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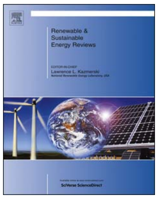

Historical energy security performance in EU countries

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ABSTRACT

It is vitally important for all countries to ensure they have a secure energy supply. This is especially true for European Union (EU) countries, because of geopolitical considerations and ongoing reforms of energy markets. This study applied time-series clustering approaches and three energy security indicators based on the Shannon–Wiener diversity index. The aim was to enhance understanding of how energy security of EU countries, in terms of energy supply, has evolved. An overall improvement in energy security in most EU countries between 1978 and 2014 was identified, with Denmark and the Czech Republic evidencing the greatest improvements. The main driver of improvement has been diversification of primary energy sources. Factors relating to imports (share and diversity of the origins of imports) have also substantially influenced improvement levels. Three groups of countries were identified using cluster analysis: (1) consistently high levels of energy security and showed moderate improvements over time; (2) lower levels of energy security than those in the first group, and also evidenced moderate improvements; and (3) initially low energy security levels, yet followed by significant improvements. The first and third groups were of particular interest because the former reveals best practices while the policies of the latter, in leading to improvement, can serve as guides for other countries.

1. Introduction

Energy is an important driver of economic activity worldwide and is therefore one of the most significant topics of discussion in modern-day global society. The question of how to secure energy is a critical one, especially for energy-importing (notably, fossil-fuel-consuming) countries. In recent years, high levels of economic and population growth in emerging economies such as China and India have resulted in increased energy demands. This trend is projected to continue into the future [1,2], leading to shortfalls or disruptions in supplies of energy, particularly oil, owing to accelerated re-ordering of energy trade flows toward Asian markets and associated increase in energy-import needs [2]. Moreover, because of uneven distribution of quantities of available fossil fuels and their production [1], price fluctuations and geopolitical risks are greater for countries with limited energy resources and high dependence on imports. These countries may consequently face substantial problems with energy security.

Risk dispersion is critical for improving the energy security of countries highly dependent on imports to cover their energy needs. This approach enables them to secure sufficient energy supply to support their economic and societal needs and ambitions, and can be achieved through diversification of energy supplies, energy sources, and production sites (globalization) [3]. Reducing the quantities of imported energy and improving energy self-sufficiency are also important measures for boosting energy security.

Europe imports more than half the energy it consumes, at a total import cost surpassing €1 billion each day. Import dependency is particularly high for crude oil and natural gas. In 2012, imports accounted for 90% of Europe's total crude oil demand and 66% of its natural gas demand [4]. Many European (EU) countries also heavily rely on a single external supplier (e.g., Russia) for their natural gas and electricity imports. In 2013, Russia supplied 39% of all EU natural gas imports. Russia in fact exported 71% of its gas to Europe, with the largest volumes going to Germany and Italy [4]. After Saudi Arabia and Russia, Norway is the third largest exporter of oil and gas; in 2012 accounting for about 31% of the EU's total natural gas imports and 11% of its crude oil imports [5]. Following the Ukraine crisis, the EU has made efforts to diversify its energy suppliers [6]. For example, the Baltic state of Lithuania established a liquefied natural gas terminal in 2014, enabling the country to break Russia's monopoly on gas and to instead import gas from Norway [7].

Hartley and Medlock III [8] concluded that in the long term, although Russia is a dominant supplier of natural gas within Europe, it

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Abbreviations: HC, hierarchical clustering; DTW, dynamic time warping

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would have limited influence on the international natural gas market. However, the same study noted that coordinated action by Russia and the Middle East could pose a greater threat to energy security in the rest of the world. Holz et al. [9] also suggested that Russia would continue to be an important supplier within Europe, yet without playing a dominant role.

The above conclusions are particularly salient at the present, primarily because of increased penetration of renewable energy into the EU's electricity production, as well as the commoditization of natural gas (in the form of liquefied natural gas). This has largely occurred because of the shale gas revolution in the United States. This situation can be illustrated using the examples of Estonia, Latvia, and Lithuania, which, until recently, were dependent on just one external Russian transmission system operator for operating and balancing their electricity networks [10,11]. This sort of heavy dependence on a single external energy supplier leaves EU members vulnerable to supply disruptions or infrastructure failure. To address these challenges and respond to concerns regarding delivery of Russian gas via the Ukraine, in May 2014, the European Commission released its Energy Security Strategy. This was aimed at securing a stable and abundant energy supply within the EU [4]. In particular, the strategy proposes actions for strengthening emergency and solidarity mechanisms, and for protecting critical infrastructure. The underlying intent is to consolidate the internal energy market and build in missing infrastructure links. This would enable quick response to possible supply disruptions by directing energy flows across the EU whenever and wherever necessary. The strategy also lays out measures such as increasing energy efficiency and indigenous energy production. Energy supply security concerns are shared by all member states, especially those located in regions poorly integrated and connected, such as the Baltics and Eastern Europe [10]. The EU works closely with its supplier countries, and with countries situated along supply routes, with the aim of developing new transit routes (e.g., the Southern Gas Corridor, which provides a conduit for gas supplies from the Caspian region) to diversify its supplies [12]. In line with this objective, in February 2016, the European Commission unveiled a package of energy security measures for strengthening the EU's resilience to gas supply disruptions [13].

These measures are based on the “solidarity principle” developed by EU member states [14]. The principle obligates EU countries to assist neighboring EU countries experiencing a gas supply crisis. The measures will also strengthen energy-related intergovernmental agreements between both EU and non-EU countries, thereby fulfilling the aim of boosting energy security via increased or new access to liquefied natural gas and gas storage.

Another important step was taken in March 2015, when 28 European heads of state adopted a plan for creating an energy union. This union would seek to bolster Europe's energy security, create an internal energy market, improve energy efficiency, decarbonize, and enhance energy-related research and innovation.

Many studies have investigated energy security, and from a variety of angles. These include studies of different countries and regions, comparisons of different methods, and assessments conducted during different periods. Many such studies have particularly targeted Asia [15–30]. Comparatively fewer studies have focused on EU countries. However, analyses at the EU and individual European country scales also exist in the literature. Certain key studies using historical (or current) data and information can be summarized as follows. At the EU level, similar to the scope of the present study, Le Coq and Paltseva [31] evaluated the energy security of all EU countries (as of 2006) in terms of energy supply. They focused on fossil fuels, using separate indicators based on import diversification and related risks. However, they only covered a single year (2006) and did not assess aggregated energy security performance of the entire energy supply. Radovanović et al. [32] proposed an energy security index that incorporated both environmental and social aspects for evaluating the energy security of 28 EU countries for 1990–2012. Valdés Lucas et al. [33] also used panel data, on 21 EU countries, to analyze the relationship between energy security and renewable energy deployment. However, in contrast with most of the existing energy security studies, their study used regression models (panel data analysis) and energy security indicators to explain the share of renewable energy in primary energy demand. Escribano Francés et al. [34] used a portfolio-based approach to analyze the relationship between energy security and renewable energy sources, focusing on the Mediterranean Solar Plan.

There have also been multi-national comparative studies (excluding the EU scale). Winzer [35] applied various separate indicators, including the system average interruption duration index of electricity and heat, renewable energy potential, loss of gross domestic product, and CO_2 emissions per capita, to evaluate energy security in Austria, Italy, and the United Kingdom, and compared these countries by the selected indicators. Lefèvre [36] developed energy security indexes composed of energy price and physical availability indexes. That study focused on fossil fuels and applied the indexes to France and the United Kingdom, covering from 2004 to 2030. Löschel et al. [37] used ex-post and ex-ante indicators for evaluating the energy security of the Netherlands, Spain, and Germany (as well as the United States). Findlater and Noël [38] assessed the level of gas supply security in the three Baltic countries (Latvia, Lithuania, and Estonia), using qualitative methodology based on interviews, policies, and national statistics. Jones et al. [39], using an online survey and statistical methods, revealed the relationship between public perceptions and energy security, focusing particularly on pro-environmental and pro-cultural attitudes.

At the national level, Augutis et al. [40] evaluated power supply security, with focus on dependence on nuclear power, in the past and future. Their study used indicators including technical, economical, socio-political, and environmental aspects. Augutis et al. [41] evaluated energy security retrospectively, and that based on natural gas and nuclear power scenarios, in Lithuania, focusing on technical, economic, and socio-political aspects. Angelis-Dimakis et al. [42] evaluated energy security (or energy system sustainability) in Greece over 1960–2007, using three dimensional (social, environmental, and economic) indicators. Franki and Višković [43] evaluated the energy security of Croatia's energy system in 2015, applying an energy security index composed of energy cost, reliability, and sustainability. That study also conducted sensitivity analysis against parameters in the energy market analysis. Lehr [44] evaluated energy security in Germany mainly in terms of energy supply covering 1995–2006. That study also conducted scenario analysis (reference and renewable energy scenarios) up to 2030. Demski et al. [45], focusing on the United Kingdom, used questionnaires to explore public views on energy security.

These studies can also be classified as (1) studies of whole energy sources or systems [32,33,39,41–44] and (2) those focusing on specific energy sources [31,34–38,40].

Studies also exist on energy security based on future scenarios. At the Europe level, Umbach [46] analyzed critical global and geopolitical dimensions of future international energy security, and their implications for Europe and the EU27. That study examined global demand, global trends relating to re-nationalization, refinery crises, climate change, and other relevant factors, using qualitative rather than quantitative analytical methods. Gracceva and Zeniewski [47] used an energy system model and energy security indicators covering five dimensions to assess the relationship between a low-carbon scenario and energy security up to 2030. Jonsson et al. [48] qualitatively evaluated the EU energy roadmap (for low-carbon transition) from the perspective of energy security. That study used a broad approach, including energy supply, demand, and import, as well as economic, political, and social aspects. Holz et al. [9], who applied a strategic model of European gas supplies for simulating future natural gas scenarios up to 2025, found that Europe could use diversification to increase its supply security. Based on their application of a natural gas infrastructure model for simulations for 2020, Dieckhöner [49] concluded that the Nabucco and South Stream Pipelines had a positive effect on the security of the EU's supply. Specifically, the study found both pipelines could increase the security of supplies, leading to less disruption for consumers along with more moderate price increases.

An example of multi-national studies (excluding the EU scale) is that of Kruyt et al. [50], who applied a selection of available indicators partly related to the 4As – availability, affordability, acceptability, and accessibility – of energy in their assessment of the future security of energy supply, focusing on Western European (Organisation for Economic Co-operation and Development [OECD]) countries.

At the national level, Katinas et al. [51] discussed energy supply security in Lithuania, focusing on renewable energy development. Although that study used numerical data, covering areas such as use of renewable energy sources and their percentages, no energy security indicators were applied to the discussion. Grubb et al. [52] evaluated the relationship between a low-carbon objective and future energy security in the United Kingdom. That study focused on energy security in terms of power generation and diversity of power sources.

The aforementioned studies can be also classified into (1) studies of whole energy sources or systems [46–48,50] and (2) studies focusing on specific energy sources [9,49,51,52].

Apart from the above energy security studies that target EU countries, applying data (including statistical and questionnaire data) and various indicators, other types of study also include theoretical research and policy analysis/discussions [53–58]. However, they are few in number.

While many studies have addressed energy security issues at the EU or EU-country scale and from the broad perspectives as above, few studies have focused on all EU countries within a time series. Furthermore, there are relatively few studies that have analyzed energy security over the long term (in any country). Radovanović et al. [32] is one example that evaluated energy security in all EU countries within a time series. Angelis-Dimakis et al. [42] evaluated energy security over the long term, though they only focused on Greece. However, the present study differs from the aforementioned ones, as it entails an analysis of energy security during earlier periods, including that of the oil crisis in the 1970s, in all EU countries. This evaluation also focused on secure energy supply, which is the most important and frequently addressed aspect of energy security. Moreover, it extended analysis of the evaluated performance of energy security in EU countries by applying clustering approaches to obtain further insights into patterns of transition of energy security performance (see Section 2.3).

From a methodological perspective, various indicators are applied in relation to statistical data or the results of a model or scenario analysis. Indicators used in existing studies define energy security differently. These definitions (also called dimensions of energy security) vary, but can be summarized into the following seven categories [59].

- Energy availability: This is mainly determined by diversification and geopolitical factors. It includes import sources, geographical areas, energy mix, technology, and transport routes.
- Infrastructure: This is integral in providing stable and uninterrupted energy supply. Facilities encompass energy transformation, distribution, and transmission.
- Energy prices: These determine the affordability of energy supply, including absolute price level, price volatility, and competitiveness of energy markets.
- Societal effect: This is based on the relationship between society (social issues) and energy. it includes energy poverty and acceptability.
- Environment: Sustainability and environmental issues are closely related to energy because of carbon emissions, pollution, and other environmental issues resulting from development of power plants, including those for renewable energy.
- Governance: Good governance helps hedge against short-term energy disruptions, and forward-looking governments seek to ensure long-term energy security. This includes the government's roles in policymaking, regulatory processes, diplomacy, and information collection.
- Energy efficiency: This is closely related to energy intensity. Energy-intensity-improving technologies, systems, and practices reduce energy demand, thereby improving energy security.

Indicators for each dimension also vary among research according to the various interests in the aspects of energy security. In addition, one to 200 indicators selected from one to seven dimensions were used in the literature [59].[1] However, there are no uniform definitions or evaluation methods for assessing energy security performance. When evaluating countries' energy security, the most important element is energy availability, as this is included as an indicator in 99% of related studies [59]. Given that policymakers use such indicators to establish energy policy measures, a simple and lucid methodology needs to be developed in this field.

The present study aimed to address the abovementioned shortcomings (i.e., no studies on EU-scale analysis using long-term time-series data and analysis based on calculated energy security performance for further understanding performance patterns). It accomplishes this by introducing three novel indicators for evaluating country-level energy security performance in terms of energy supply. Meanwhile, it simultaneously illustrates their applicability as demonstrated in empirical results obtained for EU countries during 1978–2014. It should be noted that Norway was also included in the analysis because it participates in the EU energy market and is an important energy producer/exporter. Consequently, "EU countries" hereinafter includes Norway. This study contributes to development of a comprehensive and historically grounded understanding of energy security in the EU. Further, the methodology used herein can be applied for any other country.

The remainder of this article is organized as follows. Section 2 describes the methods used in the analysis, including the construction and interpretation of the proposed energy security indicators, the data used for the analysis, and the statistical approach employed. Section 3 presents and discusses the results in detail, and Section 4 presents the study's conclusions and discusses future research directions.

2. Material and methods

2.1. Energy security indicators

Three energy security indicators were applied to analyze the historical transition of energy security performance in terms of energy supply in EU countries [44,60]. The indicators mainly focused on energy availability, but also encompassed country risks, and enabled historical energy security trends to be analyzed. The results obtained can be used to help formulate energy policy recommendations.

The first indicator ($S1$, Eq. [1]) evaluated the diversity of 10 primary energy sources (coal, oil, gas, nuclear, hydro, solar, wind, geothermal, biomass, and other forms of renewable energy), based on the Shannon–Wiener index [61], an established indicator for evaluating diversity. Also known as the Shannon index or Shannon entropy, this was first proposed in information science to quantify the entropy of strings of text [61]. It has been a popular diversity index in ecology for measuring areas such as species diversity [62–64]. However, it has also been used for general measurement of diversity, including that in energy security [44,60]. Diversity is important for maintaining a high level of energy security. This is because the probability of other energy sources compensating for the loss, for any reason, of a primary energy source will increase; thereby ensuring energy security is partly preserved.

$$S1 = -\sum_{i=1}^{N} p_i \ln(p_i) \tag{1}$$

where i denotes types of primary energy, p_i denotes the share of primary energy i, and N denotes the number of primary energy types. This equation was applied to each country.

However, when evaluating the energy security of countries, it is important to consider the energy sources' origins. Domestic energy is considered safer, while procurement risks exist for imported energy. Similar to energy source diversity, the origin diversity also

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[1] See Ang et al. [59] for a comprehensive review of energy security studies.

contributes to energy security. Consequently, the probability of imports from other countries compensating for the loss of imports from one particular country should increase. The second indicator ($S2$, Eq. [2]), therefore, considered each country's import dependence for its energy sources, as well as its imports by origin.

$$S2 = -\sum_{i=1}^{N} c2_i p_i \ln(p_i) \tag{2}$$

$$c2_i = \left(1 - dm_i\left(1 - \frac{IM2_i^m}{IM2_i^{max}}\right)\right) \tag{3}$$

$$IM2_i^m = -\sum\nolimits_{j=1}^{M} m_{ij} \ln(m_{ij}) \tag{4}$$

$$IM2_i^{max} = -M\frac{1}{M}\ln\left(\frac{1}{M}\right) \tag{5}$$

where j denotes the origins of primary energy imports, dm_i denotes the share of imports of primary energy i¸ m_{ij} denotes the share of imports of primary energy i from country j, and M denotes the number of origins of primary energy imports (this differs by country and by energy source). These equations were applied to each country.

In the second indicator, all energy exporters were treated equally. However, even though energy is imported, energy security will be higher if energy sources are imported from safer, lower-risk countries. Therefore, the above indicator was extended with a third indicator ($S3$, Eq. [6]) that incorporated a country's risk factor associated with the origins of that country's energy imports. By definition, the values of the three indicators were: $S1 \geq S2 \geq S3$.

$$S3 = -\sum_{i=1}^{N} c3_i p_i \ln(p_i) \tag{6}$$

$$c3_i = \left(1 - dm_i\left(1 - \frac{IM3_i^m}{IM3_i^{max}}\right)\right) \tag{7}$$

$$IM3_i^m = -\sum\nolimits_{j=1}^{M} A_j m_{ij} \ln(m_{ij}) \tag{8}$$

$$IM3_i^{max} = -M\frac{1}{M}\ln\left(\frac{1}{M}\right) \tag{9}$$

$$A_j = \frac{r_j}{\max\limits_{j} r_j} \tag{10}$$

where r_j denotes the risk indicator for country j. These equations were also applied to each country.

The indicators were calculated for each country for each year from 1978 to 2014. However, for countries for which data were not available for earlier years, only those years for which data were available were included in the evaluation (also see Section 2.3 with regard to data availability).

2.2. Hierarchical clustering

A clustering approach was applied to perform analysis of the obtained time series for the three proposed indicators. Specifically, hierarchical clustering (HC) was used to identify groups of countries with similar characteristics regarding their historical patterns for each of the three indicators. HC was therefore used as a descriptive data analysis tool that provides analytical results complementing the pure qualitative inspection of the proposed security indicators' historical evolution. HC was implemented in accordance with an agglomerative bottom-up approach in which the clusters were formed progressively, starting with elementary clusters, each consisting of one country. These were then merged based on a similarity metric. The main advantages of applying HC include avoidance of the requirement to predefine the number of clusters, the ability to cluster time series of different lengths, and the visualization abilities associated with this approach that greatly facilitate interpretation of the results [65].

HC was performed for each of the three indicators described in the previous section. For the aims of the analysis, alternative similarity metrics to measure the differences between the time series for each pair of countries were considered. The first was Euclidean distance (D), expressed as follows:

$$D_{kn} = \sqrt{\sum_{t=1}^{T} (x_{kt} - x_{nt})^2} \tag{11}$$

where k and n denote countries; t denotes the year; x_{kt} and x_{nt} denote the historical data of countries k and n relating to the indicator under consideration during year t; and T denotes the number of years in the data set.

Euclidean distance is widely used as a dissimilarity metric in clustering methods, including HC. However, the disadvantage is that it does not account for acceleration/deceleration that may occur along the time axis [66]. This may lead to failure to identify similarities when there is a minor time lag between two time series.

Therefore, dynamic time warping (DTW) was used as another alternative method for considering the (dis)similarity between countries' time series [67]. Similar to Euclidean distance, DTW has been extensively used for data clustering, particularly for time-series data. It entails identifying the optimal alignment of a pair of time-series data via nonlinear mapping so that the two series match each other to the best extent. Thus, it is less sensitive to distortions over time when computing the distance (e.g., Euclidean distance) between the aligned series. The optimal alignment is defined through iterative dynamic programming algorithms.

Stirling [68] also applied a clustering approach in energy diversity analysis conducted for the United Kingdom. However, this approach was applied for grouping energy sources, revealing disparities among them in relation to three criteria (environmental quality, economic value, and social wellbeing), which were then used for evaluating the diversity of energy options. This study differed from that of Stirling [68] in that it used this approach for clustering countries based on their energy security performance.

2.3. Data

Data were obtained to calculate the three indicators. Data on each country's production, import, and export of primary energy (used to calculate the share of primary energy p_i and dependence on imports dm_i) were extracted from two International Energy Agency (IEA) publications: *Energy Balances of OECD Countries* and *Energy Balances of Non-OECD Countries* [69,70]. Because the types of primary energy included in these sources were both broad and detailed, they were aggregated into 10 types of primary energy, as mentioned in Section 2.1. Of note, data for 1978–1989 were not available for Croatia, Estonia, Latvia, Lithuania, and Slovenia. Data were also unavailable for Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, and Romania for 2014. Therefore, the energy security performance in these countries was calculated for the years for which data were available.

The primary energy imports by origin (used to calculate the share of imports m_{ij}) in each country were obtained from other IEA publications: *Coal Information*, *Natural Gas Information*, and *Oil Information* [71–73].

Last, this study applied the average of six governance indicators (control of corruption, government effectiveness, political stability and absence of violence/terrorism, regulatory quality, rule of law, and voice and accountability) from the *World Governance Indicators* [74] for the risk indicator. Because the data ranged from approximately −2.5 to 2.5,[2] they were

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[2] http://info.worldbank.org/governance/wgi/index.aspx#doc-methodology.

converted into a scale of 0–1, with values closer to 0 indicating higher risk.

The above sources did not contain data on natural gas imports by origin and risk indicators in or before 1992 and 1995, respectively. To widen the scope of the analysis, data available for the closest years – 1993 and 1996 – were used to compensate for the missing data.

3. Results and discussion

3.1. Energy security performance in EU countries

Using the methods and data discussed in the previous section, the energy security performance of different EU countries was evaluated. However, as no data existed on primary energy imports by origin for non-OECD EU countries (Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, and Romania) in the IEA databases [71–73], only the *S*1 indicator was applied for them.

As shown in Table 1, the overall trends in 2014 showed an improvement in the indicators over their levels in 1978 by a factor of 1.43–1.50. In addition, the coefficient of variation of the three indicators indicated that dispersion among countries was greater for indicator *S*3 and that these dispersions had been reduced in recent years.

Table 1
Descriptive statistics for the three indicators in 1978 and 2014.

	Average		Standard deviation		Coefficient of variation	
Year	1978	2014	1978	2014	1978	2014
*S*1[a]	0.93	1.40	0.31	0.24	0.34	0.17
*S*1[b]	0.98	1.40	0.23	0.24	0.24	0.17
*S*2[b]	0.74	1.09	0.26	0.27	0.35	0.25
*S*3[b]	0.63	0.94	0.24	0.24	0.37	0.26

[a] This calculation included 29 countries. However, data for non-OECD countries were not available for 2014. Comparative statistics for 2013 were as follows. The average, standard deviation, and coefficient of variation values were 1.35, 0.35, and 0.26, respectively.

[b] This calculation did not include seven non-OECD EU countries. The same situation applied for the *S*2 and *S*3 calculations.

Fig. 1 shows the changes in energy security performance for the three indicators in 2014 compared with the 1978 level. Values for 2013 were used instead of those for 2014 for seven non-OECD EU countries because of data availability. The figure indicates an overall improvement in EU countries' energy security, with very few exceptions. Fig. 1 also shows that the greatest improvement occurred in Cyprus for the *S*1 indicator. However, this was an exception because Cyprus' energy security performance was very low in 1978, as well as during the last quarter of the previous century (see also Fig. 2a). Apart from Cyprus, the greatest improvements in all three indicators (over 100%) occurred in Denmark and the Czech Republic, with higher increases for the indicators that considered the origins of energy imports and country-related risks. Ireland also showed an increase in *S*1, resulting from greater diversification of the country's primary energy sources. In Ireland, oil and coal accounted for more than 99% of primary energy consumption in 1978 (with oil accounting for 79.0%). However, the share of these fuels decreased by 64.9%, with the consumption of other energy sources, particularly natural gas (35.5%), evident in 2014. However, increases in the other two indicators were moderate for Ireland because, while its imports of primary energy increased, the origins of the imports became less diversified.

During 1978–2014, both Luxembourg and Slovenia experienced a decline in energy security performance relating to the *S*2 indicator. Luxembourg also experienced a decline relating to *S*1. Diversification of primary energy sources was the main reason for the weakening of these two indicators for Luxembourg. A comparison of the proportions of use of the three fossil fuels in 1978 and 2014 revealed that their proportions in 1978 were relatively balanced. In contrast, in 2014, the proportion of coal consumption showed a considerable decrease and that of oil a considerable increase (Table 2). Although the share of renewable energy sources in relation to total energy consumption has increased, it is still very small (Table 2). In Slovenia, increased dependence on imported coal contributed to a decline in energy security performance (net imports of consumed energy were 9.6% in 1990 and 26.3% in 2014).

Fig. 2 shows the calculated values of energy security performance of EU countries. Clearly, the energy security performance of most countries in relation to the *S*1 indicator was higher in 2014 than in 1978. The main reason here was that the primary energy structure changed from greater oil concentration in 1978 to greater diversification among fossil fuels, renewables, and nuclear power in 2014 [69,70]. The lowest energy security performance results in 1978 were for Cyprus (0.13), Malta (0.25), and Ireland (0.55), all of which evidenced consumption of an oil-dominated energy mix (with oil comprising over 75% of primary energy demand). Cyprus and Malta both had exceptionally low energy security performance. Countries demonstrating better performance in 1978 – such as Finland (1.31), Austria (1.29), and France (1.24) – depended less on oil and used alternative energy sources such as natural gas, nuclear, and hydropower. Nevertheless, in 1978, oil's share in the energy mix remained above 50% in all these countries. Improved energy security performance in recent years can be largely attributed to reduced oil share in relation to primary energy demand [69]. Slovenia, which showed the highest performance for the *S*1 indicator (1.70) among all EU countries for 2014, illustrates this. While its shares of nuclear and coal energy were 23.6% and 16.6%, respectively, its oil share remained higher, at 32.5%. Denmark, which performed best after Cyprus, demonstrating an improvement in relation to the *S*1 indicator during the last quarter-century, presented a similar picture. Its oil share was reduced by half, with significant increases in natural gas and biomass shares. Denmark's wind power has also increased.

In most EU countries, the *S*2 indicator also improved over time. The lowest levels of performance, in 1978, were observed for the Czech Republic (0.36), Poland (0.39), and Luxembourg (0.39). Thus, the three countries that performed the poorest in relation to *S*2 differed from those that performed the poorest for the *S*1 indicator for different reasons. Luxembourg imported all its fossil fuel needs, while the Czech Republic and Poland imported approximately 97% of their oil needs, mostly from Russia [73]. Such high dependence on imported energy from a single country led to reduced energy security, according to the indicator. Other countries demonstrating low *S*2 values exhibited similar trends. In 1978, countries with high *S*2 values, such as the United Kingdom (1.10), France (1.09), and Sweden (1.09), evidenced a low level of import dependence; otherwise, their imported energy supplies, particularly oil, were sourced from multiple countries [69,71–73]. The increased *S*2 values during the study period owed to country-specific reasons. For example, the main factors influencing improved performance for Germany, which had the best performance among all EU countries in 2014, were its reduced shares of oil and coal and increased diversification of energy imports [69,71–73]. In Denmark, which had the greatest improvement during the study period, reduced oil imports were the most important factor. Denmark transitioned from being mostly dependent on imports (97.8%) in 1978 to becoming a net exporter in 2014 [69]. The most influential factor for the Czech Republic, which showed the second greatest improvement after Denmark, was diversification of energy sources, with increased consumption of natural gas and non-fossil fuels [69].

As with the first two indicators, the levels of energy security performance of all countries were consistently lower for the *S*3 indicator in 1978 than in 2014. However, a few countries showed lower performance levels for certain years than those in 1978 (see Figs. 1, 2, and A1). The lowest levels, in 1978, were observed for Luxembourg (0.29), Denmark (0.30), and the Czech Republic (0.32). These countries also demonstrated low energy security levels according to the *S*1 and *S*2 indicators. Better performance was observed for the United Kingdom (1.04), Norway (0.98), and Sweden (0.95). Although the *S*3 indicator accounts for the risk factor (i.e., it decreases if a country imports energy from high-risk countries), other factors, such as diversity of primary energy sources and dependence on imports, were the primary ones associated with this indicator. Norway's

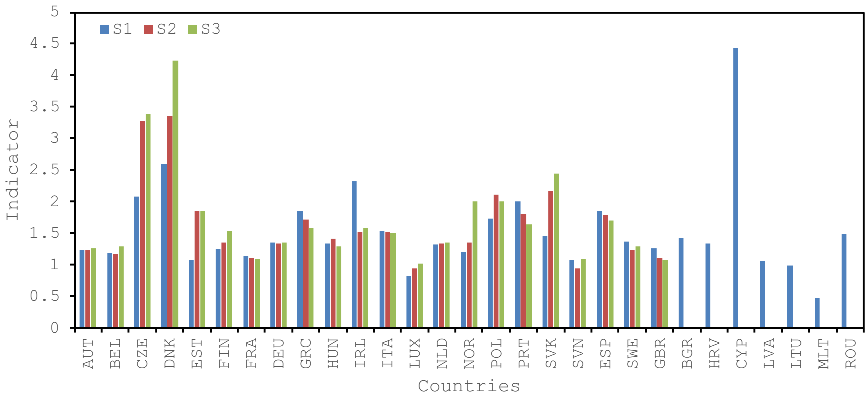

Fig. 1. Changes in energy security performance in EU countries for the three indicators in 2014 compared with the 1978 level. Seven non-OECD countries were included only in the *S*1 indicator because of limited data availability. ISO 3166-1 alpha-3 was used for the country codes.

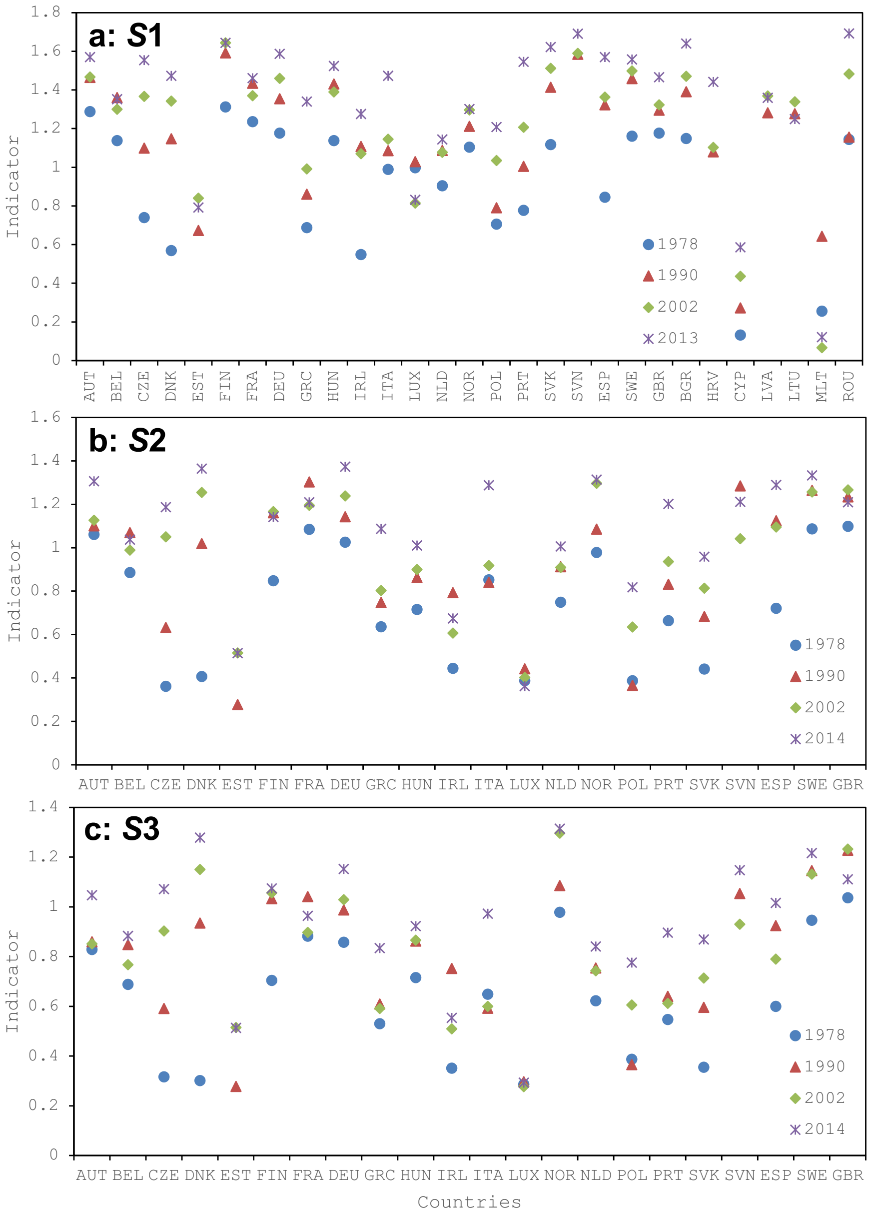

Fig. 2. Calculated values of energy security performance in 1978, 1990, 2002, and 2014 for the three indicators; *S*1 (a), *S*2 (b), and *S*3 (c). Panel a was the only one that included the seven non-OECD countries in the study. Because data for 2014 were not available for non-OECD EU countries, these data were substituted by available data for 2013 used for the *S*1 indicator. ISO 3166-1 alpha-3 was used for the country codes.

Table 2
Share of primary energy sources in Luxembourg in 1978 and 2014.

Year	Coal	Oil	Natural gas	Hydro	Solar	Wind	Biomass
1978	51.6%	35.9%	11.8%	0.2%	0%	0%	0.5%
2014	1.4%	71.2%	22.2%	0.2%	0.2%	0.2%	4.5%

Source: Energy Balances of OECD Countries [69].

performance in relation to *S*3 was relatively good because it is an oil exporter [69]. However, its performance compared with those of other EU countries was only moderate in relation to *S*1. The same countries – Denmark and the Czech Republic – demonstrated significant improvements for *S*3 during the study period as those identified in relation to *S*2. However, Denmark's improvement related to *S*3 that occurred during 1978–2014 exceeded that for *S*2. This greater improvement resulted from the country's transition from oil importer (in 1978) to exporter (in 2014) [69]. Its declined *S*3 energy security performance during its period as a net oil importer was attributed to the risk indicator. However, this did not apply when it became an exporter. Denmark thus experienced a greater degree of improvement in relation to *S*3 than *S*2.

In the above analyses for the three energy security indicators, four factors – primary energy diversity, dependence on energy imports, diversity of energy-import origins, and country risk of energy exporters – were considered in the equations, depending on the indicators. Although situations were specific to each country, the main factor among these for determining energy security performance, particularly in terms of countries' transition and ranking in relation to one another, was diversity of primary energy sources. Fossil fuels have been the main energy source in most EU countries; consequently, achievement of a balance in consumption of the three fossil fuels increased their energy security performance. Substitution of fossil fuels by renewable energy and nuclear power further improved this performance.

Dependence on energy imports and diverse origins of energy imports were two further influential factors. However, the effect of country risk was relatively small compared with that of the other factors. This is because the ranking of countries in relation to associated risks does not frequently change. Moreover, countries do not regularly change the countries from which they import energy [71–73]. Evidently, all the factors influence the indicators' values. Additionally, energy security improvements were higher from the late 1970s to early 1980s, but slowed from the mid-1980s to early 2000s, peaking again after 2005 because of the increasing penetration of electricity from renewable energy sources.

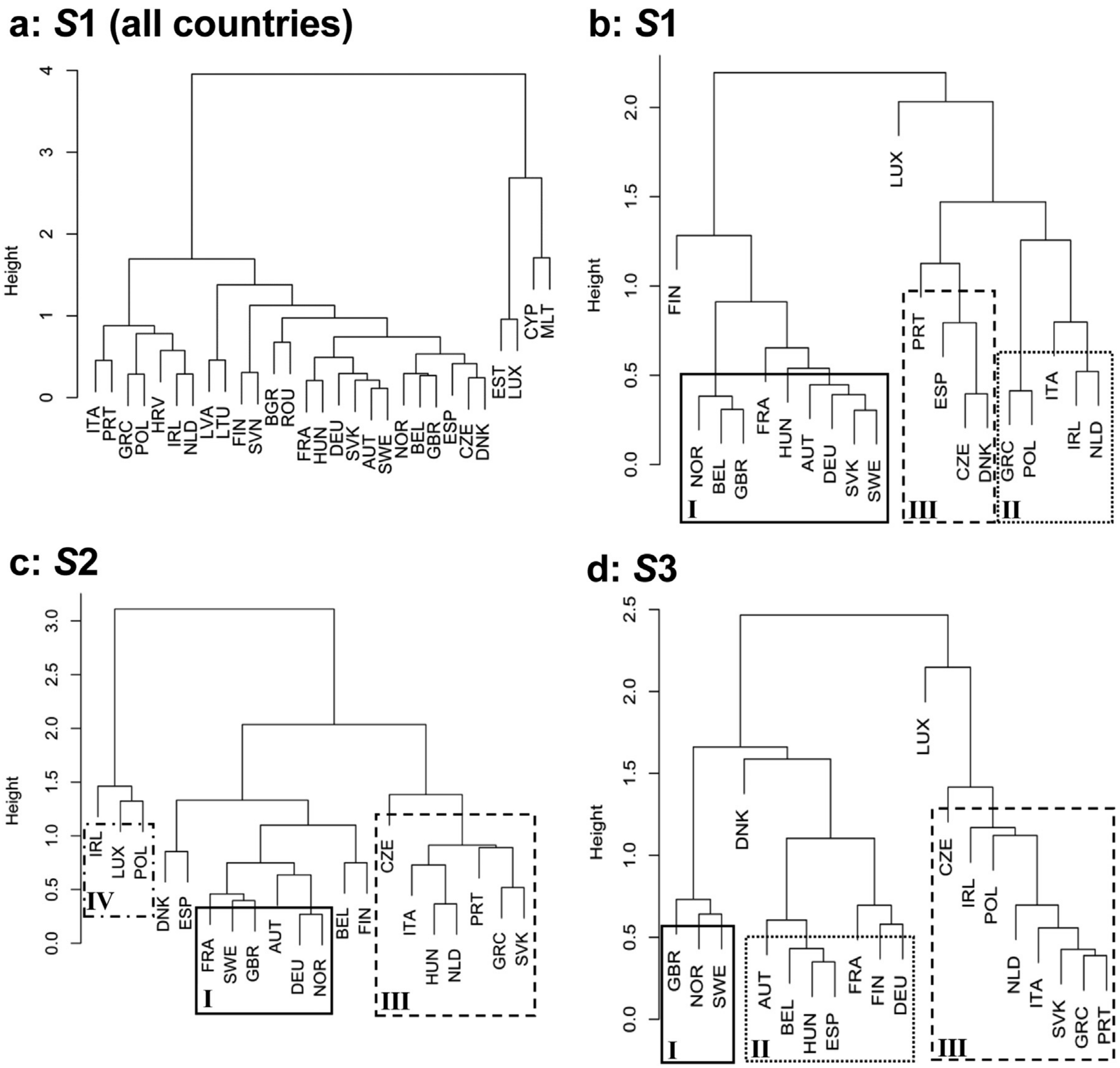

Fig. 3. Hierarchical clustering by Euclidean distance: *S*1 (all countries) (a), *S*1 (excluding non-OECD EU countries) (b), *S*2 (c), and *S*3 (d). Cluster I (solid lines): high performance with smaller changes over time. Cluster II (dotted lines): lower performance than Cluster I but shared similar trends over time. Cluster III (dashed lines): low initial performance with rapid improvement. Cluster IV (chain lines): low performance throughout the study period. Because the countries in panel a differed from those in the other panels, and therefore were not comparable, associated groupings are not shown for this panel. ISO 3166-1 alpha-3 was used for the country codes.

3.2. Results of hierarchical clustering

HC analysis, as discussed in Section 2.2, was implemented to obtain further insights into the patterns of the three energy security indicators observed in the time series. With this analysis, clusters (groups) of countries with similar characteristics in terms of historical patterns (e.g., high/low energy security, experienced large/small improvements) could be identified. Such information is potentially useful for policymakers who refer to examples gleaned from clusters of interest to improve energy supply security in their countries. Identifying groups of countries with similar historical energy security patterns can also facilitate quantitative or qualitative analysis of fundamental factors affecting energy security, while taking the structural differences and unique characteristics of each group into account.

Two clustering approaches were applied to the results of the calculation with the three indicators (for $S1$, this HC analysis was implemented for situations with and without the seven non-OECD countries). Based on the results obtained for each of the three, different groups of countries with similar energy security and time trend patterns were identified. Dendrogram visualization of the HC results facilitates this identification. As shown in Figs. 3 and 4, a dendrogram starts from the individual cases (countries) and builds up a hierarchy of clusters. At each level of this hierarchical structure, clusters from lower levels are merged. Lower-level clusters are more homogenous, whereas clusters formed at upper levels are more heterogeneous. The final grouping of countries was defined through examination of the hierarchical structure of the dendrograms in connection with examination of the input data for countries belonging in the same or nearby clusters in the dendrogram. Figs. 3 and 4 depict the respective results obtained for the Euclidean distance and DTW dissimilarity measures. Each panel shows the clustering based on different energy security indicators. Despite some differences among the results obtained after applying the two clustering methods, common patterns were discernible within the groups. These were interpreted based on examination of the countries' time-series data, as discussed below.

Three main clusters were found. Cluster I (marked with solid lines in Figs. 3 and 4) comprised countries evidencing consistently high levels of energy security (i.e., high energy security performance for all three indicators), but which showed moderate improvements over time. Because the levels of energy security performance in this group were mostly high, their improvement potential was low. The high-performing group for the $S1$ indicator comprised Norway, Belgium, the United Kingdom, France, Hungary, Austria, Germany, Slovakia, and Sweden (Fig. 3b). With application of the DTW, Italy and Finland were then also included (Fig. 4b). High-performing groups for the $S2$ and $S3$ indicators were similar, but contained fewer countries. Thus, the $S2$ group (Figs. 3c and 4c) comprised France, Sweden, the United Kingdom, Austria, Germany, and Norway, whereas some of the same countries were found in the $S3$ cluster; namely, the United Kingdom, Sweden, and Norway (Figs. 3d and 4d), as well as Germany (for the DTW application); however, there were fewer countries in this group. The factors associated with energy security improvement differed by country. For example, while Germany was dependent on fossil fuels (coal, oil, and natural gas) in 1978, its consumption was more balanced compared with that of other EU countries (coal: 36.0%, oil: 46.0%, and natural gas: 13.4%). Moreover, by 2014 Germany had reduced its reliance on fossil fuels (80.2% in total) and was using a higher proportion of nuclear power and several types of renewable energy.

Cluster II (marked in dotted lines in Figs. 3 and 4) contained countries that had pursued a largely similar path to those in Cluster I, reflecting relatively moderate (or inconsistent) improvements over the years. However, the countries Cluster II evidenced lower levels of energy security. Countries in this group face more challenges than those in Cluster I, and therefore should seek to intensify their improvements in the future. Such countries are marked in dotted lines in Figs. 3 and 4. The second group in relation to the $S1$ indicator comprised the Netherlands, Ireland, Greece, and Poland (common to both the Euclidean and DTW groupings), as well as Italy (based on the Euclidean result). Italy, Spain, Belgium, and Finland were incorporated into the $S2$ group based on the DTW results. However, the results obtained with the Euclidean distance measure were less homogeneous, and countries with characteristics such as the ones described above could not be clearly identified. The group relating to the $S3$ indicator comprised Austria, Spain, Belgium, Hungary, Finland, and France (common to both clustering approaches), as well as Germany (based on the Euclidean results).

Cluster III (marked in dashed lines in Figs. 3 and 4) comprised countries with low levels of energy security at the outset of the study period, but that demonstrated considerable improvements over time. For the $S1$ indicator, this group included Portugal, Spain, the Czech Republic, and Denmark. Those in the $S2$ group included Hungary, the Netherlands, Portugal, Greece, Slovakia (common to both clustering approaches), the Czech Republic, and Italy (based on the Euclidean result). For the final indicator, $S3$, the cluster consisted of Greece, Portugal, Slovakia, Italy, the Netherlands, Poland, and Ireland (common to both clustering approaches), as well as the Czech Republic and Slovakia (based on the Euclidean result). As previously discussed, improvements in energy security performance for the countries in this group were mainly attributable to the diversity of their primary energy sources. For example, in the Czech Republic, which featured in this group for all of the indicators entailing both approaches, apart from the $S2$ indicator (DTW approach), the share of coal in 1978 was 71.2% and that of fossil fuels was 99.6% [69]. However, from the mid-1980s, this country incorporated nuclear power, the share of which rose to 18.3% in 2014. Moreover, the share of renewable energy, particularly biomass energy, increased to 7.8% in 2014.

There were some further findings resulting from the HC analysis. As shown in Figs. 3a and 4a, Cyprus and Malta evidenced distinctive characteristics. These two countries had the lowest energy security performance (Cyprus: 0.13, Malta: 0.25) among all EU countries because of their near-total dependence on fossil fuels, especially oil (Cyprus: 97.5%, Malta: 93%), for their primary energy. As shown in Fig. 1, the two countries significantly improved their performance. Whereas Cyprus' energy security gradually improved, Malta's improved rapidly, but subsequently declined. These increases and/or decreases reflect a balance in consumption of the three fossil fuels because the share of non-fossil fuels did not surpass 5%. However, despite the visibly improved energy security, the countries' performance levels are currently ranked lowest among all EU countries because of their continued dependence on fossil fuels. Therefore, they were considered as a separate group.

A final finding relates to the $S2$ indicator. The application of both clustering approaches resulted in identification of a fourth group (Cluster IV) comprising three countries – Poland, Ireland, and Luxembourg – that showed consistently low levels of energy security throughout the study period. The results of applying both clustering approaches for Luxembourg in relation to the other two indicators indicated this country was a special case. Of all the surveyed countries, Luxembourg had the lowest level of energy security for all three indicators, with no notable improvement being observed over time. This is because this country mostly depends on imported fossil fuels (accounting for over 94% during the study period), with high coal consumption in the past (51.6% in 1978) and, currently, high oil consumption (71.2% in 2014) [69]. The diversity of the sources of Luxembourg's fossil fuel imports has also decreased over time [71–73], causing a flattening or decline in relation to the $S2$ and $S3$ indicators.

Based on the above cluster analysis, the first group of countries (Cluster I, marked in solid lines) represents current best practices related to their energy security levels in terms of energy security indicators applied herein. The progress achieved by countries in the third group (Cluster III, marked in dashed lines) is also highly significant, as the actions taken to achieve this progress can serve to guide low-performing countries in improving their future positions. Energy security in terms of energy supply is one of the most important aspects of national energy policies, and the ability to secure an (affordable) energy supply directly relates to the economy. Therefore, the experiences of these countries can be considered as illustrative of ways for EU countries to improve energy security. This is especially applicable to

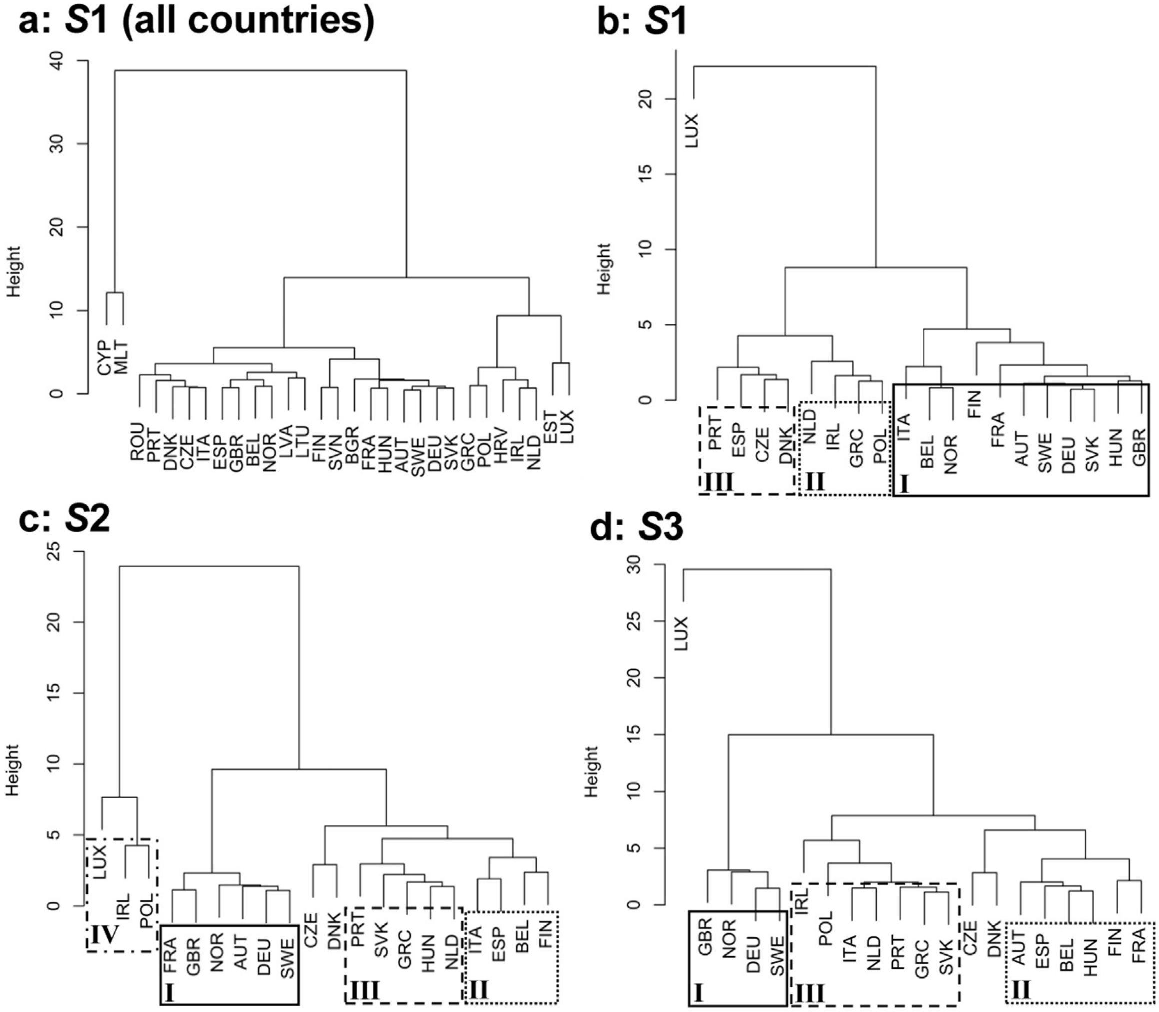

Fig. 4. Hierarchical clustering by dynamic time warping: *S*1 (all countries) (a), *S*1 (excluding non-OECD EU countries) (b), *S*2 (c), *S*3 (d). Cluster I (solid lines): high performance with smaller changes over time. Cluster II (dotted lines): lower performance than Cluster I but shared similar trends over time. Cluster III (dashed lines): low initial performance with rapid improvement. Cluster IV (chain lines): low performance throughout the study period. Because the countries in panel a differed from those in the other panels, and were not, therefore, comparable, associated groupings are not shown for this panel. ISO 3166-1 alpha-3 was used for the country codes.

countries that have not yet succeeded in enhancing their energy security performance as per the results of this study.

4. Conclusions

As energy is an important driver of current economic activities, it is important for countries to secure their energy sources. This is particularly true for EU countries in light of geopolitical considerations and ongoing reforms in the EU energy market. In this context, this study aimed to develop an understanding of how the performance of EU countries with relation to energy security in terms of energy supply has evolved over the past few decades. The energy security performance of these countries (and including Norway) for 1978–2014 were evaluated, applying three energy security indicators in combination with time-series clustering approaches.

The three proposed indicators were based on the Shannon–Wiener diversity index. The study's findings revealed an improvement in EU countries' energy security in 2014 compared with 1978 (1.43–1.50 times higher on average), with few exceptions. Within the EU, Denmark and the Czech Republic presented the greatest improvements for all three indicators. The main driving factor for them among the four factors included in the indicators was diversification of primary energy sources. Furthermore, import-related factors (dependence on foreign energy sources and diversity of origin) were also significant. In contrast, diversity of both primary energy sources and of imports was the primary negative influence on countries' performance (as measured by the three indicators).

In addition to analyzing the evaluation results obtained for the indicators, cluster analysis was performed for EU countries that had similar levels of energy security and trends over time. Three main groups of countries were identified: those with (i) consistently high levels of energy security and showing moderate improvements over time (Cluster I); (ii) lower levels of energy security than the first group and also showing moderate improvements over time (Cluster II); and (iii) initially low levels of energy security and demonstrating significant improvements over time (Cluster III). Countries in the first and third groups were of particular interest. The first group evidences best practices given that these countries' security levels, in terms of energy supply, were highest, whereas the third group is of interest because these countries' policies have helped substantially improve energy supply security and can serve as guides for other countries (e.g., the second group and Luxembourg in our analysis).

Policies have been introduced in the EU to create electricity and gas markets, increase competition, diversify sources and supplies, and reduce consumption and emissions. They aim to increase competitiveness and keep prices affordable while progressing toward a more sustainable energy system, and are equally important for achieving energy security, as the EU is a major energy importer. Thus, with the implementation of the EU's 2020 energy and climate policies, and its energy efficiency and renewable policies, as well as the planned 2030 policies, various measures are being put in place that also address concerns relating to the security of energy source supplies.

Further investigation of application of energy-related scenarios, such as the IEA's World Energy Outlook, to examine how energy security in EU countries will evolve is a compelling topic for deeper research. Examination of the close and possibly synergetic relationship between climate change, energy security, and sustainable development is also needed. Investigation of this relationship is essential for expanding sustainable prosperity at a global scale.

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Appendix A

This appendix shows transition of energy security performance in EU countries by three energy security indicators (Fig. A1). Fig. 1 is based on this information. HC was implemented based on these transitions (see Section 2.2 for the clustering analysis and Fig. 4 for the results).

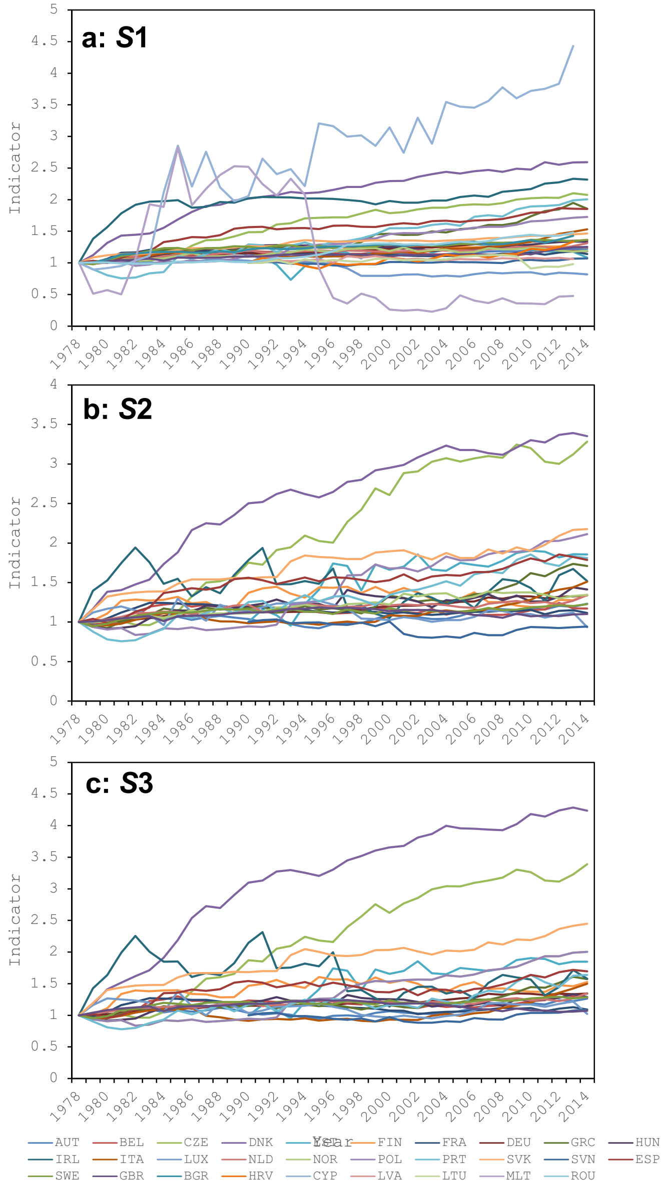

Fig. A1. Transition of energy security performance in EU countries: *S*1 (a), *S*2 (b), and *S*3 (c). Values were scaled to 1 in 1978. Seven non-OECD countries were included in panel a, but not in the other panels. ISO 3166-1 alpha-3 was used for the country codes.

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