from a limited number of countries. Moreover, an increasing trend in renewable electricity production share is evident over the last decade, albeit with differences between member states, as a result of the decarbonisation policies implemented by the European Union.

1. Introduction

Given the importance of a continuous and stable supply of energy in modern society, the progression and wellbeing of humankind has been shaped by the availability of secure energy resources. Moreover, given that energy resources are limited and unevenly distributed across the globe, the supply of energy is a critical aspect of the security and economic stability of nation states [1].

As the energy sector continues to evolve towards a global and interconnected energy market, it faces many outstanding challenges, including: increasing energy demand, fluctuating prices, population growth, geopolitical uncertainties, growing dependence of industrialised economies on energy imports, climate change and energy-related sustainability issues, socioeconomic inequalities and political conflicts [2]. These issues are becoming more pronounced due to population growth and industrial developments in emerging economics, which may lead to potential future shortfalls of energy supplies, price increases and geopolitical tensions [3]. In this context, knowing both the current value and the general trend of the energy security of a nation represents an invaluable perspective for policy makers to shape energy policies and regulations to contain the risks of disruption of the energy supply chain, especially when the causes of insecurity can be identified.

At its most basic concept, energy security quantifies the state of energy supply to the population, and hence the likelihood, or risk, of an energy supply disruption or energy shortage, which can have severe implications for economic and social prosperity and national security. The International Energy Agency (IEA) defines the energy security as *“the uninterrupted availability of energy sources at an affordable price”* and *“the ability of the energy system to react promptly to sudden changes in the supply-demand balance”* [4]. Evaluation of these definitions makes clear that numerous issues

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influence the energy security - from investment, technological and economic developments to resource availability, environmental needs, infrastructure resilience, etc. Table 1 summarises the key areas generally considered in the energy security assessment [5,6].

Considering the complexity and key areas involved, assessing the energy security is not a trivial issue, which renders any attempt to develop a unique methodology with standardised key performance indicators challenging [7]. Generally all indicators developed and used to measure energy security are focused on specific aspects of the supply chain, e.g., supply diversity and dependence [8], economy and markets [9,10], investments [11], socio-political aspects [12], infrastructure and technologies [13,14], environmental issues [15], resilience [16], etc. Esfahani et al. [17] developed a comprehensive knowledge map of energy security in order to detect the main dimensions related to energy security that researchers and scientists have explored over recent decades. The authors reviewed more than 130 papers, from conceptual analysis to qualitative and quantitative assessments, and highlighted that more research activities should be focused on a broader understanding of the different dimensions, problems and methods, while also links between energy supply security and renewable energy security should be explored further. Furthermore, although several attempts have been made to capture different aspects of energy security, difficulties in acquiring the large amount of data required to cover the all the aforementioned aspects is still an outstanding challenge, thereby limiting the research in this field [18].

Furthermore, measuring energy security is highly context-dependent [19], since it is influenced by historical, socio-political and economic specificity of each country. Consequently, the assessment of energy security needs to reflect the particular characteristics of the country under analysis, which may change with time, and should be modified along with changes in strategic priorities defined by the country itself [20,21]. Typically, developing countries focus the energy security assessment on analysing the access to energy services and technologies and they generally look at financial services and investments, infrastructure reliability and resource diversification to address increases in industrial consumption and population growth [8]. On the other hand, industrialised countries aim at reducing energy consumption and its environmental impact by implementing measures to reduce the carbon footprint, fossil fuel production or consumption and import dependency. These polices will likely transform the energy sector of those countries in the coming years, making the energy security assessment crucial to ensure the reliability and long-term sustainability of energy supply [22].

Table 1
Energy security key areas [5,6].

Key area	Description
Energy availability	Diversification of the energy mix: - Spatial distribution diversity - Source and imports channel diversity - Technological diversity - Transportation system diversity
Infrastructure	- Reliability - Robustness
Markets and prices	- Price affordability - Price stability - Degree of competition
Environment	- Long-term sustainability - Energy efficiency and demand reduction - Pollutants emissions - Greenhouse gases emissions - Hydro-geological risks
Social aspects	- Energy poverty - Energy equality - Social acceptance - Social welfare and well being
Geopolitical aspects	- Energy governance - Policies and regulations - Taxation - Foreign policies
Information	- Data acquisition - Data security - Monitoring and assessment

Among all the dimensions mentioned, diversity and dependence of an energy portfolio are two of the main energy security domains [23]. While dependence metrics measure the capability of a country to produce its own energy needs, diversity metrics monitor the variety of its energy portfolio and, therefore, the capability of compensating any potential disruption of a primary energy supply by the exploitation of other supply chains [22]. Therefore, the diversification of the EU energy supply, the reduction of its import dependence and the decarbonisation of the energy sector through the stimulation of policies supporting efficiency and renewable deployment are among the main long-term objectives of EU energy policy [24].

As a case in point, European countries have endorsed ambitious greenhouse gas (GHG) emission reduction targets and accompanying strategies for the decarbonisation of the energy sector over the past decade [25]. In the framework of the EU Sustainable Development Strategy, the European Commission has also developed energy security of supply and climate change policies and has adopted several regulatory measures aimed at introducing low-carbon technologies, which will ultimately impact the market structure of the sector. Despite being worldwide leaders in emissions reduction, the European Union (EU) and the United Kingdom (UK) only account for about 12% of the worldwide energy consumption, while their energy sectors are still characterised by a lack of indigenous energy resources [8], making the EU highly dependent on imports amounting to approximately 53% of total gross energy available [26]. The large dependency on external supplies, together with the geopolitical context and infrastructure issues, strongly influences the European energy security perspective.

In this context, the present paper investigates the diversification and renewability of the energy supply in the European Union and the United Kingdom, both at single country and EU-28 aggregated level, over the past decade. In particular, the work focuses on assessing the variety, disparity, import dependence, market concentration and renewability of the European energy portfolio. In addition, the uncertainty associated with the results is assessed. These aspects are highly relevant for the European Union in light of its high structural dependence on imported energy in the context of its ongoing decarbonisation strategies. The analyses are carried out both at single country level and aggregated level. This adopted pan-European perspective allows internal EU energy dependencies between EU countries to be highlighted, as well as the status of the renewable energy deployment across Europe to be explored. It also provides insights on crucial aspects of import dependency and renewable energy deployment at an aggregated EU level. The analyses are carried out both at single country level and aggregated level. This adopted pan-European perspective allows the internal EU-dependency between the EU countries and the status of the renewable energy deployment across Europe to be highlighted, while also providing insights on crucial aspects of import dependency and renewable energy deployment at an aggregated EU level. The applicability and exploitation of the results obtained lies in the extent by which they can assist in the formation of policies. This perspective is discussed in the paper to highlight critical issues and the current challenges that EU countries are facing with reference to the analysed domains. However, it is important to note that, despite being not included in the present paper, other dimensions (see Table 1) can affect the overall energy security and should be considered in the design of effective policies.

The paper is structured as follows: section 2 provides a general overview of the European energy sector in terms of energy consumption, fuel mix and imports, while section 3 describes the methodologies adopted in the present work, mainly focused on resource diversity and concentration, import dependence, geopolitical stability and renewable energy source deployment. Section 3.5 describes the main source of uncertainty associated with the diversity metrics in terms of data acquisition and elaboration, scenario analysis and statistical methods. Finally, section 4 describes and discuss the results obtained, while section 5 provides a summary of the main findings and policy implications of the present assessment.

2. The European energy sector

With a market size of about 250 billion and more than 1.6 million people employed, the European energy sector is still characterised by a strong disparity between its energy sources or energy production and its energy consumption [26]. Whilst the EU and the United Kingdom consume almost 12% of energy available worldwide, only 5.4% of the total produced worldwide is generated internally [26]. It can be observed in Fig. 1, which shows the EU-28[1] energy flow in 2017, that about half of the EU-28 total gross available energy is imported, and only 69% is available for final consumption due to transformation and distribution losses.

Table 2 reports the total energy supply per fuel type (in MTOE/year) over the period 2010–2017. Despite the decarbonisation policy implemented by the EU-28 over the last two decades, fossil fuels (i.e., coal, gas and oil) and their products are still the predominant energy sources utilised in the EU-28, accounting for 71.8% of the total energy supply, with a decreasing trend from the 75.9% share in 2010. While oil and oil products share has remained almost constant with values fluctuating in the range 31.9%–33% and no clear trends, solid fossil fuels (i.e., coal) and natural gas decreased from 18.4% to 25.2%–16.1% and 23.3%, respectively, in the period 2010–2017. In a similar manner to solid fossil fuels, the nuclear energy share shows a relative constant trend with fluctuations in the range 12.9%–13.8%. On the other hand, the share of renewable energy exhibited an increasing trend from 10.2% in 2010 to 14.4%, due to the new regulations and policies supporting RES deployment across the EU. Finally, the category *Others* - which includes peat and peat products, oil shale, manufactured gases and non-renewable wastes - exhibited a stable share $\leq$ 1% of the total energy supply over the period considered.

The final energy consumption in the EU-28 decreased from 1103 MTOE in 2010 to 1060 MTOE in 2017 (Fig. 1), with a minimum of 1006 MTOE in 2014 (Table 3). With reference to the last year available (i.e., 2017), the transport sector had the highest share (30.8%), followed by the residential (27.1%), industry (24.6%) and service (14.6%) sectors. While industry, services and transport shares show a stable trend over the period 2010–2017 - with values fluctuating in the range of 24.4%–25.5%, 13.7%–14.6% and 29.1%–30.8%, respectively - the residential sector share decreased from 29.4% in 2010 to 27.1% in 2017.

These aggregated figures give some insights of the EU-28 energy flows. The European energy sector is still far from homogeneous and a closer examination at a country level is therefore required. Fig. 2 gives an overview of the European energy sector per country over the period 2000–2017. Fig. 2a shows the energy intensity of the economy, calculated as the total gross available energy in MTOE divided by the gross domestic product at market price, measured in purchasing power standards (PPS) [26] for all European countries for selected years over the period 2000–2017. It can be observed that all countries show a decreasing trend over the period considered (reaching values below 200 $MTOE/M$, 2017), with average values of 117.6 and 113.8 for EU-27 and EU-28 respectively.

Fig. 2b presents the share in % of electricity production from renewable sources in the European countries. First of all, a general increase can be observed for all European countries over the period considered, as a result of the European policies supporting RES deployments implemented by the EU over the last two decades. Most of the EU-28 countries reached RES shares over 30% in 2017, with the notable cases of Austria, Croatia, Denmark, Latvia, Lithuania, Luxembourg and Sweden. On the other hand, a few countries still have RES share of the electricity production below 15%, i.e., Bulgaria (13.7%), Cyprus (8.7%), Estonia (13.9%), Hungary (10.6%), Malta (10.4%), etc.

As already discussed earlier, the share of fossil fuels (Fig. 2c) is confirmed to be high for most of the EU-28 countries, reaching

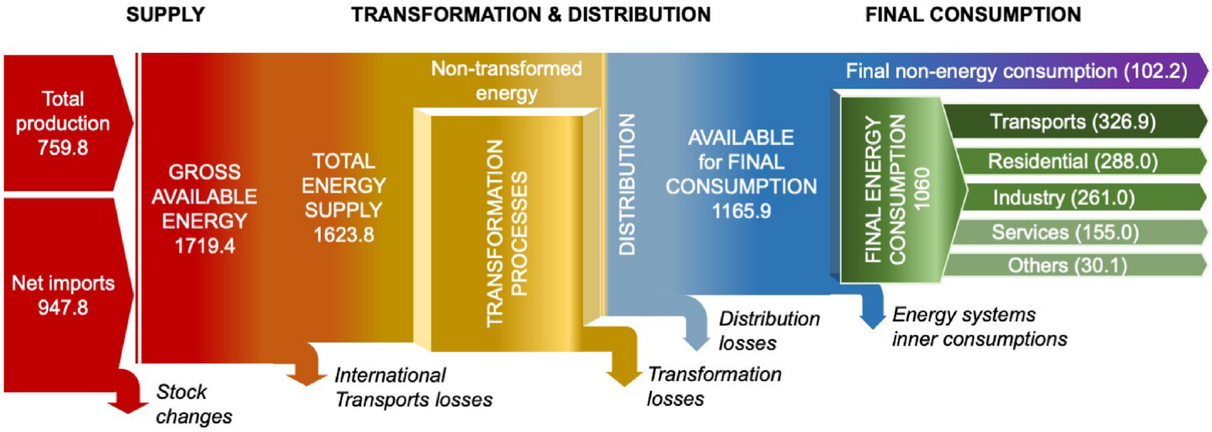

Fig. 1. EU and UK (EU-28) energy flow in MTOE for the year 2017 (adapted from Ref. [26]).

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[1] EU-28 includes all the member states of the EU, plus the UK. Although, the UK withdrew from the EU on the 31st January 2020, the data and analysis presented in this paper refer to a period when the UK was still part of the EU. The term EU-28 is therefore used by the authors without prejudice to positions on the current status of the EU or UK.

Table 2
Total energy supply (in MTOE/year) per fuel in the EU and the United Kingdom (EU28) in the period 2010–2017 [26,27]. The bars indicates the percentage of each fuel over the overall yearly energy supply.

Sectors	2010	2011	2012	2013	2014	2015	2016	2017
Solid Fossil Fuels	325.7	300.9	264.1	280.3	284.6	291.1	284.0	261.3
Oil and oil products	574.2	555.3	532.6	518.4	515.0	521.6	525.7	525.5
Natural gas	447.6	403.8	393.8	387.1	343.4	357.9	382.3	378.9
Renewables	181.0	179.0	197.6	208.7	210.9	219.8	224.2	233.9
Nuclear	234.6	232.0	224.5	223.0	223.6	220.1	213.5	208.7
Others	11.70	12.57	13.74	13.51	14.49	14.77	16.43	15.58

Table 3
Final energy consumption (in MTOE/year) per sector in the EU and the UK (EU28) in the period 2010–2017 [26,27]. The bars indicates the contribution of each sector (in %) over the overall yearly energy supply.

Sectors	2010	2011	2012	2013	2014	2015	2016	2017
Industry	269.7	267.5	262.7	259.9	255.9	256.1	257.1	261.0
Transport	320.5	319.0	309.0	305.2	309.3	313.6	321.0	326.9
Service	156.4	144.1	147.8	149.7	139.3	146.9	149.9	155.0
Residential	324.0 0.294	288.3	302.5	306.3	269.6	281.1	288.6	288.0
Others	32.57	32.24	32.25	32.55	31.98	31.37	32.25	30.10

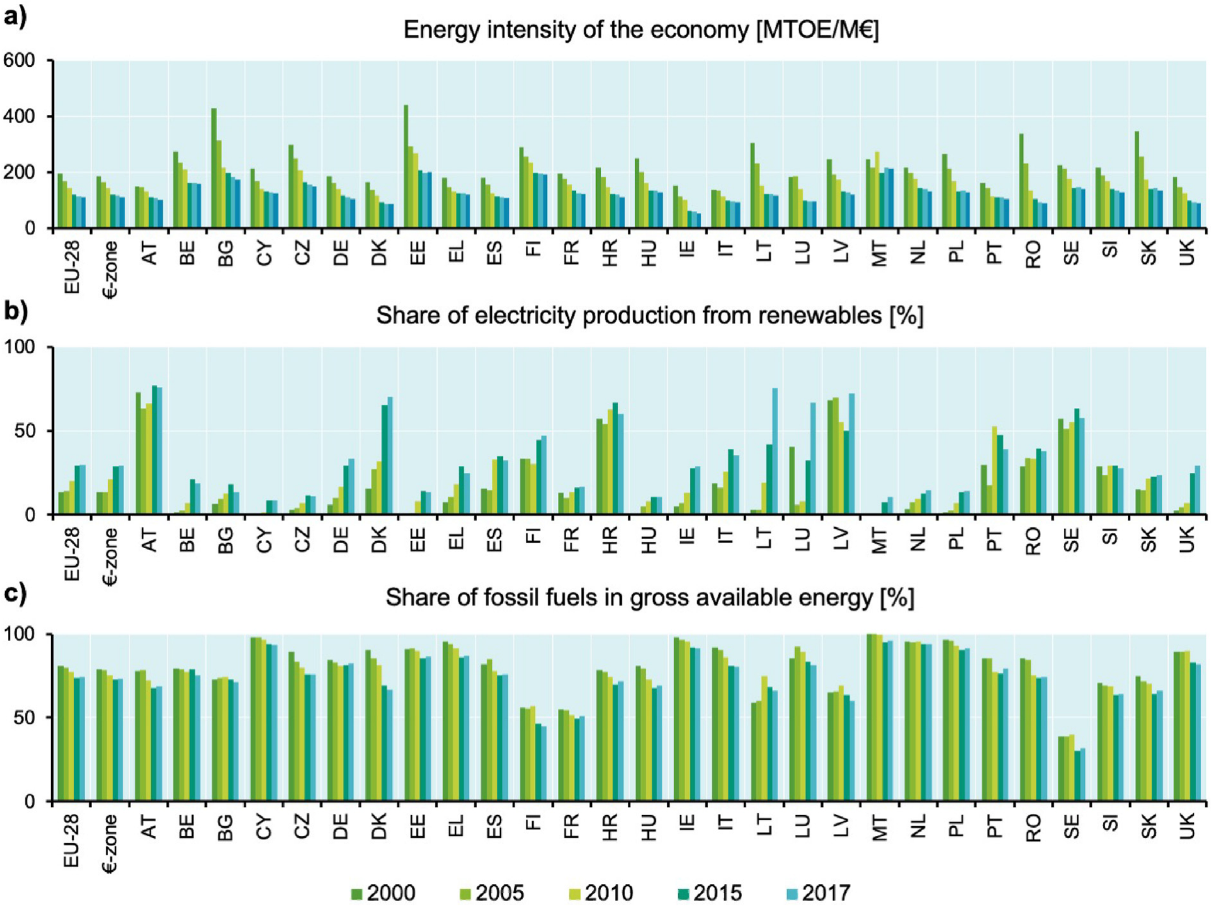


Fig. 2. The European energy sector per country over the period 2000–2017. a) Energy intensity of the economy in GWh/GDP_{PPS}. b) Share of electricity production from renewables. (c) Share of fossil fuels in gross available energy [26,27]. Country codes follow the glossary established by Eurostat [28].

values greater than 85% (2017 data) in Cyprus (93.7%), Estonia (86.3%), Greece (87%), Ireland (91.3%), Malta (96.1%), Netherlands (94%) and Poland (91.3%). On the other hand, only Sweden (32%), Finland (44.8%) and France (50.9%) show values below 55%: while Sweden and Finland has a high exploitation of renewable energies (approx. 37% and 30.6% of the gross inland consumption, respectively), whereas the low value associated with France is due to the strong exploitation of nuclear energy (about 40% of the gross inland consumption) [29].

This high share of fossil fuels, together with the low internal

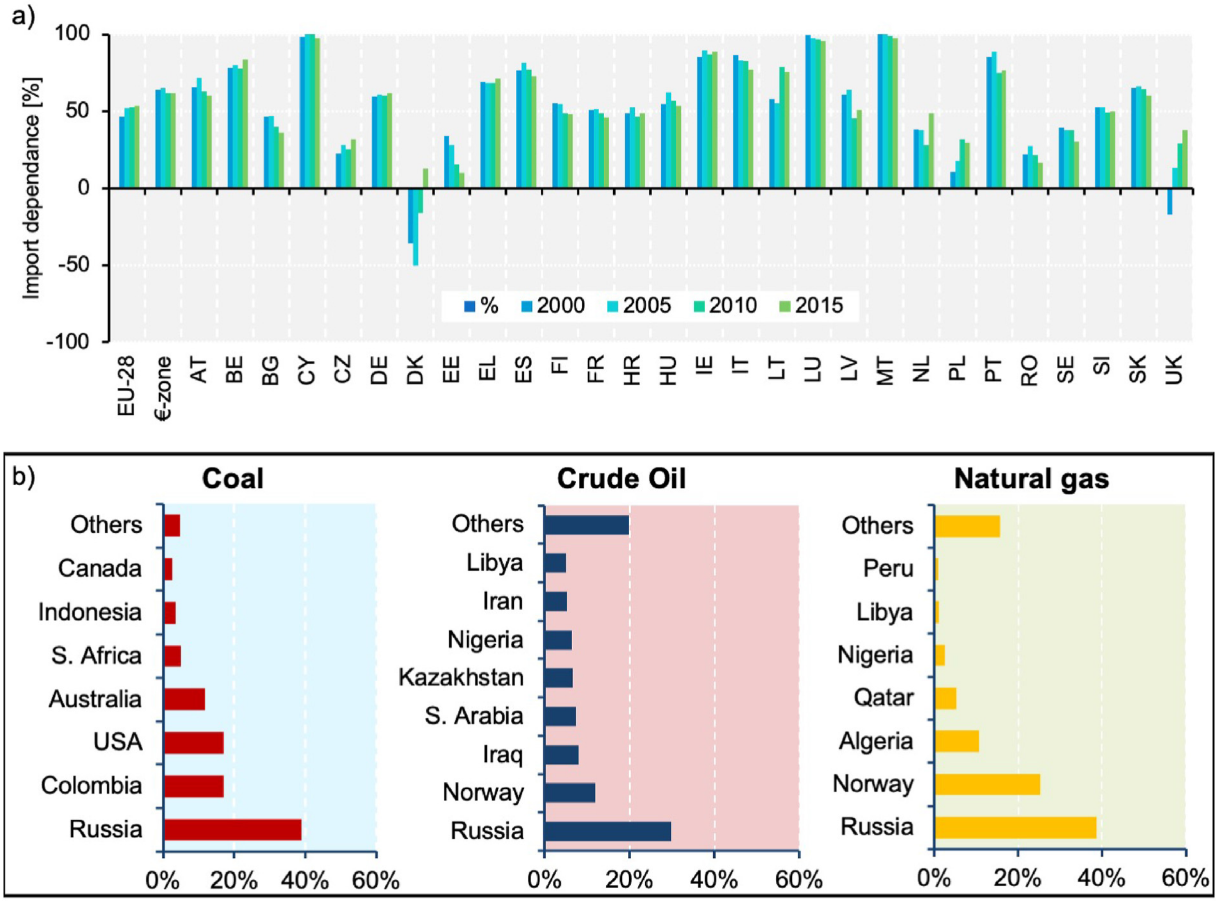


Fig. 3. a) Import dependency of the European countries - Country codes follow the glossary established by Eurostat [28]. b) Import countries per fossil fuel [26,27].

production, is reflected in the high import dependency. Fig. 3a presents the fossil fuel import dependency of the EU-28 countries for selected years from 2000 to 2017. It can be noted that the EU-28 countries show an overall import dependency of 55.1% in 2017, with an increasing trend over the period considered. While some countries such as Cyprus, Luxembourg and Malta have an import dependency over 95%, due to their specific geographical configurations, only four countries show values lower than 25% - i.e., Estonia (3.9%), Denmark (12.4%) and Romania (23.3%). These low values have a different explanation: while Estonia is a producer of solid fossil fuels and an exporter of renewable electricity, Denmark is an exporter of natural gas and Romania covers most of its gross consumption of solid fuels and natural gas by its internal productions [29].

Fig. 3b shows the share of imports per country and fossil fuel type (Year 2017). First of all, it can be noted that Russia accounts for 38.8%, 29.8% and 38.7% of all imports of coal, crude oil and natural gas, respectively, making it the largest exporter for the EU-28 countries. The remaining coal imports come from Colombia, the USA and Australia, while crude oil and natural gas is also imported from Norway, Middle East, Kazakhstan and African countries. This large dependency on external supplies, together with geopolitical context and the reliability of the supply chain, strongly influences the security of supply, which is discussed further in the following sections.

3. Methodology

Assessing energy security is not a trivial problem due to the multiple dimensions involved [30]. A common starting point for defining the components of energy security is the so-called 4A's approach [31]: *availability*, *affordability*, *accessibility* and *acceptability*. Generally, all indicators used to measure energy security will be encompassed by one or more of these categories. A recent literature review on the different indexes used to compare the energy security of different countries can be found in Gasser [32]. As highlighted by Ang et al. [5], energy security is also a highly context-dependent concept and, despite some basic key ideas, no universal definitions have been established. Furthermore, the classification of indices into indicator ‘groups’ is a non-uniform process and subjective to the researcher. Regardless of grouping categories of indicators chosen, there is always likely to be multiple indices used in research for each indicator category, and similarly indices that could be deemed to fit in multiple indicator groups.

Among all the dimensions involved in the energy security assessment, the present work is aimed at investigating the energy fuel mix of the European countries (EU-28), focusing on its diversification, import dependency and renewability. The following sections introduces the indices utilised in the present work for assessing the energy security of the European countries: diversity and concentration (section 3.1), dependence (section 3.2), political stability (section 3.3) and renewable energy share (section 3.4).

3.1. Diversity, concentration and dependence indexes

The concept of *diversity* is based on the assumption that a more diverse energy supply is a more secure energy supply, given that the country is less reliant on one type of energy, or on supply from one source. Stirling [33] defines diversity as consisting of 3 components:

- *Variety*: the number of categories which the total primary energy supply (TPES) can be divided into - i.e., the type of energy sources, the geographical region of their production (import, in-house production), etc.
- *Balance*: the spread of total distribution of the above categories as a proportion of the overall (i.e., the total primary energy supply).
- *Disparity*: the degree to which the categories themselves are different from each other. The greater the disparity, the stronger diversity, as an impact on one type of supply is less likely to impact another. It should be noted that this is a subjective component, thus limiting Stirling's definition to a certain extent Stirling [33].

For each of these components, a larger value would indicate greater diversity, and hence, a greater degree of energy security.

3.1.1. Fuel mix diversity - the Shannon-Wiener index (SWIs)

Currently, the measurement of diversity is largely based on the Shannon-Wiener Index (SWI) [34], which is typically used in ecology and genetics to characterise the variety of species populations and genomes. The first utilisation of the SWI index in the energy-supply field can be referred to Stirling [33], who determined the diversity and financial performance of the UK supply portfolio. Starting from N options (i.e., energy sources) and assuming that no relations between them [8], the SWI can be determined as shown in Eq. (1), where p_i is the proportional share of the option i (expressed in decimal form) and c_i is the correction factor to p_i for the specific indicator used.

$$SWI = -\sum_{i=1}^{N} c_i p_i \log p_i \tag{1}$$

For the first indicator (SWI^I), the correction factor $c_i^{(I)} = 1$, leading to the basic SWI (equation (2)), in which the share between the primary energy sources is taken into account only.

$$SWI^{(I)} = -\sum_{i=1}^{N} p_i \log p_i \tag{2}$$

The SWI can be only positive, with a value of 0 when only one option is available, and it increases with the increment of the number of options. Therefore a low value of SWI means a low grade of diversity of the energy supply, while higher values mean a greater diversification of the energy mix.

3.1.2. Concentration of the energy supply - The Herfindahl-Hirschman index (HHI)

Generally, reducing geographical and market concentrations of technology, services and commodities is paramount to promote competition and equality which, in turn, lead to more reliable supply chains [23]. This is of particular importance in the energy sector, especially considering that more than 80% of all proven oil reserves are concentrated in 12 OPEC countries based in the Middle East, and that only three countries account for 56% of the proven gas resources [35]. Such concentration of energy resources leads to energy dependence, making importing countries vulnerable to potential political instabilities of countries or regions.

Assessing the energy resource concentration becomes crucial to carry out comprehensive long-term assessments of the energy sector. For this purpose, the Herfindahl-Hirschman index (HHI) is widely used to describe the concentration (or diversification) of a portfolio of energy resources among the different supplies [36]. This index is determined as the sum of the squares of each market share S_i (in percentage form) of a given portfolio, as shown in Eq. (3). Therefore, greater market concentrations leads to a higher HHI value, with a maximum value of 100% occurring for a single share, while lower values occur for distributed portfolios, with a minimum value tending to zero for $i = \infty$.

$$HHI = \sum_{j=1}^{N} S_i^2 \tag{3}$$

3.2. Dependence

Dependence on specific resources or imports can affect the energy security of a country. Generally, imported energy is far less reliable than the energy produced within the same country and, hence, the greater the extent of energy needs is dependent on imports, the less secure the supply of energy [8]. A simple indicator can be represented by the Energy Import Dependence (EIP) which is defined as the ratio between the net energy import x_{imp} over the total primary energy source ($TPES$), as shown in Eq. (4):

$$EIP = \frac{x_{imp}}{TPES} \tag{4}$$

The import dependency can also be incorporated in the Shannon-Weiner diversity index, described in section 3.1.1, by including several correlation factors taking into account the origin of each energy flow. Jansen et al. [34] defined a second indicator (SWI^{II}) to take into account the net import dependencies by expressing the correction factor $c_i^{(II)}$ as in Eq. (6).

$$SWI^{(II)} = -\sum_{i=1}^{N} c_i^{(II)} p_i \log p_i \tag{5}$$

$$c_i^{(II)} = 1 - m_i \left(1 - \frac{SWI_i^m}{SWI_i^{m,max}}\right) \tag{6}$$

$$SWI_i^m = -\sum_j m_{ij} \log m_{ij} \tag{7}$$

where m_i is the share of net import in primary energy supply of source i, m_{ij} the share of imports of primary source i from region j. SWI_i^m is the Shannon index of total import flows of resource i and $SWI_i^{m,max}$ is the maximum SWI value of total import flows of resource i, calculated considering an equal distribution between the import flows. Although these indices can provide information about the energy supply status of a country or region, there are clear limitations which need to be pointed out. Firstly, considering the energy dependency to be mainly related to imports only, means neglecting the security aspects of all domestic production. If the domestic production has no associated risks, then every country operating as net energy exporters would have 100% secure energy. Hypothetically, all imports from those countries could be also considered to be at zero risk. Therefore, if a country is a net importer, both its production and imports could be described as 100% secure energy, as per the initial assumption. It is clear that we are describing an ideal global scenario with no technical, financial and political domestic issues, with perfect market competition and no political and economic tensions between nations. Unfortunately, the reality is quite different, as it will be outlined in the next section.

3.3. Political stability

The supply of energy can be thought of as two components which are inextricably linked: a system of supply corridors and the geopolitical situation of the producing and transit countries that form the energy supply corridors. Whilst the purely subjective nature of political stability makes a reliable measure of the energy security challenging, several attempts have been made to include this aspect into measurable metrics. For instance, Muñoz et al. [37] aggregates four characteristics - namely, economic, energy specific, socio-political and EU relations - into a Geopolitical Energy Supply Risk Index.

A more straightforward approach is the extension of the diversity index, described in sections 3.1.1 and 3.2, to incorporate political stability [34]. Starting from the definition shown in Eq. (5), a third indicator SWI^{III} (Eq. (8)) can be determined. The coefficient h_j is included in the SWI_i^m formulation (Eq. (7)) to take into account the political stability of region j, as shown in Eq. (10).

$$SWI^{(III)} = -\sum_{i=1}^{N} c_i^{(III)} p_i \log p_i \tag{8}$$

$$c_i^{(III)} = 1 - m_i \left(1 - \frac{SWI_i^m}{SWI_i^{m,max}}\right) \tag{9}$$

$$SWI_i^m = -\sum_j h_j m_{ij} \log m_{ij} \tag{10}$$

In order to determine the value of h_j, Jansen et al. [34] proposed the use of the UNDP Human Development Indicator (HDI) which is an "*authoritative index compiled for each country with a convenient range between 0* [extremely unstable] *and 1* [extremely stable]". The choice of the HDI to compute the country stability is related to its capability of providing a socio-political perspective and an analytical dimension that reflect the country status and functioning in the current global economic system, as well as being effective and legitimate in their decision making processes [38]. The full procedure on how to calculate h_j, starting from the *HDI*, is reported in Ref. [34]. However, it is important to highlight that this method, although simple, has the disadvantage of subjective interpretation when assigning relevant parameters for assessing the political stability of a specific region.

3.4. Renewable energy share

The proportion of renewable energy that exists within the energy system of a country is highly relevant to the total energy security of that country, given the clear advantage of having a non-diminishing and environmental-friendly energy source. Notwithstanding, it is important to note that the intrinsic aleatory of some renewable energy systems - i.e., wind and solar - pose several challenges for their integration into the existing energy infrastructure [39], while also representing a source of uncertainty for the energy supply.

The Renewable Energy Security Index (RESI) [40], used specifically for electricity supply and demand, calculates the proportion of demand that is met by each power generation source i, and the extent to which each source is renewable. It can be defined as follows:

$$RESI_\tau = \sum_i^\tau EDS_{i,\tau} NRF_i \tag{11}$$

$$EDS_{i,\tau} = \frac{k * EP_{net,i,\tau}}{NED_\tau} \tag{12}$$

The term *EDS* represents the *Electricity Demand Satisfaction*, which can be calculated as shown in Eq. (12), where EP_{net} is the net electricity production of technology i in the period τ, *NED* is the national electricity demand in the period τ. The term k is a coefficient based on historical trends of EP_{net} and *NED*, measuring the extent to which electricity is produced within the country, or imported. However, in the majority of cases, k is close to unity, due to the fact that most renewable generation occurs locally. Finally, the term *NRF* in Eq. (11) is the *national renewability factor*, which can be calculated as shown in Eq. (13), considering the cumulative energy demand from indigenous renewable resources $CED_{r,ind}$ of every technology i and the total cumulative energy demand $CED_{i,\tau}$ of technology i in the period τ.

$$NRF_i = \frac{CED_{r,ind,i,\tau}}{CED_{i,\tau}} \tag{13}$$

Therefore, a higher renewable energy penetration will result in a proportionally greater RESI. At present, RESI is the only example of an index merging both life cycle and techno-economic energy security measurement factors, with the advantage of both retrospective and prospective analysis. However, this prospective analysis becomes more limited as the forecasts of electricity consumption and production become less reliable, as well as the applicability to the electricity sector, thereby not necessarily reflecting the overall trend of the whole energy sector.

3.5. Data source and uncertainty

Several datasets were consulted in order to extract the data required to perform the assessment described in the methodology (section 3). The EUROSTAT database [41] was used to retrieve statistical data on energy resources, markets and energy balances for each country analysed. Further data on energy trade - i.e., import/export of energy sources and energy carriers (crude oil, petroleum products, natural gas, electricity, solid fossil fuels and renewable resources - by country of origin and destination were extracted from Ref. [42]. A wide dataset was then created and processed by an in-house code to generate the results based on the indicators outlined earlier.

It is important to highlight that, whilst data collected on energy security are no doubt of use, as they provide relevant information, the extent of the accuracy and precision of the results is rarely discussed and thus remains an open issue. The term *uncertainty* can be defined as a measure of data variability, where the estimation of error indicates the precision of measurement or a value. Standardised methods and procedures to assess the uncertainty, while collecting and processing data, are of paramount importance to support the reliability of results and conclusions, especially when energy policies are drafted from such data.

Uncertainty in data can arise from many aspects including: data collection, data processing and data publishing. Macknick [43] identified the main sources of uncertainties in energy data, associated with statistics from the International Energy Agency (IEA), the US Energy Information Administration (EIA), British Petroleum (BP) and the United Nations (UN) energy statistics division. The authors highlighted that significant discrepancies can be found between data reported by different organisations, due to different assumptions and methodologies adopted (i.e., categorisation methods and conventions) and different data inputs, as summarised in Table 4.

Another source of uncertainty arises from the use of energy data

Table 4
Typical sources of discrepancy in energy data [43].

Area/Process	Uncertainty source
Physical Data Collection	Primary energy data sources
Categorisation	System boundaries
	Category definition
Conversion	Calorific values
	Primary energy equivalence
Energy Units	Reporting conventions

to provide scenarios for energy policies. The method of predicting significant events, and then determining their effect on energy data is clearly a challenging task. However, whilst there are an often unidentifiable number of variables affecting each scenario, associating a precise figure to a variable context, where specific assumptions can prove incorrect, involves an element of uncertainty, whereby it can be assumed that the actual results of the energy security in the future will lie somewhere within the bounds of what has been predicted. An example of this approach can be found in Augutis et al. [44], who investigated the Lithuanian energy security by using a specific Bayesian method, where 68 security indicators were divided into three different blocks (i.e., technical, economic and socio-political aspects) and were used to predict results for the projected period 2016–2030. The work analysed four different scenarios based on the occurrence or absence of significant industrial or political events. A similar method of scenario analysis for predictions was made in Glynn et al. [9], where scenarios are based on import capacity or commodity prices of fuel sources.

While the use of multiple scenarios may give approximations to a data range for each period considered, the influence of each value on the results cannot be determined. This represents a major shortcoming as the reliability of data is potentially open to question. Therefore any reduction in associated uncertainties is therefore an important step when assessing the energy security. For instance, Scheepers et al. [45] investigated the energy security for 27 EU countries by adopting a composite indicator - the Supply/Demand index - whereby multiple factors are normalised, weighted and aggregated. Since the weighting process is often subjective, as parameters are often determined by *expert judgement*, the authors performed a sensitivity analysis on the adopted weights for targeted countries which resulted in a 10% average uncertainty.

In order to estimate the geopolitical risk for energy security, Muñoz et al. [37] identified four separate risk vectors: economic, energy specific, socio-political and diplomatic relations. Across these four vectors, 143 variables are split, each of which is a nominal set of statistics which are deemed to be a contributing factor to one of the four vectors. These vectors are aggregated to form the *Geopolitical Energy Security Risk Index* (GESRI). The important aspect of the work is that data groups are averaged over the period 2000–2010, in order to reduce the effect of outliers on the data collected. This means that the final composite indicator produces a single value for the time period, rather than on a year-by-year basis. This method increases the reliability and accuracy of an indicator, as it assumes that the variables chosen are not set to change significantly within the time period, and most variation year-on-year is a result of the variability in measurement of each indicator. Variables such as political rights or natural gas self-sufficiency, for example, are unlikely to change significantly for most countries within the time period typically considered, except for extraordinary events, and hence, their averaging increases their reliability. Furthermore, averaging data over the time period produces results that are likely to stay relevant for a longer period after the study, given the assumption that the majority of variables will not change dramatically in the time period. On the other hand, should variables change year-on-year as a result of significant changes in the variables themselves, rather than the measurement error, then the results may be compromised. Ultimately, disruptive events should be included as part of a subsequent risk analysis on the energy security assessment carried out [46].

4. Results

The results of the energy security assessment are organised as follows: diversity and dependence (section 4.1), market concentration (section 4.2) and renewable energy production (section 4.3). For each set of results, analysis and discussion focuses on the highest and lowest ranking nations, along with highlighting any particular intermediate trends or trends over the studied period, as well as inter-index relations. Moreover, information on data distribution and uncertainties are provided. Whilst it is impractical to discuss all results for all 28 countries, the discussion involved within this section aims to highlight particular points of interest and relevance to the EU as a whole.

4.1. Diversity and dependence assessment

As discussed in section 3.1, the Shannon-Index provides a measurement of the diversity of the energy supply ($SWI^{(I)}$, Eq. (2)), which also takes into account imports ($SWI^{(II)}$, Eq. (5)) and political stability ($SWI^{(III)}$, Eq. (8)). Fig. 4 reports the three SWI indices for each EU country (plus the United Kingdom) and the EU-28 average in the period 2007–2017. All indexes were normalised to allow a more clear comparison between the countries in accordance with Ferreira et al. [47]. As a general reference, SWI values greater than 0.5 indicate an acceptable degree of diversity of the energy supply for all indexes analysed [47].

Observing the first Shannon-Wiener index $SWI^{(I)}$, it can be noted that a large number of countries show similar values, with most lying between $0.6 \leq SWI^{(I)} \leq 0.75$, mainly due to the strong interdependence between EU members, as already discussed in section 2. More specifically, Finland shows the highest energy security, driven by the reduced reliance on fossil fuels (none of which supplied more than 30% of total primary energy consumption at any point during the period considered), while Malta and Cyprus occupy the lowest rankings due to their geographical specificity.

It is important to note that the $SWI^{(I)}$ index takes into account the fuel mix only, without specifying the origin of each energy source. The inclusion of the import factor leads to the $SWI^{(II)}$ index, shown in Fig. 4 for each EU country and the United Kingdom. As for the previous index, there is a high density of countries populating the middle values, in this case between $0.4 \leq SWI^{(II)} \leq 0.6$. Again, it is reasonable to consider that countries in this range are largely similar in their energy security given their independence for the examined time period. It is a point of interest to study the difference between these values when compared to the standard SWI. Given that the correction factor included in the index formula is between 0 and 1 for a net importer, the values will inevitably decrease for the vast majority of the EU, in light of the import dependency present (with the only exception of Denmark in the period 2007–2009, which acted as net exporter during this period, despite the lower variety of the energy mix). The original values can be observed to have decreased by approximately 0.15–0.2 from the base SWI. This would imply that if the diversity of the imported fuel were to be included, the measure of diversity for the average EU country would fall by approximately 20–25%, highlighting the impact of fuel import dependence on the EU for its energy supply.

As with the diversity indicators, countries with the most extreme values are of particular interest. At the lower end, the

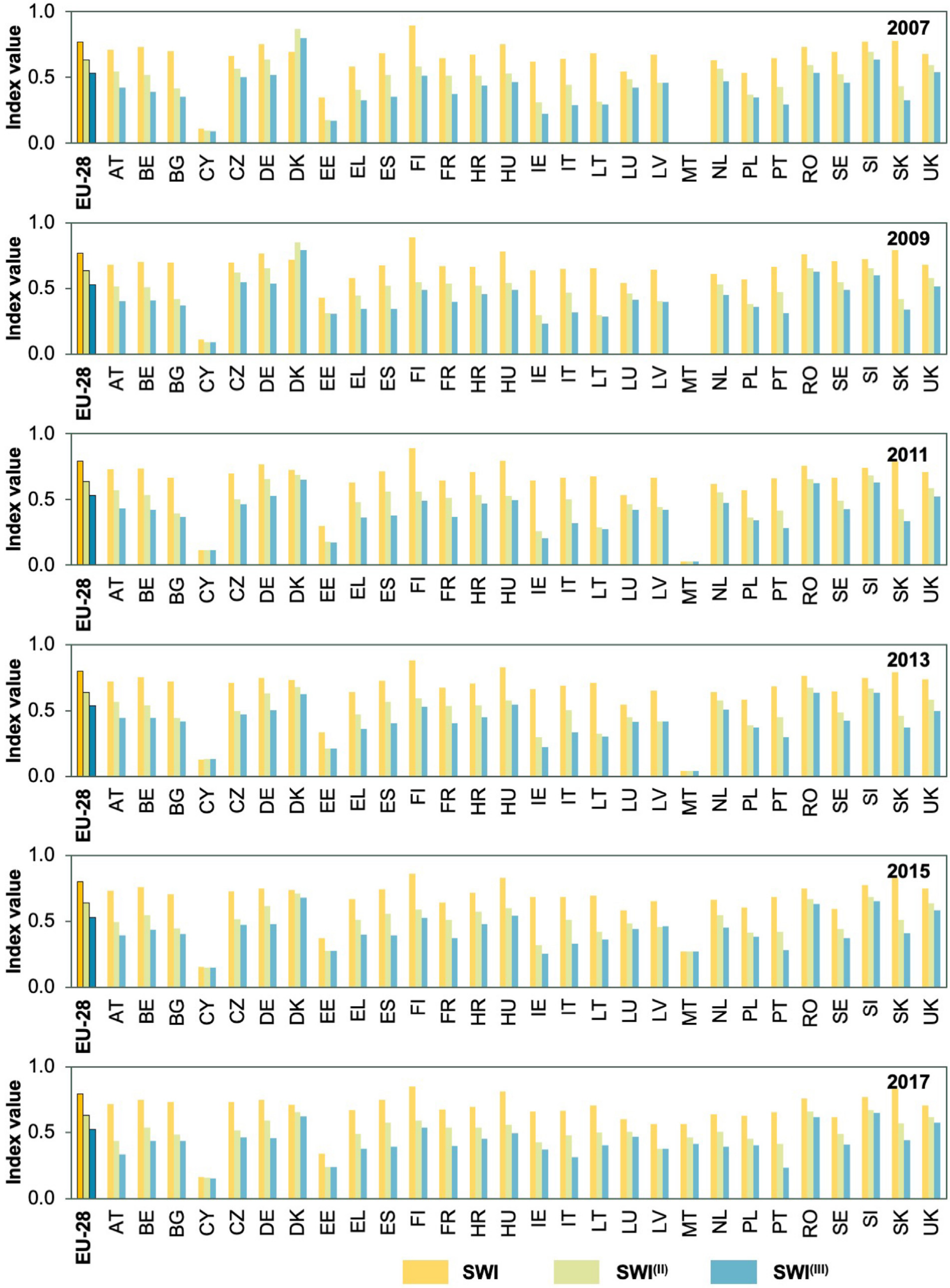


Fig. 4. Diversity assessment for the EU (EU-28) in the period 2007–2017: Shannon-Wiener *SWI* (normalised), Dependence $SWI_{(II)}$ (normalised) and Political $SWI_{(III)}$ (normalised) indices. Country codes follow the glossary established by Eurostat [28].

results are largely unchanged following the inclusion of the import factor. Malta, Estonia, Cyprus, Latvia and Poland all exhibit lower values for both indicators. At the higher end of the scale, there is a more noticeable change: after being a clear leader in the measure of diversity, Finland is no longer discernible from the majority of the other countries. Despite the share of its renewable fuel sources being over 30% which was a key reason for its strong SWI value, Finland is highly import dependent on other key fuel types, requiring over 90% of imports across the time frame considered. This is particularly relevant to gas, which comprises roughly 25% of energy supply in the country, 40% of which is imported from Russia. As already discussed in section 2, the high market share of imports from Russia is a key factor impacting on European energy security.

In order to make the origin of each import flow accountable, the third $SWI^{(III)}$ index is used, as explained in section 3.3. $SWI^{(III)}$ adds a political factor to each import type, which considers the political risk of disruption of that particular import. It can be noted in Fig. 4 that adding these political factors reduces the values in the range $0.35 \le SWI^{(III)} \le 0.5$. Note that the fall in these values is not as large as the one between the $SWI^{(I)}$ and the $SWI^{(II)}$: with the majority of countries being dependent on imports from within the EU and Norway, which generally have a relatively high political factor, the impact on the majority of index values is not as significant. The limitation of this result, however, is that in the case of a composite index (such as this one), as the number of factors or aspects included in the index increases, the impact of each additional factor on the overall result decreases. This means that whilst it is likely to be reasonable to suggest that including a political perspective has less impact on the overall energy security than the import factor, the extent of this cannot be fully evaluated, given that the inclusion of any additional factor at this stage would have a reduced impact on the overall value.

However, there are larger changes in countries that do not follow this trend as, for instance, the case of Portugal, which unlike the majority of other members, primarily imports from outside the EU. This means that its overall value has fallen more significantly than others, given that non-EU imports are potentially less stable than EU imports. Another notable changes are represented by Germany and Italy, which show lower rankings if the political factor is included ($SWI^{(III)}$), compared with the $SWI^{(II)}$ index, mainly due to their high dependence on fossil fuel imports from Russia. For instance, Italy relies on natural gas imports for 91% of its consumption (2017), with about 41.5% is imported from Russia, 23.7% from Libya and Algeria and the remaining from other European countries (mainly Netherlands and Norway) and through LNG terminals (8.7%) [48]. Therefore, the inclusion of the geopolitical factor into the diversity index highlights higher risks of disruption due to geopolitical tensions potentially emerging for any of those countries.

Finally, considering the variation of the SWI indices in the EU over the period considered, it can be noted a relative stable diversity of the energy supply for all countries, with 7.2%, 7.5% and 7.7% for the $SWI^{(I)}$, $SWI^{(II)}$ and $SWI^{(III)}$, respectively. The fact that this is largely consistent across all indicators would indicate that there have been improvements in the base SWI, namely the fuel mix responsible for the increased average energy security, since the correction factors input into Jensen's indicators have remained reasonably consistent over the time period.

Next, the issue of uncertainty is examined. As discussed earlier, the evaluation of the uncertainty associated with the diversification of the energy supply, imports and political stability allows the assessment of the drivers influencing the energy security of the European arena, while also providing a clear picture of the expected deviations from the results obtained. A full sensitivity analysis, however, is affected by errors in the acquisition of data, while data scarcity may lead to unreliable results. Statistical methods can represent a useful tool to evaluate the distribution of energy security indexes. In the present work, a Monte Carlo approach is employed to model the stochasticity of the diversification of the energy supply, imports and political stability (Shannon-Wiener indexes) in the EU and the United Kingdom. The analysis is carried out both at country level and at aggregated European level by assuming a stable geopolitical situation of the energy supply without major disruption events. For each variable, 200 scenarios were created to evaluate the indexes, leading to 3200 different cases of variability being analysed for each index.

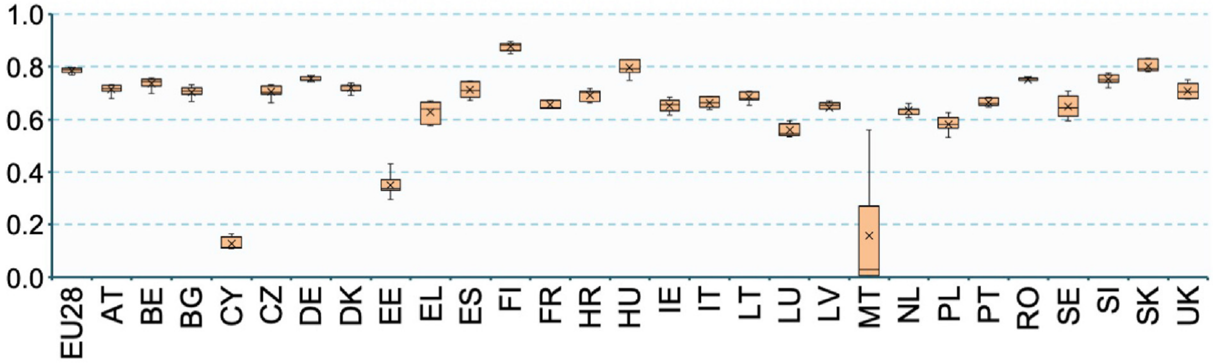
Fig. 5 shows the results obtained from the Monte Carlo analysis for the three indexes considered: the energy source diversity ($SWI^{(I)}$, Fig. 5a), the imports diversity of the energy supply ($SWI^{(II)}$, Fig. 5b) and the geopolitical stability of the energy supply ($SWI^{(III)}$, Fig. 5c). The very low distribution of the Shannon-Wiener indexes obtained at European level (aggregated EU-28) is observable in contrast with the wider disparity of results obtained by individual countries. The strong interdependence between European countries is also demonstrated by the wider variability of the indexes shown in Fig. 5 in comparison with the aggregated EU-28. Despite the disparity between the countries in terms of absolute values and distribution, at aggregated level (EU-28), the European countries show a relatively high value of the diversity indexes with very limited distribution. This means that if the EU-28 is considered as a single or standalone entity from an energy perspective, thereby removing the effect of inter-European energy exchange, little variation in terms of diversity of the energy mix and imports have occurred over the last decade, especially for those countries representing the biggest European economies in terms of population, energy consumption and economy size. Fostering the development of shared policies supporting the diversification of the energy portfolio is therefore critical to achieve a more homogeneous distribution within European countries.

4.2. Energy portfolio concentration assessment

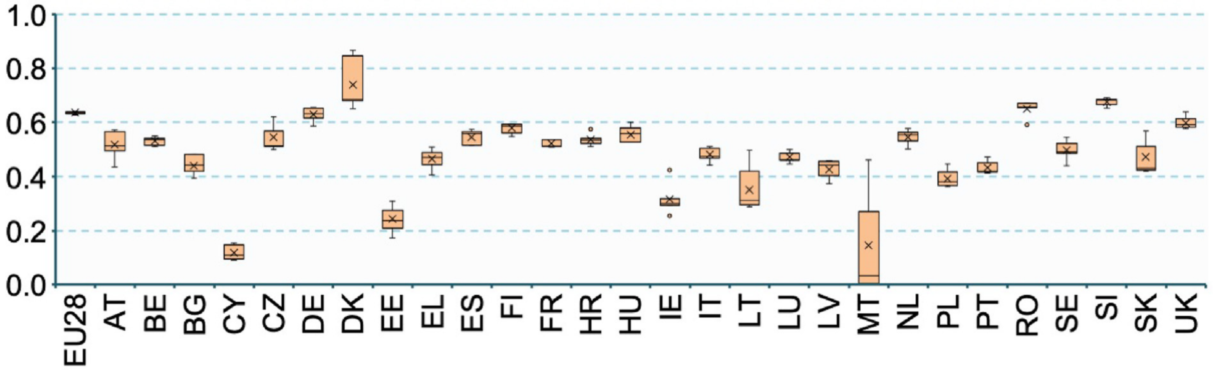
Assessment of energy resource concentration is crucial in order to carry out comprehensive long-term assessment of the energy sector, Fig. 6 shows the Herfindahl-Hirschman index obtained for each EU country and the United Kingdom over the period 2007–2017. As explained in section 3.1.2, the HHI index is a measure of the energy market concentration among different energy resources and suppliers. The maximum value of the HHI is equal to 1.0 and this corresponds to a *monopoly* market, while a lower index indicates a lower concentration - i.e., a higher energy security. As a general reference, threshold values between 0.1 and 0.18 are generally employed in literature to distinguish between competitive and concentrated markets [47].

Similarly to the SWI indices shown in section 4.1, it can be noted in Fig. 6 that most of the countries lie within a close range, in this instance $0.24 \le HHI \le 0.34$. Given that the definitions for $SWI^{(I)}$ and HHI are based only on the market share of each fuel source, similarities between the results should be expected. This is true to a large extent, with Cyprus and Malta having the highest energy market concentration (with the recent improvement of Malta visible), mainly due to their geographical specificity. However, the two best performing countries, Finland and Slovakia, are seen to be far closer in value to the rest of the EU, with Slovakia observed as having the lowest measure of market concentration for the years 2014–2017. It is reasonable to conclude that, while a small number

(a) Energy source diversity - SWI$^{(I)}$



(b) Import diversity of the energy supply SWI$^{(II)}$



(c) Geopolitical stability of the energy supply - SWI$^{(III)}$

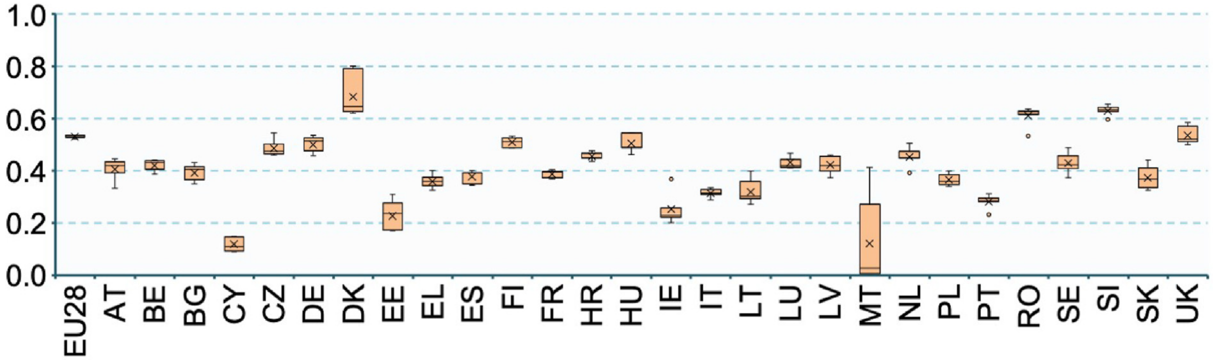


Fig. 5. Uncertainty analysis of the Shannon indexes (normalised) for each EU country and EU28. Country codes follow the glossary established by Eurostat [28].

of countries perform at least somewhat noticeably better than the rest, the majority of the EU members are similarly valued in terms of market concentration which, however, is still greater than the established threshold, to be classified as a fully open and competitive market.

4.3. Renewable energy share assessment

In order to analyse the share of renewable energy in the different European countries, the RESI index was introduced in section 3.4. The RESI index evaluates the proportion of electricity demand fulfilled by renewable sources and it can range between 0, if no RES production occurs, and 1, in the hypothetical case of the full demand covered by RES. RESI values greater than 1 may occur in the uncommon case of a strong exporter country. Unlike the previous indicators, however, the RESI cannot be taken as a full evaluation of total RES to the same extent, given its specification with respect to the electricity market alone, and that an absolute direct correlation between the *renewability* of the energy supply and security cannot be established.

Table 5 reports the RESI values for the EU countries and the United Kingdom over the period 2007–2017. It can be noted that values between $0 \leq RESI \leq 0.521$ were obtained for examined countires over the period considered, with a clear positive trend resulting from the energy policies implemented by the EU (including the UK) to foster the deployment of renewable energies in that period. Most of the EU countries show a high improvement of the RESI score, with the notable cases of Lithuania and Croatia who increased their scores from the low band ($RESI < 0.1$) to the upper band ($RESI \geq 0.35$). Other countries - such as, Germany, Denmark Italy, Portugal and Spain - were also able to improve a relatively low score ($RESI \leq 0.18$) at the beginning of the period considered (i.e., 2007) to an upper band ($RESI \geq 0.25$), mostly because of the incentives deployed to finance the development of

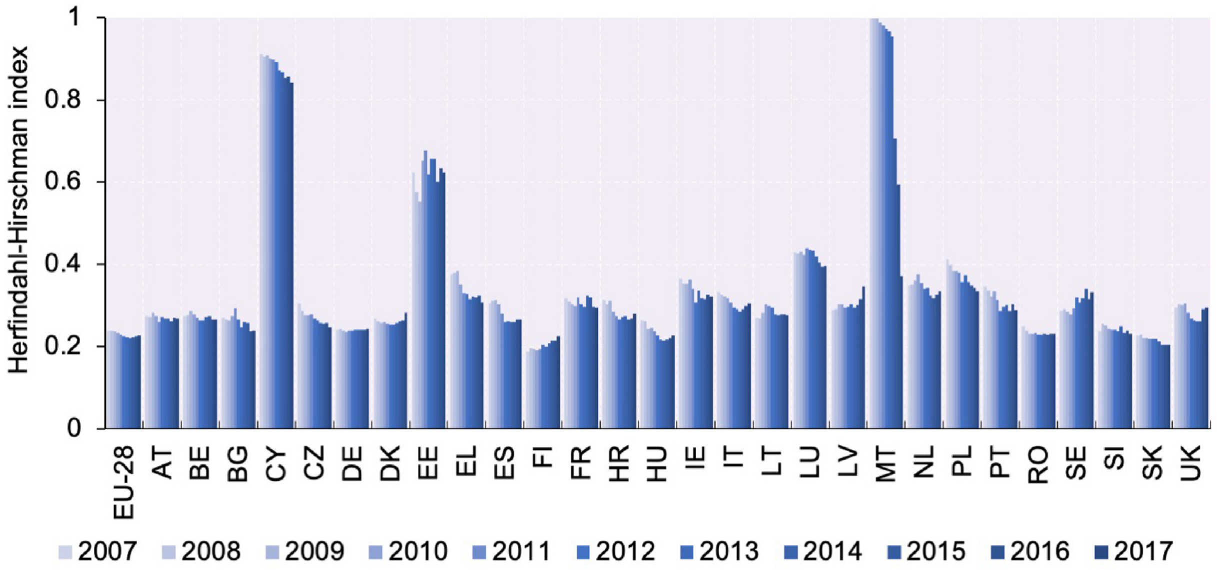


Fig. 6. Market concentration of the energy sector (Herfindahl-Hirschman index) in the EU and the UK. Period: 2007–2017. Country codes follow the glossary established by Eurostat [28].

Table 5
Renewable Energy Security Index (RESI) of the EU and UK over the period 2007–2017. EU renewable share target by 2030: 32%. Colour codes - Red: $RESI < 0.10$. Orange: $0.10 \leq RESI < 0.25$. Light green: $0.25 \leq RESI < 0.32$. Green: $RESI \geq 0.32$.

Country	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Austria	0.320	0.392	0.439	0.444	0.439	0.452	0.473	0.435	0.471	0.498	0.521
Belgium	0.025	0.033	0.042	0.047	0.047	0.055	0.053	0.052	0.068	0.116	0.145
Bulgaria	0.060	0.094	0.129	0.086	0.118	0.160	0.145	0.164	0.145	0.156	0.150
Croatia	0	0.054	0.145	0.284	0.315	0.344	0.319	0.344	0.419	0.464	0.417
Cyprus	0	0	0	0.018	0.035	0.052	0.035	0.043	0.043	0.058	0.076
Czech	0.027	0.036	0.045	0.027	0.044	0.053	0.044	0.044	0.044	0.066	0.058
Denmark	0.186	0.184	0.193	0.246	0.293	0.290	0.377	0.439	0.372	0.448	0.422
Estonia	0.017	0.026	0.027	0.025	0.033	0.034	0.042	0.069	0.050	0.060	0.051
Finland	0.217	0.180	0.162	0.180	0.245	0.189	0.206	0.263	0.270	0.277	0.266
France	0.120	0.119	0.128	0.098	0.134	0.152	0.143	0.133	0.142	0.138	0.166
Germany	0.046	0.047	0.047	0.115	0.124	0.124	0.132	0.184	0.175	0.246	0.271
Greece	0.056	0.130	0.165	0.117	0.129	0.168	0.156	0.188	0.202	0.239	0.251
Hungary	0.009	0.009	0.018	0.025	0.025	0.024	0.023	0.024	0.024	0.032	0.039
Ireland	0.108	0.144	0.118	0.172	0.168	0.188	0.193	0.229	0.196	0.228	0.264
Italy	0.170	0.206	0.216	0.188	0.195	0.230	0.267	0.214	0.205	0.255	0.294
Latvia	0.314	0.335	0.339	0.331	0.370	0.410	0.374	0.331	0.381	0.461	0.407
Lithuania	0.068	0.077	0.197	0.257	0.207	0.238	0.243	0.241	0.308	0.378	0.361
Luxemb.	0.184	0.160	0.187	0.177	0.182	0.190	0.190	0.138	0.124	0.176	0.119
Malta	0	0	0	0	0	0	0	0.013	0.024	0.058	0.055
Netherl.	0.037	0.038	0.038	0.043	0.042	0.052	0.051	0.061	0.061	0.103	0.120
Poland	0.045	0.054	0.072	0.081	0.098	0.098	0.115	0.132	0.123	0.095	0.087
Portugal	0.185	0.331	0.422	0.441	0.398	0.455	0.479	0.348	0.426	0.326	0.394
Romania	0.249	0.253	0.308	0.247	0.246	0.329	0.351	0.329	0.361	0.341	0.367
Slovakia	0.156	0.185	0.212	0.154	0.158	0.180	0.171	0.156	0.185	0.191	0.163
Slovenia	0.244	0.279	0.264	0.220	0.245	0.288	0.248	0.262	0.273	0.261	0.309
Spain	0.161	0.223	0.290	0.230	0.210	0.298	0.292	0.241	0.274	0.255	0.314
Sweden	0.433	0.461	0.435	0.442	0.471	0.433	0.458	0.426	0.455	0.462	0.450
UK	0.036	0.045	0.043	0.051	0.067	0.093	0.118	0.150	0.151	0.195	0.196
EU-28	0.124	0.146	0.167	0.169	0.180	0.199	0.204	0.202	0.213	0.236	0.240

distributed renewable energy systems. At the top end of Table 5, Austria and Sweden present the highest RESI values ($RESI \geq 0.35$), with a relative constant trend over the period considered. On the other end, Cyprus, Czech, Estonia, Hungary, Luxembourg, Malta and Poland, showed the lowest RESI values and increments over the period considered.

These results are summarised in Fig. 7 which shows the overall trend and distribution of RESI in the EU and UK. As already mentioned, a positive trend of the EU28 average RESI was found, from 0.124 to 0.239 in the period considered. Notwithstanding, the introduction of these new regulations has had different impact on the EU28 countries, due to the variation of their socio-economic and political conditions. While some countries - such as, Croatia, Italy, Lithuania and the UK - improved their RESI scores considerably, others saw the gap from the EU28 average increased (i.e., Cyprus, Czech, Estonia, Hungary, Estonia, Luxembourg, Malta, Poland and Slovakia), as shown in Fig. 7. From an aggregated point of view (Fig. 7a), the positive trend of the RESI value is accompanied

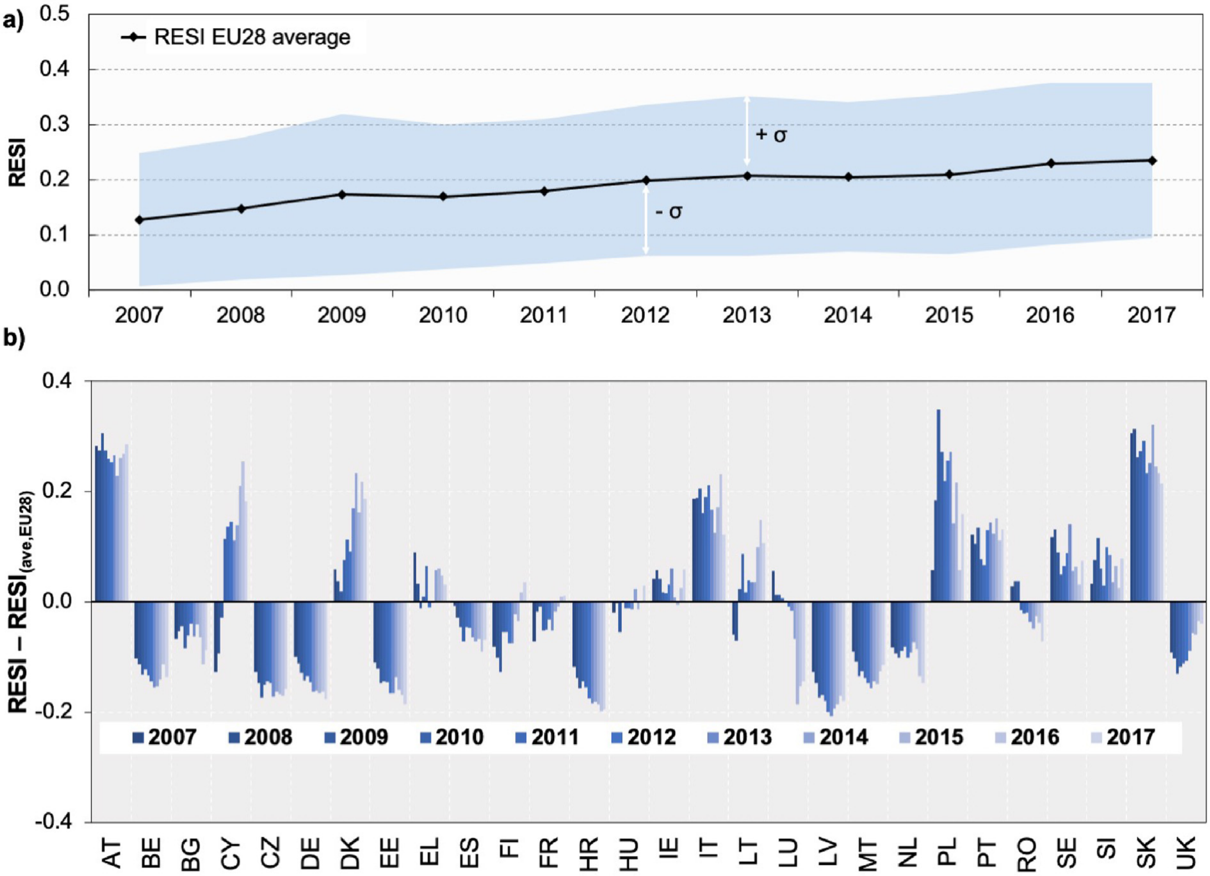


Fig. 7. Renewable Energy Source Index in the EU and UK in the period 2007–2017. a) EU28 average and distribution. b) Variation of the RESI values of each country from the EU28 average. Country codes follow the glossary established by Eurostat [28].

by an increment of the distribution across the EU28, with a more marked improvement in some countries than others. This is a potentially useful perspective since, in order to address these gaps, targeted energy policies, customised depending on the specific conditions of each country, need to be implemented to complement the EU general directives.

5. Conclusions and policy implications

Having uninterrupted energy sources is paramount to ensure economic prosperity and national security, especially in the current global market context. However, assessing the energy security at a national level is a complex task due to the multidimensional critical areas involved - from resource availability, technology, infrastructure and markets to environmental, social and geopolitical aspects. Moreover, energy security is highly context-dependent, being linked closely with national priorities and strategies, which may also change over time.

Among all key areas involved in the energy security, the present paper depicts the diversification of the energy supply, import dependence and renewable energy source deployment in the European Union and the United Kingdom over the last decade, both at national and European levels. The relevance of this analysis relies on the fact that the aggregated European energy production is insufficient to meet energy demand; therefore, the EU is importing more than half of its energy resources from other countries. Moreover, the EU is implementing ambitious policies supporting decarbonisation and sustainability of its society, which will lead to a profound change of the paradigm for the energy sector over the coming decades. Therefore, ensuring the security of energy supply is critical for European countries in order to develop and monitor the implementation of adequate measures to minimise shortages of supply, disruptions such as power blackouts or grid curtailment, infrastructure or market stress during this transitional period.

Whilst the present work has a policy focus, the applicability of the results lies in the extent to which they can assist in the formation of policy. Commencing with the assumption that a more diverse fuel mix leads to a greater security of supply, the Shannon-Wiener indicator has been used in the present work to analyse the diversity of the energy supply at a European level. Most of the European countries lie in the range $1.2 \leq SWI^{I} \leq 1.5$, with Finland showing the highest values and Cyprus and Malta the lowest, mainly due to their geographical specificity. These results are also reflected in the concentration index (Herfindahl-Hirschman index) which measures the energy market concentration amongst different energy sources and suppliers. Average values between $0.24 \leq HHI \leq 0.34$ for most of European countries, with again higher values shown by Cyprus and Malta.

The extreme dependency on imports, as highlighted in section 2, is one of the most significant sources of uncertainty. The inclusion of the imports in the calculation of the metrics reduces the SWI index consistently, leading to values between $0.8 \leq SWI^{II} \leq 1.2$, with an average reduction of about 30%. This is due to the concentration of imports from a limited portfolio of countries, such as Russia, which for 2019, accounted for approximately 45% of coal, 40% of natural gas and 27% of crude oil imports. Such figures become relevant when the geopolitical stability factors associated with each import country are taken into account. As result, the SWI index decreases to values between $0.7 \leq SWI^{III} \leq 1$.

A Monte-Carlo analysis was implemented to model the stochasticity of the energy supply diversity, import dependency and political stability of imports by assuming a stable geopolitical situation of the energy supply without major disruption events. Interestingly, the assessment of all European countries as a single entity at aggregated level (EU-28), leads to a narrow distribution of the SWI indexes, in contrast with the higher variance exhibited by individual countries. This means that if the effect of the interdependency between European countries is removed by considering the EU-28 as a single entity, a stable energy mix and import dependency are evident over the last decade, especially for the largest countries in terms of population, energy consumption and economy size. This, however, does not reduce the strong importation dependence of the EU countries overall, which still expose them to uncertainties related to supply chain disruption, especially in case of sudden changes of international markets and geopolitical conditions.

The renewable energy share of electricity production has been analysed to provide the current status of RES deployment in the considered European countries. Generally, values between $0.06 \leq RESI \leq 0.521$ were obtained with a clear positive trend over the last decade. This is mainly due to the decarbonisation policies implemented by the EU and the UK, which strongly fostered the deployment of renewable energy sources. Notwithstanding, the present research demonstrates that the introduction of these new policies have had different effects on the EU-28: while some countries such as Croatia, Italy or the UK have improved their RESI score considerably, some others have seen the gap, compared to the EU28 average, increased. This reflects the non-homogeneous nature of the implementation of the European policies among the EU members which should be addressed by future customised and targeted actions for those countries which need to decrease these gaps.

From a long-term perspective, policies need to promote the diversification of the fuel mix and the reduction of the concentration of the import dependency, while also supporting the use of domestic energy sources, especially renewable energy resources to meet the ambitious decarbonisation goals. Whilst this would likely be an effective action to enhance energy security and to tackle climate change, it may be challenging to achieve in the short term, due to the significant changes required by the current energy market, which is still largely based on fossil fuels. Moreover, a large penetration of renewable energy cannot be easily sustained by the current energy infrastructure - e.g., the electricity network - without appropriate investment to support a paradigm shift from a centralised generation to a distributed and interconnected network, where the balance between production and consumption will be also ensured by an optimal management of the demand side and any associated energy storage. Future policies need to merge decarbonisation targets with energy security constraints in order to obtain a smooth and secure transition to a more sustainable energy system.

The current work has highlighted how different indexes within the EU are converging as a consequence of the legislative EU framework which is harmonising the internal differences between EU countries. However, it is evident that policies are clearly not sufficient to significantly increase the overall European diversity of the fuel mix. A common effort for reducing the import from non-EU countries requires coordinated long term planning, investment and commitment at a political level. Notwithstanding, different political cycle times among countries, changes in political and public opinion within EU members, different institutions, regulatory accountability and lack of coordination of information sharing processes are still outstanding barriers that require a more pragmatic and invested approach by the EU. Moreover, common market policies to negotiate EU-shared contracts and partnerships with third countries should be implemented to minimise market risks, reduce costs and optimise the overall supply chain.

Although the current paper focuses primarily on specific areas of the energy security debate for European countries - namely, diversification, import dependence and renewability of the EU energy portfolio - further conclusions are likely to be obtained from the analysis of other dimensions, such as price affordability, acceptability, infrastructure resilience, etc. Furthermore, specific developments which may lead to the disruption of the energy supply (or part of it) are best identified separately, so as to identify specific measures to limit their negative impact on economies and society. This is particularly relevant for the EU due to its large dependence on non-EU supply chains, the lack of indigenous resources and the societal and political push for a sustainable transition over the next decades. In this context, the authors hope that this work will stimulate further discussions on the status of the EU energy sector and possible solutions to the outstanding challenges it is facing.

Credit author statement

Mattia De Rosa: Conceptualisation, Methodology, Validation, Writing – original draft preparation, Writing – review & editing, Supervision.**Kenneth Gainsford:** Methodology, Data curation, Formal analysis.**Fabiano Pallonetto:** Data curation, Formal analysis, Writing – original draft preparation, Writing – review & editing.**Donal Finn:** Validation, Writing – original draft preparation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

τ	Time period
c_i	Correction factor of resource i
$CED_{i,\tau}$	Total cumulative energy demand from resource i in the period τ
EDS	Electricity Demand Satisfaction
EIP	Energy import index
EP_{net}	Energy electricity produced from resource i
$GESRI$	Geopolitical Energy Security Risk Index
h_j	Correction factor of country j
HDI	Human Development index
HHI	Herfindahl-Hirschman index
ind	Indigenous
k	Coefficient
m_i	Share of net import of resource i
$m_{i,j}$	Share of net import of resource i from import country j
N	Number of option of the country energy portfolio
NRF	National renewability factor
p_i	Proportional share of resource i
PPS	Purchasing Power Standard
r	Renewable
RES	Renewable Energy Source
$RESI$	Renewable Energy Security index
S_i	Market share of resource i
SWI	Shannon-Wiener index
$TPES$	Total primary energy source
x_i	Net energy import of resource i

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