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ORIGINAL RESEARCH

Evaluating Energy Security using Choquet Integral: analysis in the southern E.U. countries

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Abstract

The aim of this paper is to introduce a novel approach for assessing the risks to the continuous availability of cost-effective energy sources by proposing a Multi-Criteria Decision Making method that considers the interdependence between the indicators utilised in the measurement process. The paper focuses on Spain and Portugal into the EU energy market and investigates the consequences of their particular conditions. To account for the significance of each criterion and its subsets, the Choquet Integral is integrated into the analysis. The findings demonstrate the effectiveness of this approach in incorporating expert knowledge into Energy Security evaluations, which can be utilised to develop enhancement policies.

Keywords Energy Security · Multi-criteria decision making · Choquet Integral · Climate risk · Risk of poverty

Abbreviations

APERC	Asia Pacific Energy Research Centre
ARPR	At Risk of Poverty Rate
B	Ratio between GDP per capita and the price of a barrel of oil
D	Diesel price
E	Electricity prices for household consumers
EID	Energy imports dependency
ElC pc	Electricity capacity per capita
ElGD	Electricity generation diversity measured by the Shannon index

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En	Electricity prices for nonhousehold consumers
ERD	Energy reserves diversity Shannon index
ES	Energy Security
ESP	Energy Security Performance
ESS rate	Energy self-sufficiency rate
FEC pc	Final energy consumption per capita
G	Gasoline price
GCRI	Global climate risk index
GGpc	Greenhouse gas emissions per capita
IEA	International energy agency
NEI pc	Net energy imports per capita
NG	Natural gas prices for household consumers
NGn	Natural gas prices for nonhousehold consumers
PNEC	National energy and climate plan (Portugal)
PNIEC	National energy and climate plan (Spain)
TES pc	Total energy supply per capita
TREl	Time required to get electricity
UNS&S-CI	Unsupervised and Supervised Choquet Integral
SDGs	Sustainable development goals
ShRWC	Share of renewables in total final energy consumption
ShRWG	Share renewable energy generation
UNFCCC	United Nations Framework Convention on Climate Change
WDI	World development indicators

1 Introduction

Energy Security (ES) has long been a concern for any policymaker. According to Sovacool and Brown (2010), the notion of Energy Security emerged in the early nineteenth century as the mechanisation of warfare accelerated the energy requirements for coal-powered warships and vehicles. These authors present a historical review of political events related to ES issues. Indeed, the development and well-being of a population are strongly linked to the availability of reliable and affordable energy sources. The first attempts to define and measure ES in its modern sense were made at the beginning of the twentieth century when it received special attention from energy policy scholars and professionals. The cause was the shift from local energy sources to imports in industrialised countries.

World War II emphasised the importance of uninterrupted energy supply for national ES even more. And by the mid-century, governments of various nations became aware of the vulnerability posed by the inability of many nations to independently secure sufficient energy resources to meet their increasingly broad and demanding needs.

In that context, and following the war, six European countries (Belgium, France, Italy, the Federal Republic of Germany, Luxembourg, and the Netherlands) signed the Treaty establishing the European Coal and Steel Community (ECSC) in Paris on April 18, 1951 (which would come into effect in 1952 for a period of 50 years). This treaty later evolved into the European Economic Community in 1957 and finally into the European Union in 1993. The main aim was to organise the free movement of coal and steel and ensure unrestricted access to sources of production, essentially guaranteeing energy access for the signatory countries. However, in that same decade of the 1950 s, the coal consumption had begun to decline, replaced by other fuels (oil, gas). Faced with the potential threat of an energy dependence on other countries, in the pursuit of securing supply, the six countries of the ECSC signed, in Rome in 1957, along with the Constitutive Treaty of the European Economic Community (EEC), the Treaty of the European Atomic Energy Community (EAEC or Euratom), whose strategic objective was to promote research on the emerging atomic energy and to achieve supply security for the EEC.

Notwithstanding, among all the signing countries, only France firmly decided to opt for this path, designing a complex system of electricity generation from nuclear power plants, whose high production costs and possible accidents discouraged the rest of the countries, which chose oil as their energy source instead; oil was abundant, cheap, and readily available in a stable market.

Concern about ES increased sharply in the 1970s following supply disruptions and price volatility, which resulted from the OPEC oil embargoes in 1973 and the Iranian revolution in 1979.

Returning to the European Union there was no common energy policy in the aftermath of these crises. Why? Mainly due to the rejection of several Member States, which considered energy to be a "strategic asset", prioritising a nationalist vision of the different energy models of each nation: type of market, composition of primary energy, supply sources, efficiency and so forth. However, at that time, the confluence between energy policy and environmental policy was being consolidated, which, curiously enough, was not considered "strategic" by the majority of Member States (which posed a contradiction when legislating or recommending on ecological issues, knowing the impact it should have on national energy aspects).

But it was not until the Treaty of Lisbon of 13 December 2007 that common energy policies began to be established in a specific title on energy (Title XX). The document "An Energy Policy for Europe"[1] (European Commission, January 2007) is where the concept of strategic supply security is consolidated, although it had already appeared six years earlier in the draft of the Commission's Green Paper of November 29, 2000, "Towards a European strategy for the security of energy supply".[2]

"The European Union's long-term strategy for energy supply security must be geared to ensuring, for the well-being of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development, as enshrined in Articles 2 and 6 of the Treaty on European Union".

This definition did not come to fruition, despite (or perhaps because of) incorporating the three main aspects: sustainability, competitiveness, security of supply and including all actors: consumers (citizens, enterprises, industries, and so on), producers (market, industrialists) and regulators (welfare, affordability, environmental requirements, sustainable development).

In 2014, the European Council identified the creation of an energy union as one of the main priorities of the EU, which was a consequence of the rise of various types of gas supply problems. In 2015, the Energy Union Strategy (2015) was published, which aims to provide EU consumers with a secure, sustainable, competitive and cheap energy supply. At the same time, the entire energy system is to be ultimately environmentally neutral by 2050 (Tutak & Brodny, 2022).

[1] https://eur-lex.europa.eu/EN/legal-content/summary/an-energy-policy-for-europe.html.

[2] https://op.europa.eu/en/publication-detail/-/publication/0ef8d03f-7c54-41b6-ab89-6b93e61fd37c/language-en., which was not published in the Official Journal and contains one of the best definitions of Energy Security:

The International Energy Agency (IEA) defines Energy Security as the uninterrupted availability of energy sources at an affordable price. Energy Security has many aspects. Long-term Energy Security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term Energy Security focuses on the ability of the energy system to react promptly to sudden changes in the supply–demand balance.

A consensus regarding the definition of ES (see, e.g. (Axon & Darton, 2021)) has yet to be reached due to its context dependence. This concept has evolved into a wide variety of fragmented interpretations in scholarly and policy literature where ES means different things in different countries and for different people. An influential skin for classifying ES consensus proposed by the Asia Pacific Energy Research Centre (APERC) in 2007 includes what is called the 'four As' of Energy Security: Availability (geological and physical elements), Accessibility (geopolitical elements), Affordability (economic elements) and Acceptability (social and environment elements). These 'four As' have given rise to different interpretations; in particular, they reflect the issues related to energy reserves, infrastructures, pollution, prices and political interest, among other things. This broadened approach has become the basis for our empirical study, where 21 ES indicators were selected within the included four dimensions. However, we emphasise that the methodology presented applies to alternative definitions of ES.

The aim of this paper is to propose a process for evaluating ES taking into account a plurality of indicators related to the set dimensions for ES. The complex concept that encompasses ES in all its different definitions should be measured by a dashboard of suitable indicators. The non-aggregate handling of the set of indicators implies a complicated interpretation, and it would be very difficult for policymakers to identify common trends among various individual indicators. For ease of understanding and comparison, a possible solution would be to aggregate the entire plethora of indicators into a composite index. The construction of such indexes has been used in many research areas. In addition, global institutions (e.g. the OECD, the World Bank, the EU, etc.) have widely used these types of measures (Greco et al., 2019). The most critical steps in the construction of a composite index refer to the weighting and aggregation of the individual indicators. A crucial aspect in both steps is the degree of intervention of the decision-maker/expert/stakeholders, from no intervention applying data-driven methodologies based on statistical techniques such as, for example, principal components analysis or entropy, to more interventionist methodologies with a key role of the decision maker (DM) (e.g., in the Analytic Hierarchy Process (AHP)). Indeed, there is not an ideal weighting methodology. On the contrary, it is up to the modeller to choose a weighting system that is best fitted to the goal of the construction.

Multi-criteria decision-making (MCDM) techniques have been extensively used to build composite indices (Liern & Pérez-Gladish, 2022). Specifically, MCDM methodologies allow for explicitly identifying the relevant criteria of each ES dimension and the integration of said criteria into the decision-making process (Belton & Stewart, 2010). However, in most MCDM studies applied to ES, it is assumed that criteria are mutually independent, while in practice, they are interrelated. The use of the Choquet Integral (CI) with non-additive measure (Choquet, 1953; Grabisch et al., 2008; Abastante et al., 2018; Duarte, 2018; Pelissari & Duarte, 2022; de Oliveira et al., 2022; Divsalar et al., 2022) offers the possibility of including interactions between criteria in the aggregation process, which serves to improve the modelling. The choice of the CI solves the two critical steps mentioned above. First, the weighting system is based on considering the importance of each subset of criteria and, therefore, allows to model synergies between criteria and, second, an aggregation operator based on a CI discrete. To highlight the relevance of aspects related to synergy and redundancy, we consider, for example, two indicators. The first is the share of renewable energy in total final energy consumption, and the second measures CO2 emissions. In this case, there is a redundancy between the two indicators since one can expect that a significant participation of renewable energy in energy consumption yields a decrease in CO2 emissions. Therefore, in this case, to avoid an over-evaluation, it is reasonable to reduce the score that the usual weighted sum would give. By contrast, the case of synergy occurs when one faces the two As representing Affordability and Acceptability. This is a case of synergy between the two criteria; hence, it appears natural to give a bonus if there are good performances for both As.

The price of enriching the model by abandoning the preferential independence hypothesis is that it could significantly increase the cognitive effort of the DM. Here, assigning a measure to each subset of indicators is necessary. Such measure must verify the monotonicity property that models the rationality that any subset of indicators containing another has a greater or equal measure. As mentioned above, there are two main ways of approaching the determination of the necessary parameters. Unsupervised methods have advantages; for example, the output does not contain any degree of subjectivity, and are comfortable for the developer, as the inquiry to the DM is not required. Of course, these advantages become disadvantages if the incorporation of expert knowledge in the evaluation is considered valuable. More modelling effort is required when a supervised method is applied. However, given the complexity and geographical and chronological dependence of the concept of Energy Security, we consider it advantageous that our proposal can allow expert knowledge in the evaluation. In the context of the supervised CI methods, it is necessary to have previous information about the behaviour of the alternatives. This is a drawback to our proposal since we do not have that information. As discussed below, our contribution overcomes this obstacle and makes modelling more flexible, allowing comparison between evaluations driven exclusively by data and those in which expert intervention exists.

In this study, we propose a supervised method combined with the unsupervised one proposed by Rowley et al. (2015). Firstly, an initial capacity is obtained based on principal components analysis. This proposal objectively carries out the whole estimation and uses no external information about the searched capacity. The second step is devoted to identifying a capacity that verifies as far as possible preferential information ((the country situation)) and is 'close' to the CI scores found in the first step. This capacity is the necessary input for applying the CI to the Energy Security assessment to obtain a global score for each country. To the best of our knowledge, we are unaware of any previous study that combines the methodology described above with CI for this specific topic. Furthermore, this combination provides a framework for an optimal design of policies.

The proposed methodology takes advantage of the assignment of indicators to the ES dimensions to build a hierarchical structure in the evaluation process. In the first stage, we score each country in the considered dimensions. In the second stage, an aggregation process of the evaluated dimensions is carried out that considers each country's situation measured by public access indices. Specifically, we have used the Global Climate Risk Index (GCRI) and the At Risk of Poverty Rate (ARPR). We have defined four profiles based on the scores on these two indices, and each country is classified in one of these four profiles. Then, the supervised capabilities are built according to these profiles that determine the preferences on the ES dimensions.

Our proposal allows several strategies: a pure unsupervised evaluation is available, a mixed unsupervised and supervised evaluation and a pure supervised evaluation. Also, a feature of our method is related to the nature of the interactions, they can be data-driven or set by the DM.

We summarise our contribution in the following points. We have proposed modelling the interactions between ES indicators. We have overcome the difficulty of applying the CI in the evaluation of ES of countries by proposing a hybrid methodology between modelling without expert information and with it. The methodology makes it possible to assess Energy Security by considering each country's behaviour in matters that affect the dimensions of ES.

In this paper, we apply the methodology described above to analyse the evolution of ES in the Iberian Peninsula. In order to compare with the situation of other Mediterranean countries, we build a panel composed of three more countries, two of them belonging to the EU, France and Italy, and Turkey.

The situation of the Iberian Peninsula is more adverse than it is in the EU as a whole (Sovacool & Brown, 2010) since neither Spain nor Portugal have reserves of oil or natural gas, and their geographical position makes gaining full access to the internal European market more difficult. This leaves these countries with the EU's highest energy dependency rates. For this reason, the National Energy and Climate Plan for the period 2023-2030, called PNIEC (2020) in Spain and PNEC (2020) in Portugal, comply with Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the governance of the Energy Union and Climate Action, proposed by the Spanish and Portugal Governments aim to reduce this rate by 15 pps and 35 pps by 2030, respectively, mainly through a reduction in energy intensity and greater use of renewable energies.

Primary energy production in Spain and Portugal is practically based on renewable energies, and solid bio-fuels stand out in both cases, followed by wind energy. At this time, the governments of Spain and Portugal have requested the EU to implement a measure to improve the affordability of their energy (limiting the price of gas). These policies are criticised from several forums because it is argued that they introduce rigidity in the energy market. Our work entails comparing our findings with neighbouring countries like France and Italy. Additionally, we analyse Turkey as a country with distinct characteristics from the four previously studied. For these countries, 21 ES indicators have been obtained for the 4As for the period 2017–2020, the last year in which data for the chosen indicators were available. These chosen indicators have allowed us to identify the strengths and weaknesses of each country's energy system and the potential areas for improvement. According to them, the results display that France has a high level of ES in terms of Availability, Accessibility and Affordability but faces some challenges in terms of Acceptability. France has a target to reduce the share of nuclear energy in its electricity mix to 50% by 2035 and to increase the share of renewable energy to 40% by 2030. Also, it strongly focuses on reducing greenhouse gas emissions and air pollution to ensure the energy transition. [3] On the opposite side, Portugal has to improve in Availability, Accessibility and Affordability. However, it has a high Acceptability of its energy system thanks to its expanding renewable generation. According to IEA (2022), Portugal has developed a broad policy framework with robust measures to achieve emission reductions. Italy has to improve on Acceptability and Accessibility. However, Italy has always achieved good results in Availability, a dimension with poor performance in Spain, Turkey and Portugal. Spain has improved considerably in 2020 in Acceptability, on the contrary, this dimension has suffered a sharp deterioration that year in Turkey.

The rest of this research is organised as follows. The next section presents a literature review that provides the motivation for this research. The methodology is presented in Sect. 3. The empirical application is described in Sect. 4. Section 5 concludes.

[3] https://www.iea.org/reports/france-2021/executive-summary.

2 Literature review

Related studies published from 2018 to 2022 were extensively reviewed, both the ones where the definition of Energy Security was analysed (see Azzuni and Breyer (2018), Axon and Darton (2021), Esfahani et al. (2021) and references therein) and the works where Energy Security was indeed evaluated. Studies with Energy Security evaluations are summarised in Table 1. Models based on Multi-Criteria Decision Making (MCDM) methods are predominant. Several authors use classical multi-criteria methods such as weighted arithmetic and geometric means, while others apply more recent methodologies. Among the first, Amin et al. (2022) analysed Bangladesh's Energy Security level using the 4As framework for 2014–2019. They normalise the data of the indicators by the min–max method. From normalised data, exploratory analysis is carried out. Azzuni and Breyer (2020) propose a methodology for preparing the Energy Security index based on 15 dimensions. It was highlighted that due to the heterogeneity across countries, single-approach techniques to improve Energy Security across the globe should be avoided. Bekhrad et al. (2020) compared the Energy Security variables of Andalusia with those of Spain, Estonia, Latvia, Lithuania, Poland, and Slovenia. To facilitate the comparison, they calculated the normalised values of 12 Energy Security variables for each country and used the arithmetic mean of the indicators within each aspect (reliability, affordability, and sustainability). In their study, Fuentes et al. (2020) developed a composite index using a normalisation method that calculated the ratio to a reference level. They used the equal weight model to assign the same weight value to each variable within the index. The aggregation process was conducted by applying a weighted geometric mean. Coutinho et al. (2020) applied an Energy Security index adjusted to the context of Cape Verde using a weighted average mean calculation method. They used the Delphi method to obtain the weighting system by surveying key actors in Cape Verde's energy sector. Sixteen individuals were interviewed in total in two rounds of the survey. In the first round, the panellists were asked to distribute 100 points among the five dimensions of Energy Security used by the authors, whereas, in the second round, the panellists had access to the average scores of the first round, which were converted into weights and used for calculating the index. The compound weight of each component was determined by multiplying its weight by the weight of its corresponding dimension. Alternatively, Tutak and Brodny (2022) belong to the second group of papers using state-of-art MCDM methodologies and suggest utilising a combination of the Grey Relational Analysis with CRITIC, Entropy, and Standard Deviation methods to derive weights for the 17 indicators that define the Energy Security of analysed nations across economic, environmental, energy, and social dimensions. Fuzzy AHP is used by Zhang et al. (2021) to assess the significance of dimensions and indicators and the hybrid model of Grey Relation Analysis (GRA)-TOPSIS is introduced to evaluate Energy Security performance. Further, a qualitative root cause analysis is conducted with the Why-Why Diagram to identify the possible causes affecting Energy Security. Ziemba et al. (2021) seek to establish a novel approach to evaluate current and future Energy Security issues based on a complex security index supported by the computationally transparent fuzzy multi-criteria decision analysis method. The utilisation of fuzzy MCDA methods allows for the quantification of uncertainty in evaluations and forecasts. The forecasts, which were generated using Holt's method, relied on the International Energy Security Risk Index as the primary data source.

Regression methods are used by Bamisile et al. (2021), Podbregar et al. (2020), Le and Nguyen (2019), Lee et al. (2022), Gong et al. (2021), Wang et al. (2020). Bamisile et al. (2021) construct the dynamics of China's Energy Security index and analyse using comprehensive functional data analysis (FDA) techniques. The Energy Security indices of 30 provinces in China between 2004 and 2017 are considered. The main goal of the study by Podbregar et al. (2020) is to analyse the reliability of the International Energy Security Risk Index. The Index is composed of 29 aggregated variables (grouped into eight categories), and the research is conducted on a research sample of 25 countries over 36 years. The reliability assessment is performed using Multiple Regression Analysis—the methodological validation involves conducting Multicollinearity tests, including a Multicollinearity test with Variance Inflation Factors. The test results indicate the Index's high degree of unreliability based on the observed errors. These errors primarily relate to a high degree of multicollinearity in all variables, whereby independent variables lose their independence and thus jeopardise the reliability of the total Index.

Another set of studies employs Principal Component Analysis (PCA). Abdullah et al. (2020) assess Pakistan's Energy Security performance based on a study of its Energy Security index during 1991–2018. The indicators were normalised using the z-score method and weighted based on PCA. Supply, consumption and import indicators played a key role in the Energy Security performance in the studied period.

Filipović et al. (2018) present a method of measuring Energy Security that includes economic and environmental indicators and the political and social aspects within the composite indicator of country risk. The new Energy Security Index is constructed applying PCA. Analysis of the values of a new indicator shows that Energy Security is greatly influenced by GDP per capita, country risk, carbon intensity, energy intensity, final energy consumption per capita and electricity prices; the geographical scope of application is the European Union. Karatayev and Hall (2020) develop an Energy Security estimation model applying a methodology of integrated estimation: a multiplicative form of the integrated index, a formalised definition of the safe existence limits in order to provide scientific substantiation of the threshold vector, a modified rationing method, the PCA method and the sliding matrix method to substantiate dynamic weighting coefficients. Wu et al. (2021) introduce an evaluation technique based on the integrated application of PCA and Data Envelopment Analysis - Assurance Region (DEA-AR) for determining the Energy Security Performances (ESPs) of each country was proposed. In addition to the ESP results and rankings for 125 countries, a cluster analysis was conducted based on the ESP trend results, with the main objective of identifying a benchmark group of countries.

3 Methodology

As indicated already, in this study, an MCDM methodology based on Choquet Integral is used to assess countries' Energy Security. The methodology runs in two phases. Firstly, a capacity is identified according to data behaviour. Secondly, a distance minimisation process is applied to find a capacity close to the one previously found, verifying several constraints established by the expert on the importance of the indicators and interactions among them.

3.1 Choquet Integral

Let $X = \{a_1, ..., a_m\}$ be a set of alternatives (countries in this study) and a set $C = \{c_1, ..., c_n\}$ of characteristics/criteria over which alternatives are evaluated. In this context, each country $a_k \in X$ is identified with its profile of partial scores $s^k = (s_1^k, ..., s_n^k)$ with s_i^k taking a value between 0 and 1. In multi-criteria decision-making (MCDM), a search is undertaken

Table 1 Energy Security: previous studies

Author	Region	Technique	Research purpose
Abdullah et al. (2020)	Pakistan	Normalisation (z-score) and weighting (PCA)	Pakistan's Energy Security performance based on a study of its Energy Security index during 1991–2018 is assessed via 22 indicators
Amin et al. (2022)	Bangladesh	Linear transformation to normalise indicators	Compare and quantify the Energy Security level (4As) in Bangladesh between 2014 and 2019
Azzuni and Breyer (2020)	229 World countries	Normalisation	Create an Energy Security index comprehensive on a global scale using 78 indicators
Bamisile et al. (2021)	China	Functional regression models	Analysis of Energy Security index of the provinces in China (2004–2017) and the effect of investment in energy sector on these indices
Bekhrad et al. (2020)	Andalusia (Spain)	Normalisation of 12 indicators grouped in 3 aspects and aggregation by arithmetic mean	To evaluate Andalusia's renewable energy potential and its impact on the security of energy supply
Brodny and Tutak (2021)	Central EU	MCDM: TOPSIS, VIKOR, MOORA and COPRAS)	Study and assess the level of sustainable energy development in the Central and Eastern European Countries using 21 indicators between 2008 and 2018
Coutinho et al. (2020)	Cape Verde	Multi-criteria analysis and the Delphi survey	Develop an Energy Security index adjusted to Cape Verde
Filipović et al. (2018)	EU-28	PCA to create the Index and Kruskal–Wallis test for evaluating the relationship between Energy Security and macroeconomic stability	Create new Energy Security index including social and political aspects to rank EU-28 for the period 2006-2015
Fuentes et al. (2020)	Argentina	Normalisation, Weighting and Aggregation	Develop, apply and compare (to 2002) a tool based on the Power System Security Index, for the evaluation of policies affecting the security of the supply of electrical energy
Gong et al. (2021)	China	Functional data analysis entropy weight method	Quantitatively measure the Energy Security levels of 30 provinces in China from 2004 to 2017

Table 1 continued

Author	Region	Technique	Research purpose
Gong et al. (2021)	China	Weighting methods	Evaluate Energy Security by constructing a comprehensive Energy Security index based on the Belt and Road countries' data during the period from 1995 to 2017
Karatayev and Hall (2020)	Russia	Normalisation (z-score)	Comparison of the Energy Security performance in six Caspian Sea countries individually and collectively
Kharazishvili et al. (2021)	Ukraine	A multiplicative form of an integrated index, the combined rationing method, and dynamic weights by a combination of a PCA method and a 'sliding matrix' method	To support strategic scenarios of the future security situation of the energy sector in the context of sustainable development, determining the relevant macro indicators in each year for a given perspective
Le and Nguyen (2019)	74 countries	Panel data analysis	Examine from a benchmark model based on an extended version of the Cobb-Douglas whether Energy Security contributes to economic growth for a global sample of 74 countries covering the period from 2002 to 2013. Conduct the panel data analysis on subsamples of countries based on different income levels
Lee et al. (2022)	68 countries	Dynamic panel threshold approach	Explore via global panel data the relation between Energy Security and income inequality by analyzing whether income distribution is affected by 6 indicators selected for 68 countries over 2001–2018
Li et al. (2019)	19 G20 countries	Weighting (PCA) and Aggregation	Universal, multidimensional index system and comparing Energy Security systems of different countries using 14 indicators
Lin and Raza (2020)	Pakistan	MARKAL model	Estimation of Energy Security indicators for long-term energy supply using 11 indicators
Malik et al. (2020)	Pakistan	Normalisation and average	Analyze Pakistan's Energy Security under the 4-As framework over the six-years period 2011-2017 with 16 indicators

Table 1 continued

Author	Region	Technique	Research purpose
Podbregar et al. (2020)	25 OECD countries	Stepwise regression, principal component analysis, and Promax oblique rotation	Analyze model settings of the International Energy Security Risk Index developed by the U.S. Chamber of Commerce, covering data for 25 countries over the period 1980–2016
Ragulina et al. (2019)	Russia	Normalisation (z-score)	Analysis of Energy Security performance made by the Russian Federation in 1990-2015 based on an aggregated index that includes 12 indicators across four dimensions
Razmjoo et al. (2019)	12 countries	Normalisation and Correlation	Present new 17 effective indicators to enhance sustainable energy development index
Shah et al. (2019)	South Asian countries	Multiplicative Data Envelopment Analysis (MDEA)	Develop a new index, i.e., Energy Security and Environmental Sustainability Index, which combines 11 energy and environmental indicators over the period 2006–2017
Song et al. (2019)	China	Normalisation, Weighting and Aggregation	Introduction of a new aggregated indicator to the China Energy Security index, for evaluating how China's Energy Security has changed over years
Stavytskyy et al. (2021)	RF, EU, USA, China, UK	Geometric mean and clustering	Develop a methodology for calculating the Energy Security index of a state, based on 29 indicators, according to the World Bank data from 1991 to 2019
Tutak and Brodny (2022)	European Union (EU-12)	Multi-criteria decision methods: The Grey Relational Analysis	To determine the level of Energy Security in the Three Seas Initiative countries in relation to the EU energy and climate and social policy

Table 1 continued

Author	Region	Technique	Research purpose
Wang et al. (2020)	China	Functional Data Analysis (FDA) method	A dynamic Energy Security index for China by introducing FDA techniques into the Energy Security Index calculation, including 17 indicators over 2000–2017
Wang et al. (2021)	China	GPCA	An evaluation index system for regional energy economic security is constructed over the period 2009–2017
Wang and Zhan (2019)	China (30 provinces)	Weighting (PCA)	Construction of an evaluation index system of regional energy economic security from four dimension, based on panel data of 30 provinces in China from 2009 to 2017
Wu et al. (2021)	125 countries	PCA and data envelopment analysis (DEA)	This study sought to assess Energy Security performances of countries over a long period of time
Yang et al. (2022)	China	DPSIR (Driving forces-Pressures-State-Impacts-Responses) and entropy weight TOPSIS models	To construct an index system and use TOPSIS model to comprehensively evaluate the index system, so as to accurately grasp the Energy Security situation in China
Yuan and Luo (2019)	China	Multi criteria decision making method based on set pair analysis and TOPSIS	Evaluating Chinese provinces Energy Security, analyzing reasons and providing policy implications using 14 indicators from 2013 to 2017
Zhang et al. (2021)	China	Fuzzy AHP, GRA-TOPSIS and Why-Why diagram	To establish a methodological framework based on quantitative and qualitative approaches for measuring and improving Energy Security from a broad sense
Ziemba et al. (2021)	25 countries and the OECD as a group	Fuzzy MCDA	Develop a new approach for assessing current and future Energy Security issues based on a complex security index based on data from 1980 to 2015

to obtain a global utility $M(s^k)$ that associates a real number for any alternative. The form of the global utility function M depends on the hypotheses on which the MCDM model is based. When mutual preferential independence (see, e.g., Vincke (1992) and Kojadinovic (2007)) for criteria is being assumed, frequently the global utility function is additive and takes the form of a weighted arithmetic mean. This operator gives a global score for the profile $s = (s_1, ..., s_n)$ according to:

$$M_w(s) = \sum_{i=1}^{n} w_i s_i \tag{1}$$

where $w_i \geq 0$ is the weight of criterion c_i and $\sum_{i=1}^{n} w_i = 1$.

However, mutual preferential independence is rarely verified in real applications (Keeney & Raiffa, 1976; Pasi et al., 2019). In order to model the interaction among criteria, it has been proposed to substitute a monotone set function on C, called capacity (Choquet, 1953) or fuzzy measure (Michio, 1974), for the weight vector appearing in the calculation of the weighted arithmetic means (1). Using a capacity function involves considering the importance of each subset of criteria. A natural extension of the weighted arithmetic mean in such a context is the Choquet integral w.r.t. the defined capacity (Grabisch, 1996; Marichal, 2000; Grabisch & Labreuche, 2016).

The definition of a fuzzy measure as a set function with the monotony propriety with respect to the inclusion is set out as follows.

Fuzzy measure or capacity
Let $P(C)$ be the power set of C, a fuzzy measure fuzzy on the set C is a function $\mu : P(C) \to [0, 1]$ verifying $\mu(\emptyset) = 0$, $\mu(C) = 1$ and for any $S \subseteq T \subseteq C$ implies $\mu(S) \leq \mu(T)$, for any subset of criteria S, $\mu(S)$ can be interpreted as a measure of the importance of the combination of criteria included in S. In this way, by replacing the vector of weights w with a fuzzy measure μ, it is possible to represent the importance of each subset of criteria rather than working solely with the individual importance of the criteria. The capacity allows modelling the magnitude of the interaction between criteria. For any pair of criteria (c_i, c_j), the difference between $\mu(c_i, c_j)$ and $\mu(c_i) + \mu(c_j)$ reflects the degree of interaction between c_i and c_j. If the capacity of the pair (c_i, c_j) is greater than the sum of the two individual capacities, then there is a positive interaction. Otherwise, the interaction will be negative, or if equality is achieved, there will be no interaction between the two criteria. As we discussed earlier, the Choquet integral is an appropriate aggregation operator for the criteria interaction, and it generalises the weighted average.

The Choquet integral of the vector s^k with respect to the capacity μ is defined by

$$C_\mu(s^k) = \sum_{i=1}^{n} (s^k_{(i)} - s^k_{(i-1)}) \mu(A_{(i)}) = \sum_{i=1}^{n} s^k_{(i)} (\mu(A_{(i)}) - \mu(A_{(i+1)})) \tag{2}$$

where $s^k = (s^k_1, ..., s^k_n)$ is the profile of country a_k on n criteria; and the sub-index (i) is a permutation of the indices $i = 1, ..., n$ such that $0 \leq s^k_{(1)} \leq ... \leq s^k_{(n)}$ with $s^k_{(0)} = 0$ and where $A_{(i)} = \{c_{(i)}, ..., c_{(n)}\}$.

Below, we show some indices associated with a capacity which are useful in interpreting the interactions between criteria and allow alternative formulations of the Choquet integral. The importance of a criterion depends not only on that criterion at the individual level, but the contribution it makes towards the rest of the criteria in which it participates is also important.

The relevance of the criterion is not determined only by its capacity but also by the capacities of all the subsets containing that criterion. For this reason, it is necessary to introduce the definitions of the importance of a criterion and the interaction index for each pair of criteria. Shapley (1953) proposed a coefficient that measures this importance.

Shapley value
Let μ be a capacity, the Shapley index S_μ for a criterion c_i with respect to μ is defined as follows:

$$S_\mu(c_i) = \sum_{A \subseteq C - \{c_i\}} \frac{(n - \#A - 1)!\#A!}{n!} [\mu(A \cup \{c_i\}) - \mu(A)] \tag{3}$$

where A is any set of criteria that does not contain c_i; $\#A$ is the cardinal of A. The factorial normalises the values, such that $\sum_{i=1}^{n} S_\mu(c_i) = 1$. The Shapley value of μ is the vector $v(\mu) = (S_\mu(c_1), ..., S_\mu(c_n))$.

The Shapley index $S_\mu(c_i)$ can be interpreted as a kind of average value of the marginal contribution $\mu(A \cup \{c_i\}) - \mu(A)$ of the criterion c_i to a subset A that does not contain it. Therefore, the Shapley index expresses the relative importance of a single criterion within the decision problem (Marichal & Roubens, 2000). The information provided by the Shapley importance index should be complemented with information on the interaction among criteria to accurately describe the decision problem. It is possible to distinguish three kinds of interaction. A positive interaction between two criteria is present when the importance of a single criterion is very small, but the importance of the pair is large. The criteria are called complementary. A negative interaction is present when the coalition of criteria has no effect, and the importance of the pair is almost the same as the importance of the single criteria. The criteria are called redundant. Lastly, the importance of the pair is more or less the sum of the individual importance of each criterion, in this case, referred to as independent criteria.

Shapley interaction index (Murofushi & Soneda, 1993)
The phenomenon of interaction between criteria c_i and c_j can be detected from the difference:

$$\left[\mu(A \cup \{c_i, c_j\}) - \mu(A \cup \{c_i\})\right] - \left[\mu(A \cup \{c_j\}) + \mu(A)\right]$$

for any subset of criteria $A \subseteq C - \{c_i, c_j\}$. If the marginal contribution of c_j to every coalition of criteria that contains c_i is greater (resp. less) than the marginal contribution of c_j to the same combination when c_i is excluded, then the above expression is positive (resp. negative), and the criteria c_i and c_j are called complementary. This difference is called the marginal interaction between c_i and c_j, subject to the presence of criteria of coalition A. Setting

$$(\Gamma_{\{c_i, c_j\}}\mu)(A) = \mu(A \cup \{c_i, c_j\}) - \mu(A \cup \{c_i\}) - \mu(A \cup \{c_j\}) + \mu(A), \tag{4}$$

the Shapley interaction index I_μ of the pair of criteria c_i and c_j with respect to the capacity μ is defined by:

$$I_\mu(c_i, c_j) = \sum_{A \subseteq C - \{c_i, c_j\}} \frac{(n - \#A - 2)!\#A!}{(n - 1)!} (\Gamma_{\{c_i, c_j\}}\mu)(A) \tag{5}$$

Analogously to the Shapley index, the Shapley interaction index between two criteria, c_i and c_j, can be interpreted as an average value of their marginal contributions.
It is important to note that the Shapley interaction index takes values between -1 and 1, with the value 1 (resp. -1) corresponding to the maximum complementarity (resp. redundancy). The presentation of the Choquet integral's basic tools highlights the need for a capacity function. The capacity identification is a problem in practical applications. Several approaches have been proposed to deal with this problem (e.g., Lourenzutti et al. (2017) and references therein).

3.2 Our proposal: capacity identification process

In order to determine the capacity that intervenes in the calculation of Choquet's utility integral, we propose to use a supervised method combined with the unsupervised method proposed by Rowley et al. (2015). Therefore, our identification process is carried out in two steps. Firstly, an initial capacity is obtained using principal components analysis.

Unsupervised methodology
Rowley et al. (2015) use Pearson correlation matrices, which describe the correlation between criteria in the following way. Let R_S be the correlation matrix between the criteria of a coalition $S \subseteq C$ calculated from a sufficient number of profiles. Then, the eigenvalues of R_S, λ_q, are used for defining $\mu(S)$ according to the following ratio:

$$\mu(S) = \frac{J(S)}{J(C)} \tag{6}$$

where $J(S) = \sum_{\lambda_q < 1} \lambda_q + \#(\{\lambda_q / \lambda_q \geq 1\})$. The amount $J(S)$ provides an estimation of the number of non-interacting criteria within the coalition S. Rowley et al. (2015) that the ratios $\mu(S)$ determine a capacity for the set C by applying the Cauchy Interlace theorem (Hwang, 2004). The resulting algorithm is very efficient regarding computational complexity (Duarte, 2018). This proposal carries out the whole estimation objectively, and it does not use any external information about the searched capacity (unsupervised method).

Supervised methodology
The second step is devoted to identifying a capacity that reflects, as far as possible, the expert's opinion and, moreover, is 'close' to the capacity found in the first step. The approach is based on a minimum quadratic distance principle (Kojadinovic, 2007).

Our supervised method uses three types of inputs: the corresponding overall scores for each country, additional linear constraints expressing the importance of criteria and interaction between them and a capacity function. The overall score of each country is the Choquet integral w.r.t. the capacity determined in the first step.
The schedule of the unsupervised and supervised Choquet Integral (UNS&S-CI) methodology
According to what was stated above, the method is executed according to:
Step I: Unsupervised identification

1. Identify an unsupervised capacity on each set of criteria related to the corresponding concept (either indicators within each dimension or the dimensions themselves: Availability, Affordability, Acceptability, Accessibility) using the Rowley-Geschke-Lenzen (R-G-L) method: μ_{RGL}.
2. Calculate the Shapley value for each selection criterion corresponding to the R-G-L capacity determined in Step I.1.
3. Calculate the Choquet integral for the corresponding concept of each country w.r.t. the capacity obtained in Step I.1: $C_{\mu_{RGL}}(s^k)$.

Step II: Supervised identification

1. Set linear constraints for the Shapley values for significant criteria.
2. Identify a supervised capacity, μ_{mdci}, using the minimum distance capacity identification (m.d.c.i) method (Kojadinovic, 2007; Grabisch et al., 2008) for minimising the sum of squared distances between overall scores obtained in Step I.3, $C_{\mu_{RGL}}(s^k)$, and the output of the Choquet integral for those profiles, $C_{\mu_{mdci}}(s^k)$ verifying the constraints set in II.1.

3. Calculate the Shapley indices for the criteria.
4. Rank the countries for each concept from the overall scores $C_{\mu_{mdci}}(s^k)$.

3.3 Our proposal: a procedure in two stages

Following the proposal detailed above, at the first stage, we score each country with respect to the Availability, Affordability, Acceptability and Accessibility according to their metrics and using the UNS&S Choquet integral. Then, in order to evaluate the Energy Security of the countries, we need a second stage consisting of aggregating the 'four As' by the UNS&S Choquet integral, where the process is repeated to have a relative measure of Energy Security.

Therefore, a global schema of the methodology applied is summarised below:

1. First Stage: Evaluating each A.
   Each country is evaluated in each of the 4As using the UNS&S Choquet Integral methodology, a hybrid methodology for the capacity identification process that combines a supervised method with an unsupervised one:
   (a) Step I: Unsupervised method (Rowley et al., 2015) Capacity is identified according to data behaviour (PCA, Pearson correlation).
   (b) Step II: Supervised method (Kojadinovic, 2007) quadratic distance minimisation combined with expert information.
2. Second Stage: Aggregating four As.
   Rank each country on the 'four As' simultaneously, applying UNS&S Choquet Integral methodology for measuring Energy Security:
   (a) Step I: Unsupervised method (Rowley et al., 2015). Capacity is identified according to data behaviour (PCA, Pearson correlation).
   (b) Step II: Supervised method (Kojadinovic, 2007). Constraints on the importance and interplay of the elements being aggregated can be imposed by utilising various profiles, which are determined based on each country's Global Climate Risk Index (GCRI) as established by GERMANWATCH (2022) and At Risk of Poverty Rate (ARPR). These profiles can be customised for individual experts or groups of experts.

4 Empirical study

The Asia Pacific Energy Research Center (APERC) (2022) defined Energy Security as "the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy." Based on the above definition, APERC proposed the four-dimensional/4As concept of Energy Security, in which availability, accessibility, acceptability, and affordability were included. The Energy Security dimensions of this study were based on these 4As dimensions, described as follows:

- *Availability*. This dimension refers to the proven reserves and potential of exploiting energy sources. Availability is the dimension that appears the most in the literature (Fuentes et al., 2020). The focus is on energy availability, regardless of domestic tapping of energy sources, imports or reserves and stresses a country's energy independence (Wu et al., 2021). The importance of energy availability lies in its support of economic and welfare growth (Blum & Legey, 2012); when availability is weakened, it limits economic expansion (Azzuni & Breyer, 2018). To sum up, Energy Security encompasses both the availability of energy resources and the availability of energy consumers, e.g., the public's use of energy or industrial usage.

- *Accessibility*. This dimension refers to the completeness of energy supply chains/infrastructure. It measures the ability to access energy resources to provide a stable and uninterrupted supply of electrical energy (Fuentes et al., 2020). For instance, the indicator of energy supply diversification can be utilised as a measure of combining various energy production capabilities, along with using electricity accessibility as an indicator of the overall completeness of energy infrastructure.
- *Affordability*. This dimension pertains to factors regarding energy prices and expenditures on energy products and services (Zhang et al., 2021). It is crucial for countries to take into account their capacity to offer reasonable and affordable energy while implementing national energy policies. Along with decreasing energy prices, boosting a country's GDP is also a way to attain energy affordability.
- *Acceptability*. This dimension relates to adopting of green energy to mitigate environmental impacts. It encompasses energy combinations that have minimal effects on human health, decrease energy consumption and CO2 emissions, and strive to attain sustainability in energy consumption in line with the United Nations' Sustainable Development Goals (SDGs) (Razmjoo et al., 2019).

In this study, the relevant literature drove the selection of indicators for each dimension. The selection of these indicators was based on the priorities set out in the energy policy of the EU (2014), as well as their availability and completeness (Tutak & Brodny, 2022). The panel dataset was built for 5 European countries (Spain, Portugal, France, Italy and Turkey) from 2017–2020. A total of 21 indicators related to the '4As' (Availability, Accessibility, Affordability, and Acceptability) of Energy Security were collected, as well as the GCRI and ARPR. The data sources are official organisms: Eurostat (2014; 2020), World Bank (2022), The Global Economy (2022), BP Statistical Review of World (2022), IEA Atlas of Energy + World Energy Balances Highlights (2022), World Energy Council (2021) and GERMANWATCH (GERMANWATCH, 2022).

We have designed an assessment model using the UNS&S Choquet Integral. In the first stage, we evaluate the four dimensions based on the selected indicators. In order to measure Energy Security, we combine the 'four As' using the UNS&S Choquet Integral in a subsequent stage.

It should be noted that prior to calculating the Choquet Integral, the data needs to be normalised. The Min-Max method is employed for data normalisation in this study. The equation is as follows for criteria of the type 'the more better':

$$I_r^{c^*} = \frac{x_r^{c^*} - min\{x_r^c\}}{max\{x_r^c\} - min\{x_r^c\}} \tag{7}$$

where $I_r^{c^*}$ is the normalised value for indicator r of country c^*; $x_r^{c^*}$ is the value prior to normalisation; $max\{x_r^c\}$ and $min\{x_r^c\}$ represent the maximum and minimum value of indicator r across all countries c, respectively. The normalisation for criteria of the type 'the less the better' is as follows:

$$I_r^{c^*} = \frac{max\{x_r^c\} - x_r^{c^*}}{max\{x_r^c\} - min\{x_r^c\}} \tag{8}$$

4.1 Stage 1: scoring 'four As' for each country during the years 2017 to 2020

4.1.1 Evaluating Availability

The dimension of Availability refers to the geophysical existence of energy resources and its potential ability to satisfy regional demands for energy resources. It can be decomposed into four components: energy production, energy potential, energy independence and energy diversification. All these components deal with the relationships between energy supply and demand (Zhang et al., 2021). For Availability (see Table 2), the indicators were chosen based on geological and physical elements. The six indicators are: Total Energy Supply per capita (TESpc), Energy Self-Sufficiency (ESS), Net Energy Imports per capita (NEIpc), Final Energy Consumption per capita (FECpc), Electricity Capacity per capita (ElCpc) and Energy Reserves Diversity Shannon index (ERD). The energy self-sufficiency rate is defined as the ability of a country to meet its own energy needs. It is calculated as production relative to the total primary energy supply.

Although we calculate the Shannon index to measure the diversity of the country's energy means across all dimensions, we specifically computed the Shannon index for energy reserves in the Availability dimension, considering the percentage of oil, coal and natural gas reserves with respect to the total reserves:

$$ERD = -\sum p_i ln p_i$$

where p_i is the proportion of reserves i.

The preferential information that has been included in detecting the capacity (Step II.2) is the following:

- 'Net energy imports pc' is more important than 'Diversity energy reserves'.
- 'Total energy supply pc' is more important than 'Diversity energy reserves'.
- 'Energy self-sufficiency' is more important than 'Diversity energy reserves'.
- A positive interaction between 'Net energy self-sufficiency" and "Electricity capacity pc' is set.

This preferential information has been set according to the prevalence of the indicators in our literature review. On the other hand, our database shows that Net energy self-sufficiency and Electricity capacity pc indicators go in the opposite direction. Therefore, a positive synergy between them should be modelled. This is an example of how preferential information can be introduced. If there is no preferential information, we obtain the scores of the countries in Availability from the unsupervised method. Table 3 shows data about the six indicators for each country for the initial and last years of the database (the complete database is available upon request to the authors). It is worth noting that Portugal has seen a significant improvement in Energy self-sufficiency, whereas Spain has shown an improvement in Net energy imports per capita. The remaining values have remained relatively stable. France scored zero on the reserve diversity indicator in all years, as all its reserves during the study period were oil. Italy consistently performs best on the reserve diversity indicator, with values above 0.6. It has oil and natural gas reserves in all years analysed. Turkey is the best performer on the NEIpc indicator in all years but achieves poor results on the TESpc, FECpc and ElCpc indicators. In this latter, it scores half of the best result obtained by Spain.

Table 4 displays the normalised data for each indicator—country and the results of different aggregation operators for all years of the database. In 2017, France surpassed Italy with the most straightforward aggregation operator, the average. Besides, the rankings obtained from the unsupervised and final Choquet methods interchanged the two first ranks (France

Table 2 Indicators for Availability

Indicator	Unit	Definition	Source	References
TESpc	GWh/Pop	Production + imports - exports−international aviation bunkers +-stock changes.	World Energy Balances Highlights (IEA)	Abdullah et al. (2020), Brodny and Tutak (2021), Gong et al. (2021), Karatayev and Hall (2020), Tutak and Brodny (2022), Wang et al. (2021), Yuan and Luo (2019).
ESS	%	Total energy production/Total energy supply.	World Energy Balances Highlights (IEA)	Bamisile et al. (2021), Brodny and Tutak (2021), Gong et al. (2021), Le and Nguyen (2019), Li et al. (2019), Ren and Sovacool (2014), Tutak and Brodny (2022), Wang et al. (2020), Wang et al. (2021), Wu et al. (2021), Yuan and Luo (2019).
NEIpc	(Thousand tonnes of oil equivalent)/ Pop	Energy use less production. It is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.	World Energy Balances Highlights (IEA)	Abdullah et al. (2020), Azzuni and Breyer (2020), Bekhrad et al. (2020), Brodny and Tutak (2021), Lin and Raza (2020), Podbregar et al. (2020), Stavytskyy et al. (2021), Wang et al. (2021).
FECpc	GWh/pc	Total energy consumed by end users, such as households, industry and agriculture.	EUROSTAT	Abdullah et al. (2020), Bamisile et al. (2021), Filipović et al. (2018), Gong et al. (2021), Gong et al. (2021), Karatayev and Hall (2020), Kharazishvili et al. (2021), Le and Nguyen (2019); Lee et al. (2022), Li et al. (2019), Podbregar et al. (2020), Razmjoo et al. (2019), Shah et al. (2019), Tutak and Brodny (2022), Wang et al. (2020), Wang et al. (2021), Wang and Zhan (2019), Yang et al. (2022), Yuan and Luo (2019), Ziemba et al. (2021).

Table 2 continued

Indicator	Unit	Definition	Source	References
ElCpc	kW per capita	Installed capacity to produce electricity from fossil fuels (including oil, coal, and natural gas), wind, sunlight, hydroelectricity, nuclear electricity, geothermal electricity.	The Global Economy	Amin et al. (2022), Coutinho et al. (2020), Li et al. (2019).
ERD	Number between 0 and 1	Determines the diversity of the energy reserves. Its greater value indicates greater diversification of energy reserves.	BP Statistical Review and The Global Economy	Azzuni and Breyer (2020), Tutak and Brodny (2022), Wu et al. (2021)

Table 3 Data for Availability dimension (Years 2017 and 2020)

	TESpc	ESS	NEIpc	FECpc	ElCpc	ERD
2017						
France	0.0431	52	0.0019	0.0260	1.853	0
Italy	0.0295	22	0.0021	0.0221	1.695	0.618
Portugal	0.0257	23	0.0019	0.0187	1.701	0
Spain	0.0314	27	0.0022	0.0212	1.970	0.135
Turkey	0.0214	25.12	0.0015	0.0156	1.010	0.0420
2020						
France	0.0376	55	0.0015	0.0225	1.911	0
Italy	0.0269	25	0.0018	0.0200	1.747	0.630
Portugal	0.0227	30	0.0014	0.0170	1.821	0
Spain	0.0267	32	0.0017	0.0181	2.164	0.135
Turkey	0.0206	29.87	0.0013	0.0148	1.084	0.0456

TESpc: Total Energy Supply per capita
ESS: Energy Self-Sufficiency
NEIpc: Net Energy Imports per capita
FECpc: Final Energy Consumption per capita
ElCpc: Electricity Capacity per capita
ERD: Energy Reserve Diversity Shannon index

and Italy). This is due to the difference between the Shapley values assigned to the diversity Shannon index by the unsupervised (0.28) and the supervised (0.17) CI methods. The two CI operators give the same ranking for the rest of the years. In addition, the average interchanged the two last ranks in 2017, 2018 and 2019. In 2020, all three operators produced the same ranking. Portugal and Turkey always occupy the last positions. In 2017, Portugal had a better average than Turkey, but it was worse in both the unsupervised and supervised methods. Turkey outperforms Portugal in the two most important indicators for the unsupervised method, the ERD and NEIpc indicators, respectively. In the supervised method, the most important indicator is the NEIpc, where Turkey always scores best. In 2020, Portugal was better than Turkey in all three aggregation operators. The results for the Iberian Peninsula show the situation of inferiority with respect to neighbouring EU countries.

In Fig. 1, the results for all years and countries are displayed. The good results of France are noted. This country ranks the first and Italy the second. A special situation is observed for Portugal, which was always situated in the last place except in 2020 due to improving its score in NEIpc indicator. According to its Shapley value, it is one of the most important indicators in both CI methods. Spain consistently ranks third and improves its NEIpc indicator in 2020. It is noted in Fig. 1 that the worst positions are much more concentrated than the best positions, i.e. France and Italy are further away than the three countries at the bottom, Spain, Portugal and Turkey.

In the case of Spain, a policy objective in its energy plans should be to improve the NEIpc indicator. In this respect, Spain should follow the EU's energy policy recommendations. These include promoting, with public and private investment, infrastructures that enhance the use of renewable energy sources, as well as improving energy transport and distribution systems that contribute to improving the security and efficiency of electricity supply, facilitating access to diversified and complementary energy sources, and reducing energy losses in the process. The critical indicators in which Portugal should improve are TESpc and ESS. Turkey should improve the three indicators where it scores zero, i.e. TESpc, FECpc and ElCpc indicators.

Table 4 Results for Availability dimension

	TESpc	ESS	NEIpc	FECpc	ElCpc	ERD	Average	UNS CI	Final CI	Ranking
2017										
France	1	1	0.41	1	0.88	0	0.72	0.70	0.82	1
Italy	0.37	0	0.17	0.63	0.71	1	0.48	0.72	0.63	2
Portugal	0.20	0.03	0.35	0.30	0.72	0	0.27	0.35	0.33	5
Spain	0.46	0.17	0	0.54	1	0.22	0.40	0.54	0.50	3
Turkey	0	0.10	1	0	0	0.07	0.20	0.42	0.40	4
2018										
France	1	1	0.46	1	0.88	0	0.72	0.73	0.84	1
Italy	0.37	0	0.18	0.70	0.73	1	0.50	0.73	0.65	2
Portugal	0.19	0.13	0.42	0.38	0.80	0	0.32	0.41	0.41	5
Spain	0.47	0.13	0	0.62	1	0.21	0.40	0.54	0.51	3
Turkey	0	0.16	1	0	0	0.07	0.20	0.43	0.42	4
2019										
France	1	1	0.41	1	0.82	0	0.71	0.75	0.85	1
Italy	0.39	0	0.11	0.73	0.67	1	0.48	0.72	0.65	2
Portugal	0.18	0.13	0.42	0.43	0.75	0	0.32	0.39	0.40	5
Spain	0.44	0.16	0	0.63	1	0.21	0.41	0.55	0.52	3
Turkey	0	0.26	1	0	0	0.06	0.22	0.46	0.47	4
2020										
France	1	1	0.56	1	0.77	0	0.72	0.77	0.84	1
Italy	0.37	0	0	0.68	0.61	1	0.44	0.73	0.67	2
Portugal	0.13	0.17	0.74	0.28	0.68	0	0.33	0.44	0.45	4
Spain	0.36	0.23	0.17	0.43	1	0.21	0.40	0.55	0.52	3
Turkey	0	0.16	1	0	0	0.07	0.21	0.43	0.43	5

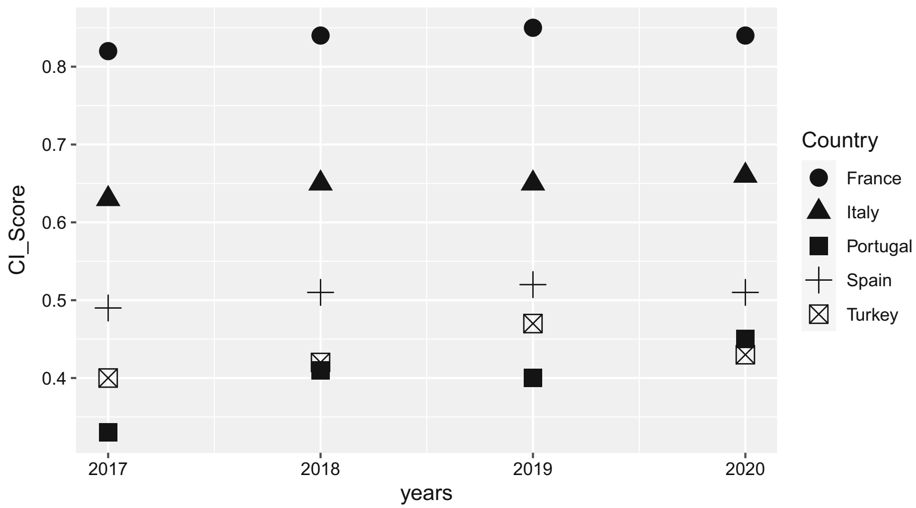

Fig. 1 Results for Availability dimension by the UNS&S Choquet integral

4.1.2 Evaluating Accessibility

The indicators for this dimension were constructed based on geopolitical elements. The three indicators are (see Table 5): Time required to get electricity (TREl), Energy imports dependency (EID) and Electricity generation diversity (ElGD) measured by the corresponding Shannon index. The TREl captures the median duration that the electricity utility and experts indicate is necessary in practice, rather than required by law, to complete a procedure. The EID is calculated as the ratio of the imports minus exports between the gross available energy, being all these magnitudes measured in thousand tonnes of oil equivalent. Similarly to Availability, for Accessibility, we have computed the Shannon index of the electricity generation, considering the electricity generation of Share Fossil fuels, Share Wind, Share Solar, Share Hydroelectricity, Share Nuclear and Share Geothermal.

Similarly to the Availability dimension, we have considered the following preference relationships to be applied in the supervised method:

- ‘Diversity index’ is more important than ‘Time required to get electricity’.
- ‘Energy imports’ is more important than ‘Time required to get electricity”.
- Positive interaction between ‘Energy imports dependency’ and ‘Diversity index’ is established.

Table 6 shows the scores and rankings for all countries for Accessibility. In 2017, the results were remarkably consistent, with all three aggregation operators producing the same ranking. However, in 2018, the three rankings are different. The loss of positions of Portugal with respect to the average operator is observed because the ’Time needed to obtain electricity’ indicator reaches low Shapley values, both in the UNS and the Final CI, compared to the ’Imports of energy dependency’ indicator. In 2019, the differences between the two CI operators appear; this is because the first two indicators are the most important according to

Table 5 Indicators for Accessibility

Indicator	Unit	Definition	Source	References
TREl	Days	Number of days to obtain a permanent electricity connection.	World Development Indicators (WDI): World Bank	Wang and Zhou (2017), Wu et al. (2021).
EID	(Imports–Exports)/ (Gross available energy)	The share of total inland energy needs met by imports from other countries.	EUROSTAT	Abdullah et al. (2020), Filipović et al. (2018), Fuentes et al. (2020), Karatayev and Hall (2020), Tutak and Brodny (2022), Wang and Zhan (2019).
ElGD	Number between 0 and 1	Determines the diversity of the energy mix. Its greater value indicates greater diversification of electricity generation.	The Global Economy	Azzuni and Breyer (2020), Tutak and Brodny (2022), Wu et al. (2021).

Table 6 Results for Accessibility dimension

	TREl[a]	EID[b]	ElGD[c]	Average	UNS CI	Final CI	Ranking
2017							
France	0.6	1	0.08	0.56	0.78	0.69	1
Italy	0.5	0.034	0.32	0.28	0.27	0.26	5
Portugal	0.75	0	0.21	0.32	0.38	0.37	4
Spain	0	0.14	1	0.38	0.55	0.57	2
Turkey	1	0.027	0	0.34	0.51	0.49	3
2018							
France	1	1	0	0.67	0.90	0.75	1
Italy	0.48	0	0.33	0.27	0.29	0.29	5
Portugal	0.71	0.02	0.39	0.38	0.44	0.44	4
Spain	0	0.09	1	0.36	0.63	0.59	3
Turkey	0.95	0.09	0.08	0.37	0.60	0.61	2
2019							
France	0.69	1	0	0.56	0.77	0.63	2
Italy	0.33	0	0.30	0.21	0.23	0.20	5
Portugal	0.49	0.12	0.40	0.34	0.37	0.35	4
Spain	0	0.08	1	0.36	0.57	0.58	3
Turkey	1	0.25	0.31	0.52	0.68	0.70	1
2020							
France	0.69	1	0	0.56	0.75	0.65	1
Italy	0.33	0	0.18	0.17	0.18	0.17	5
Portugal	0.49	0.28	0.35	0.37	0.39	0.39	4
Spain	0	0.19	1	0.40	0.55	0.59	2
Turkey	1	0.10	0.18	0.42	0.55	0.55	3

[a] TREl: Time required to get electricity (days)
[b] EID: Energy imports dependency
[c] ElGD: Electricity Generation Diversity

the UNS Choquet, and the last two are the most important according to the Final Choquet. In 2020, the average operator caused Spain and Turkey to switch places. Spain obtains the best results in the Diversity of Electricity Generation indicator in all the years of the database. This good performance is because Spain generates electricity from all possible sources except geothermal and with percentages in all of them below 47%. On the contrary, France has poor results in this indicator, with a large share of nuclear power generation falling from 73% in 2017 to 68% in 2020. However, France obtains the best results in the Energy imports dependency indicator.

Spain achieved the worst results in the time needed to get electricity (95 days). On the contrary, Turkey obtains the best results in TREl. In the case of Spain, specific regulations establish the criteria and procedures for the concession of access and connection licences, as well as the maximum time limits for their processing. In addition, Spain has a diverse geography and extensive territory, which implies greater complexity in developing and managing electricity grids. Furthermore, there are differences between the Autonomous Communities

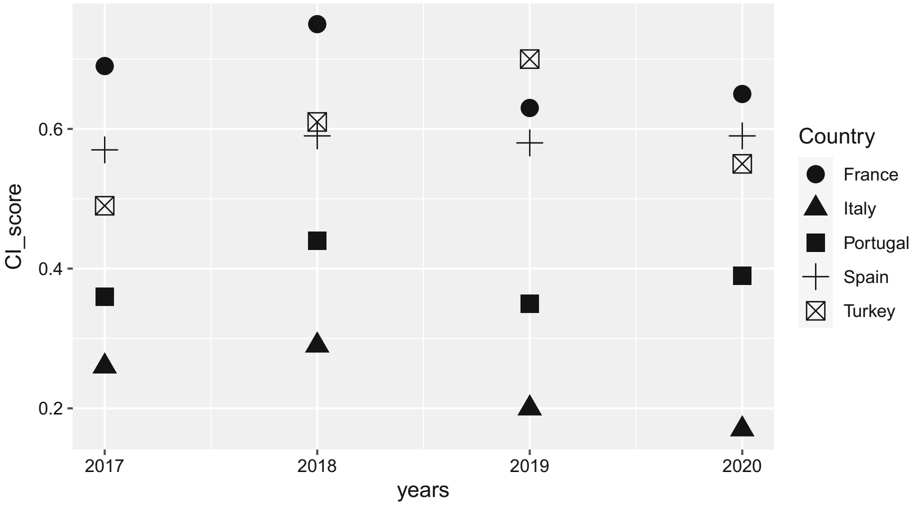

Fig. 2 Results for Accessibility dimension by the UNS&S Choquet integral

regarding competence over access to networks, which may affect the time taken to process applications. [4]

Lastly, Italy always occupies the last position in this A, with the worst results in the Energy imports dependency indicator. It is remarkable the superiority of France in the EID indicator that moves in the interval [44%, 49%] while the rest of the countries take values in the interval [65%, 78%]. In 2020, Spain and Portugal reduced import dependency in line with the targets proposed in their National Energy and Climate Plans, improving w.r.t. this indicator.

Figure 2 illustrates that Portugal and Italy always occupy the fourth and fifth positions, respectively. Except for 2019, the arithmetic mean and unsupervised Choquet operators place France in the top position, while Spain and Turkey compete for second and third.

4.1.3 Evaluating Affordability

The indicators were constructed, including economic elements (see Table 7). The seven indicators are Diesel price (D), Gasoline price (G), Electricity prices for household consumers (E), Electricity prices for nonhousehold consumers (En), Natural gas prices for household consumers (NG), Natural gas prices for nonhousehold consumers (NGn) and the ratio between GDP per capita and the price of a barrel of oil (B). 'Electricity prices for household consumers' is the average national price in Euro per kWh, including taxes and levies applicable for the first semester of each year for medium-size household consumers (Consumption Band DC with annual consumption between 2500 and 5000 kWh). Until 2007, the prices refer to the

[4] For more information about the access and connection to the networks, see Real Decreto 1183/2020 in the web of Ministry for the Ecological Transition and the Demographic Challenge, https://energia.gob.es/electricidad/acceso-y-conexion/Paginas/acceso-conexion.aspx.. However, compared to France, Italy, Portugal, and Spain, Turkey ranks below average, as these countries have longer times to get electricity. Some possible reasons for this good performance could be the liberalisation of the wholesale and retail market, the establishment of an independent regulatory authority or the splitting of power generation, transmission and distribution activities. In addition, Turkey has a modern electricity infrastructure and a simplified procedure for requesting and obtaining an electricity connection.

status on 1st January of each year for medium-size consumers (Standard Consumer DC with annual consumption of 3500 kWh).

As an example of introducing preferential information, we have proposed an Affordability measure that places great importance on affordable access to electricity for households. Specifically, we have included the following relationships in the process of detecting the capacity (Step II.2):

- 'Electricity prices for household consumers' is more important than 'Diesel price', 'Gasoline price', 'Electricity prices for nonhousehold consumers', 'Natural gas prices for household consumers', 'Natural gas prices for nonhousehold consumers' and 'GDPpc/Price oil barrel' criteria.
- Positive interaction between 'Gasoline price' and 'Natural gas prices for household consumers' is set.

Table 8 shows the rankings and scores for all countries regarding Affordability from 2017 to 2020. It is worth noting that Spain and Portugal consistently hold the lowest rankings. Table 8 also displays the normalised data for each indicator and country, as well as the results of various aggregation operators for all the years of the database. The rankings obtained by the unsupervised and final Choquet methods do not coincide in 2018 and 2020. This is a situation in which the preferential information does not adjust to that obtained by the unsupervised method, which places 'Natural gas prices for household consumers' as the most important criterion rather than 'Electricity prices for household consumers'. Specifically, in the unsupervised method, 'Natural gas prices for household consumers' reaches an average in the four years equal to 0.315, and the least important criterion is 'Natural gas prices for nonhousehold consumers' with an average of 0.084. In addition, 'Electricity prices for household consumers' achieves an average of 0.129. The final Choquet method gives averages equal to 0.218 and 0.208 for 'Electricity prices for household consumers' and 'Natural gas prices for household consumers', respectively, and they are the most important criteria. The least important indicator is 'Natural gas prices for nonhousehold consumers', with an average of 0.093. The rest of the criteria are sorted very similarly by both methods. Differences are found when the average operator ranks Italy third except in 2017, when it is in second place and Turkey in fourth position except in 2020, when it is fifth. If we consider this operator, Spain occupies the second position, except in 2017, when it ranked third.

It deserves comment on the special situation of Spain as it always presents much worse results in the prices of household consumers than those of non-household consumers. Spain obtained the worst results in the Electricity prices for household consumers indicator during 2017 and 2018 and has improved significantly in the last two years. Portugal and Spain obtained low scores in the 'Natural gas prices for household consumers' indicator throughout the entire period analysed. As in the case of Availability, the Iberian Peninsula is in a worse situation in Affordability than neighbouring EU countries. France scores low marks for oil and diesel prices. This may be due to the high taxation of these fuels, which represents more than 50% of the final price, with the aim of discouraging their consumption and encouraging the ecological transition. [5] However, it scores best on electricity and natural gas prices for consumers and industry. One of the reasons for this low electricity price is the production of nuclear power in the French energy mix, which represents almost 70% in 2020. Moreover, according to the IEA, the fact that France has one of the lowest natural gas prices in the EU is due, among other reasons, to the fact that high nuclear energy production allows it to generate electricity at low cost and reduce the demand for natural gas for this purpose.

[5] https://ec.europa.eu/energy/maps/maps_weekly_oil_bulletin/latest_taxation_oil_prices.pdf.

Table 7 Indicators for Affordability

Indicator	Unit	Definition	Source	References
D	EUR/litre	The diesel prices, published by the European Commission's Oil Bulletin for EU countries.	The official portal for European data (2022)	Azzuni and Breyer (2020), Karatayev and Hall (2020),Ragulina et al. (2019), Wu et al. (2021).
G	EUR/litre	The gasoline prices, published by the European Commission's Oil Bulletin for EU countries.	European Commission - Energy Policy	Bekhrad et al. (2020), Karatayev and Hall (2020), Malik et al. (2020), Ragulina et al. (2019), Wu et al. (2021).
E	EUR/kWh (Average of two semester price)	Average national price in Euro per kWh including taxes and levies applicable for the first semester of each year for medium size household consumers.	EUROSTAT	Amin et al. (2022), Brodny and Tutak (2021), Filipović et al. (2018), Fuentes et al. (2020), Karatayev and Hall (2020), Malik et al. (2020), Podbregar et al. (2020), Ragulina et al. (2019), Tutak and Brodny (2022), Wang and Zhan (2019), Zhang et al. (2021), Ziemba et al. (2021)
En	EUR/kWh (Average of two semestral price)	Non-household consumers are defined as medium-sized consumers with an annual consumption between 500MWH and 2000MWH.	EUROSTAT	Bamisile et al. (2021), Bekhrad et al. (2020), Gong et al. (2021), Karatayev and Hall (2020).

Table 7 continued

Indicator	Unit	Definition	Source	References
NG	EUR/kWh (Average of two semester natural gas price)	For household consumers in the EU defined as medium-sized consumers with an annual consumption between 20 Gigajoules (GJ) and 200 GJ).	EUROSTAT	Malik et al. (2020), Tutak and Brodny (2022).
NGn	EUR/kWh (Average of two semester natural gas price)	For non-household consumers in the EU (defined for the purpose of this article as medium-sized consumers with an annual consumption between 10 000 GJ and 100 000 GJ).	EUROSTAT	–
B	Number of oil barrels pc	Ratio between GDP per capita at constant prices of 2015 and Price oil barrel	WDI (World Bank)	Azzuni and Breyer (2020), Bekhrad et al. (2020), Brodny and Tutak (2021), Filipović et al. (2018), Gong et al. (2021), Kharazishvili et al. (2021), Le and Nguyen (2019), Shah et al. (2019), Stavytskyy et al. (2021), Tutak and Brodny (2022), Wang and Zhan (2019), Wu et al. (2021), Yang et al. (2022),Ziemba et al. (2021).

Table 8 Results for Affordability dimension

	D[a]	G[b]	E[c]	En[d]	NG[e]	NGn[f]	B[g]	A[h]	U[i]	F[j]	R[k]
2017											
France	0.49	0.48	1	1	0.91	0.91	1	0.83	0.85	0.85	1
Italy	0	0	0.65	0.68	0.70	1	0.75	0.54	0.62	0.60	3
Portugal	0.49	0.23	0.66	0.38	0	0.33	0.33	0.34	0.35	0.42	5
Spain	0.86	1	0	0.23	0.09	0.60	0.60	0.48	0.50	0.47	4
Turkey	1	0.93	0.29	0	1	0	0	0.46	0.64	0.68	2
2018											
France	0	0.29	1	1	0.82	1	1	0.73	0.87	0.87	1
Italy	0	0	0.69	0.66	0.54	0.99	0.75	0.52	0.66	0.67	3
Portugal	0.37	0.26	0.83	0.58	0	0.60	0.34	0.43	0.46	0.56	4
Spain	0.87	1	0	0.38	0.1	0.73	0.60	0.53	0.53	0.51	5
Turkey	1	0.92	0.38	0	1	0	0	0.47	0.72	0.76	2
2019											
France	0.02	0.11	1	1	0.69	1	1	0.69	0.76	0.82	1
Italy	0	0	0.46	0.77	0.60	0.98	0.75	0.51	0.67	0.66	3
Portugal	0.18	0.18	0.49	0.69	0.10	0.62	0.36	0.37	0.39	0.44	5
Spain	0.46	0.50	0.52	0.75	0	0.85	0.60	0.53	0.48	0.55	4
Turkey	1	1	0	0	1	0	0	0.43	0.75	0.77	2
2020											
France	0.12	0.10	1	1	1	0.98	1	0.74	0.85	0.85	1
Italy	0	0	0.78	0.89	0.86	1	0.73	0.61	0.77	0.75	3
Portugal	0.12	0.017	0.79	0.84	0	0.84	0.33	0.42	0.40	0.53	5
Spain	0.70	0.39	0.84	0.87	0.09	0.94	0.54	0.63	0.58	0.71	4
Turkey	1	1	0	0	0.85	0	0	0.41	0.76	0.76	2

[a] D: Diesel price
[b] G: Gasoline price
[c] E: Electricity prices for household consumers
[d] En: Electricity prices for nonhousehold consumers
[e] NG: Natural gas prices for household consumers
[f] NGn: Natural gas prices for nonhousehold consumers
[g] B: GDP pc/Price oil barrel
[h] A: Average
[i] U: UNS Choquet
[j] F: Final Choquet
[k] R: Ranking

Another reason is that it is well diversified in the sources of natural gas it imports, which allows it to have greater security of supply and less dependence on a single supplier. Finally, France has a good natural gas transmission and distribution infrastructure, which allows it to optimise the use of the network and reduce losses and costs.

Figure 3 displays the results for this dimension across all years and countries, with France consistently being the top-performing country while Portugal and Spain are at the bottom. The second position goes to Turkey in all years. Turkey achieves always good scores in three indicators ('Diesel price', 'Gasoline price' and 'Natural gas prices for household consumers')

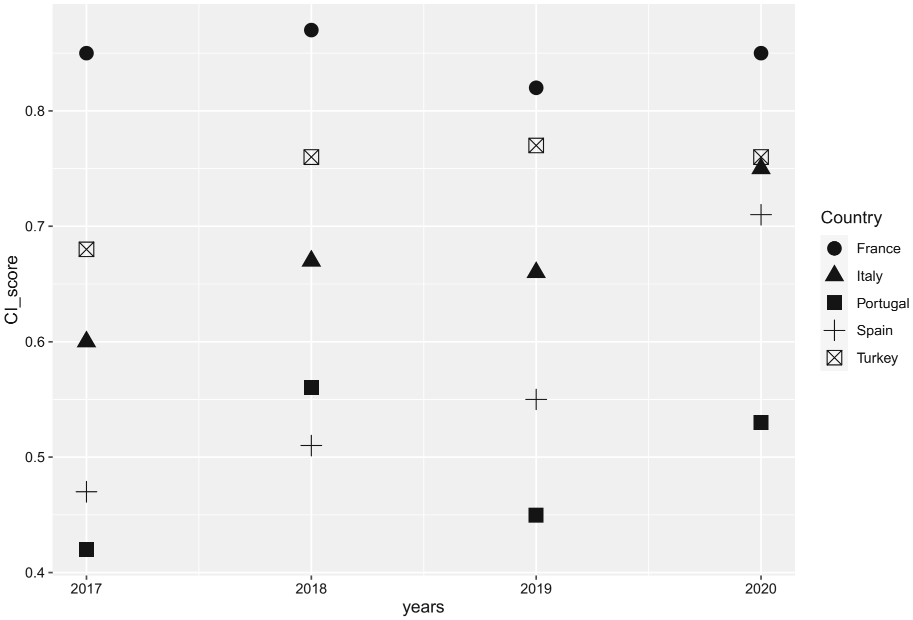

Fig. 3 Results for Affordability dimension by the UNS&S Choquet integral

4.1.4 Evaluating Acceptability

The indicators related to the Acceptability dimension were chosen based on social and environmental elements. The five indicators are Share of renewables in total final energy consumption (ShRWC), CO2 emissions per capita (CO2pc), Greenhouse gas emissions per capita (GGpc)[6], PM2.5 air pollution and Share of renewable energy generation in total electricity generation (ShRWG) (see Table 9).

The preferential information that has been included in the process of detecting the capacity (Step II.2) is the following:

- ‘CO2 emissions pc’ is more important than ‘Share of renewables in total final energy consumption’.
- ‘Greenhouse gas emissions pc’ is more important than ‘Share of renewables in total final energy consumption’.
- ‘PM2.5 air pollution’ is more important than ‘Share of renewables in total final energy consumption’.
- ‘CO2 emissions’, ‘Greenhouse gas emissions pc’ and ‘PM2.5 air pollution’ criteria are more important than ‘Renewable energy generation/total electricity generation’.
- Positive interaction between ‘Share of renewables in total final energy consumption (%)’ and ‘CO2 emissions (metric tons per capita)’ is established.

[6] For this indicator each gas’ individual global warming potential, they are being integrated into a single indicator expressed in units of CO2 equivalents. The indicator does not include emissions and removals related to land use, land-use change and forestry; it does not include emissions reported as a memorandum item according to United Nations Framework Convention on Climate Change (UNFCCC) Guidelines but does include emissions from international aviation as well as indirect CO_2 emissions.

Table 9 Indicators for Acceptability

Indicator	Unit	Definition	Source	References
ShRWC	%	Share of renewable energy in total final energy consumption.	IEA and EUROSTAT	Filipović et al. (2018), Fuentes et al. (2020), Gong et al. (2021), Le and Nguyen (2019), Malik et al. (2020), Razmjoo et al. (2019), Shah et al. (2019), Song et al. (2019), Stavytskyy et al. (2021), Tutak and Brodny (2022), Wang and Zhan (2019), Wang et al. (2020), Ziemba et al. (2021).
CO2pc	Metric tons pc	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	WDI (World Development Indicators from World Bank) and https://github.com/owid/co2-data	Abdullah et al. (2020), Amin et al. (2022), Bamisile et al. (2021), Bekhrad et al. (2020), Brodny and Tutak (2021), Filipović et al. (2018), Gong et al. (2021), Karatayev and Hall (2020), Kharazishvili et al. (2021), Le and Nguyen (2019), Lin and Raza (2020), Malik et al. (2020), Podbregar et al. (2020), Ragulina et al. (2019), Razmjoo et al. (2019); Wang et al. (2020), Wang and Zhan (2019), Wang et al. (2021), Ziemba et al. (2021).

Table 9 continued

Indicator	Unit	Definition	Source	References
GGpc	CO2 equivalents pc	Total national emissions of the so called 'Kyoto basket' of greenhouse gases, including carbon dioxide, methane, nitrous oxide, and the so-called F-gases (hydrofluorocarbons, perfluorocarbons, nitrogen triflouride and sulphur hexafluoride).	The reporting under the United Nations Framework Convention on Climate Change (UNFCCC). EUROSTAT	Brodny and Tutak (2021), Coutinho et al. (2020), Fuentes et al. (2020), Tutak and Brodny (2022), Wang and Zhan (2019).
PM2.5 air pollution	mcg per m3; Exposure is calculated by weighting mean annual concentrations of PM2.5 by population in both urban and rural areas.	Population-weighted exposure to ambient PM2.5 pollution is defined as the average level of exposure of a nation's population to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter.	EUROSTAT	Li et al. (2019), Wu et al. (2021).
ShRWG	%	Renewable energy generation as a percentage of total electricity generation.	EUROSTAT	Wang et al. (2021), Wu et al. (2021).

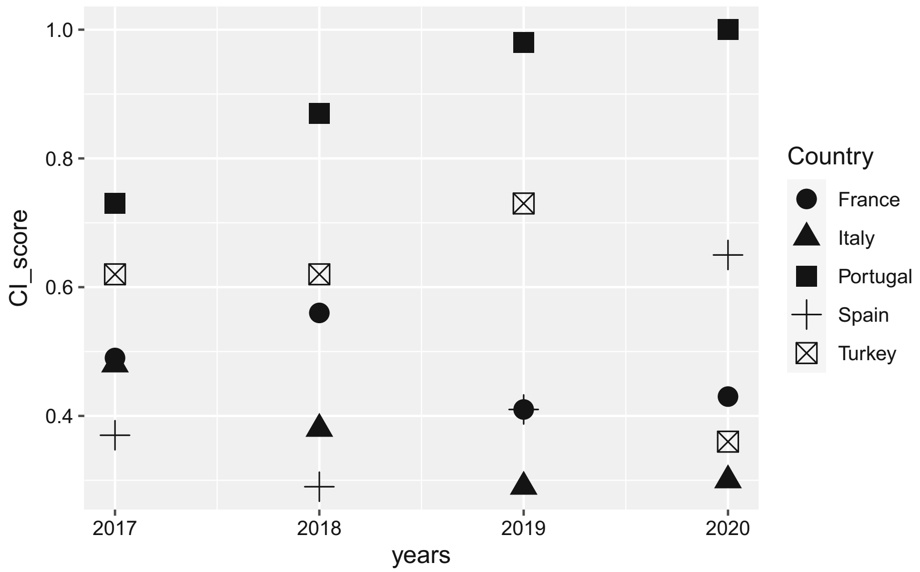

Fig. 4 Results for Acceptability dimension by the UNS&S Choquet integral

Table 10 presents the rankings and scores for all countries regarding Acceptability from 2017 to 2020. It is worth noting that Portugal consistently holds the best rankings as one of the leading countries in Europe in developing renewable energies, especially hydroelectric and wind power. In particular, it has set up the gigabattery on the Tâmega river, a branch of the Douro, in Porto, one of the largest hydroelectric projects in Europe, consisting of the construction of three hydroelectric plants, one of which is a pumped storage plant, and two wind parks. This clean energy project improves SE indicators since it optimises the use of land and the electricity grid and allows for a more stable energy supply and a reduction in dependence on imports. Table 10 also displays the normalised data for each indicator and country, and the results of the three aggregation operators for all years of the database. The rankings obtained by the unsupervised and final Choquet methods were the same. The improvement of Spain is noteworthy, as it moved up from the last position in 2017 and 2018 to the second position in 2020 thanks to its improvement in the CO_2 emissions and Greenhouse gas emissions pc indicators (see also Fig. 4). In this dimension, France never occupies the first position and reaches the worst performance in the share renewable energy generation ratio. Besides, it achieves low scores in the share of renewable in total final energy consumption and the concentration of PM2.5 particulate emissions. However, this country achieves good results in CO2 emissions due to its large share of nuclear power generation. Italy ranked in the last position in the last two years due to its bad performance in CO_2 emissions and Greenhouse gas emissions. Turkey got worse in 2020. According to the World Health Organisation's 2020 report, it was the country with the highest concentration of PM2.5 particles in Europe. In addition, it increased its greenhouse gas and CO_2 emissions.

4.1.5 Overall results

When summarising the scores for the 'four As' related to each country each year, we obtain Fig. 5. Some relevant conclusions:

Table 10 Results for Acceptability dimension

	Sh[a] RWC	CO_2 pc	GG[b] pc	PM 2.5	Sh[c] RWG	Average	UNS CI	Final CI	Ran-king
2017									
France	0.21	1	0.44	0.28	0	0.39	0.50	0.49	3
Italy	0.39	0.23	0.33	0.46	0.76	0.43	0.48	0.48	4
Portugal	1	0.51	0.33	1	1	0.77	0.75	0.73	1
Spain	0.33	0	0	0.62	0.73	0.34	0.37	0.37	5
Turkey	0	0.57	1	0	0.66	0.45	0.59	0.62	2
2018									
France	0.22	1	0.67	0	0	0.38	0.56	0.56	3
Italy	0.34	0.16	0.22	0.29	0.59	0.32	0.38	0.38	4
Portugal	1	0.75	0.67	1	1	0.88	0.87	0.87	1
Spain	0.36	0	0	0.33	0.63	0.26	0.30	0.29	5
Turkey	0	0.56	1	0.01	0.45	0.40	0.62	0.62	2
2019									
France	0.10	0.80	0.56	0.17	0	0.32	0.39	0.41	4
Italy	0.22	0	0	0.42	0.55	0.24	0.30	0.29	5
Portugal	1	1	0.67	1	1	0.93	0.99	0.98	1
Spain	0.22	0.24	0.11	0.53	0.56	0.33	0.42	0.41	3
Turkey	0	0.86	1	0	0.81	0.53	0.69	0.73	2
2020									
France	0.25	0.74	0.75	0.36	0	0.42	0.42	0.43	3
Italy	0.31	0	0	0.50	0.47	0.26	0.30	0.30	5
Portugal	1	1	1	1	1	1	1	1	1
Spain	0.36	0.52	0.75	0.56	0.63	0.56	0.65	0.65	2
Turkey	0	0.35	0.13	0	0.60	0.21	0.36	0.36	4

[a] ShRWC: Share of renewables in total final energy consumption
[b] GG pc: Greenhouse gas emissions per capita
[c] ShRWG: Share renewable energy generation

- France is the best in Availability in all years. The only bad result France obtains in this A is in the reserve diversity indicator due to its total concentration in oil. Whereas Turkey and Portugal score poorly in this dimension. Turkey has zeroed on ’Total Energy Supply per capita’, ’Electricity Capacity per capita’ and ’Final Energy Consumption’ indicators. Portugal has bad scores in Energy self-sufficiency and Energy reserves diversity indicators. The rankings remain very stable throughout the four years. There is only one change in the fourth and fifth positions. Spain occupies the third position in this A in all years, consistently below France and Italy, its strong point being Electrical Capacity per capita.
- Italy is the worst in Accessibility, which means its ability to access energy sources is improvable. France keeps its first position in all years except in the year 2019, which is surpassed by Turkey.
- The Iberian Peninsula runs worse in Affordability, a dimension defined mainly by ‘Energy price for consumers’.

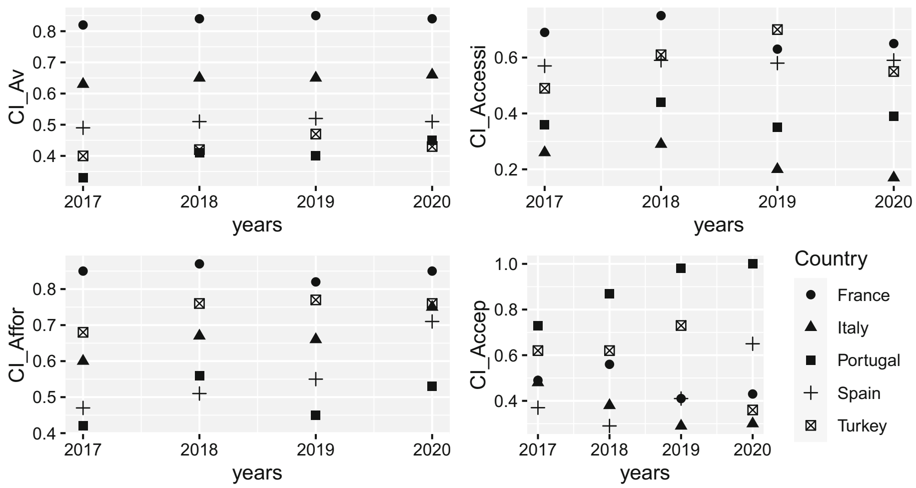

Fig. 5 The 4As for Energy Security

Table 11 At risk of poverty rate (%)

	2017	2018	2019	2020
Spain	21.6	21.5	20.7	21
France	13.2	13.4	13.6	13.8
Italy	20.3	20.3	20.1	20.0
Portugal	18.3	17.3	17.2	16.2
Turkey	22.2	22.2	22.4	23.0

- In Acceptability, Portugal is the best in using of energy that cares for the environment, and Spain improved its position in 2020 compared to previous years, reaching second place.
- France consistently scores higher in all A's except Acceptability.

4.2 Stage 2: Aggregating the 'four As' by the UNS&S Choquet Integral

As mentioned before, to evaluate the countries' Energy Security, we aggregate the 'four As' by the UNS&S Choquet integral. The process is the same, consisting of combining the unsupervised method proposed by Rowley et al. (2015) with a supervised method where we have taken into account the expert consensus of climate risk and the risk of poverty, measured by the Global Climate Risk Index (GCRI) (GERMANWATCH, 2022) and the At Risk of Poverty Rate (ARPR) (2022), respectively. ARPR (cut-off point: 60% of median equivalised income after social transfers) is measured in percentage. The GCRI quantifies the impacts of extreme weather events -in terms of the fatalities and the economic losses that occurred. Data of ARPR and GCRI for analysed countries are recovered in Tables 11 and 12, respectively.

Four distinct profiles have been defined based on specific thresholds set for the values of ARPR and GCRI. These profiles help to establish constraints on the significance and interaction between the four dimensions.

Table 12 Global climate risk index (%)

	2017	2018	2019	2020
France	61.17	46.17	52.5	NA
Italy	45.33	33.67	43.5	NA
Portugal	17.33	70.67	48.33	NA
Spain	54.17	47.67	42.83	NA
Turkey	69.17	79.17	66	NA

Table 13 Profiles of Countries

	France	Italy	Portugal	Spain	Turkey
Year 2017					
At Risk of Poverty Rate	0	1	0	1	1
Climate Risk Index	0	0	1	0	0
Profile	4	2	1	2	2
Year 2018					
At Risk of Poverty Rate	0	1	0	1	1
Climate Risk Index	0	1	0	0	0
Profile	4	3	4	2	2
Year 2019					
At Risk of Poverty Rate	0	1	0	1	1
Climate Risk Index	0	1	0	1	0
Profile	4	3	4	3	2
Year 2020					
At Risk of Poverty Rate	0	0	0	1	1
Climate Risk Index	0	1	0	1	0
Profile	4	1	4	3	2

- Profile 1: GCRI less than 45. Acceptability is the most important dimension in this profile, and a positive interaction between Affordability and Acceptability is set.
- Profile 2: ARPR greater than 20. In this situation, Affordability is the most important dimension, and it is set positive interaction between Affordability and Accessibility.
- Profile 3: Profile 1 + Profile 2. Acceptability and Affordability are the most important As, and two positive interactions are set between Affordability and Acceptability and Affordability and Accessibility.
- Profile 4: All those not included in 1, 2 and 3. Relationships of importance and interactions are not set.

Based on the data presented in Table 13, France consistently performs well in both ARPR and GCRI indicators throughout all years. Portugal also shows promising results. On the other hand, Spain has an ARPR slightly above 20% in all years and experienced a decline in its GCRI score in 2019, which is comparable to Turkey's decline.

Table 14 presents the scores for all countries regarding Energy Security in all years of the database. In 2017, France occupied the first position and Spain the last. Turkey achieves a good position due to the good results in Affordability (only below Francia). Its worst result is related to Availability (see Table 4). The top two positions (France and Turkey) hold for

Table 14 Results for Energy Security

	Acceptability	Accessibility	Affordability	Availability	Average	UNS Choquet	UNS&S Choquet
2017							
France	0.335	1	1	1	0.834	0.814	0.814
Italy	0.289	0	0.422	0.604	0.329	0.359	0.380
Portugal	1	0.237	0	0	0.309	0.453	0.527
Spain	0	0.728	0.123	0.330	0.295	0.372	0.314
Turkey	0.683	0.531	0.615	0.132	0.490	0.573	0.584
2018							
France	0.465	1	1	1	0.866	0.844	0.845
Italy	0.151	0	0.451	0.559	0.290	0.297	0.299
Portugal	1	0.330	0.131	0	0.365	0.489	0.489
Spain	0	0.656	0	0.227	0.221	0.286	0.200
Turkey	0.564	0.694	0.696	0.040	0.499	0.570	0.622
2019							
France	0.166	0.866	1	1	0.758	0.828	0.828
Italy	0	0	0.584	0.565	0.287	0.305	0.259
Portugal	1	0.294	0	0	0.324	0.517	0.517
Spain	0.174	0.761	0.293	0.267	0.374	0.458	0.349
Turkey	0.628	1	0.862	0.159	0.662	0.788	0.816
2020							
France	0.188	1	1	1	0.797	0.880	0.880
Italy	0	0	0.680	0.567	0.312	0.334	0.261
Portugal	1	0.456	0	0.054	0.378	0.569	0.569
Spain	0.502	0.868	0.564	0.204	0.534	0.600	0.594
Turkey	0.090	0.789	0.707	0	0.396	0.499	0.523

all aggregators. However, the intermediate positions change depending on the operator used. For example, UNS Choquet places Spain in the fourth position; however, UNS&S places Spain in the last.

In 2018, France was quite far from the rest of the countries. The rankings obtained by the three aggregation operators are the same. Turkey occupies the second place, and its weakness is in Availability, on which it achieves a very low score. Spain ranks last position due to its zero in Acceptability and Affordability.

In Table 14, the scores for Energy Security in the year 2019 show the two top positions (France and Turkey) and the bottom (Italy) hold for all aggregators. The difference between the scores of France and Turkey decreased this year due to Turkey's improvement in Affordability and Accessibility. Note that Affordability is the most important criterion in profile 2. The rankings obtained by both the UNS and UNS&S Choquet methods were the same, but the average operator swaps the third and fourth places (Portugal and Spain).

In 2020, the rankings obtained by both the unsupervised and UNS&S Choquet methods were the same, but the average operator changed the ranking of the intermediate ranks. Turkey lost its third position in in favour of Portugal due to bad results in Acceptability. Again, as in 2018, France moved away from the rest of the countries.

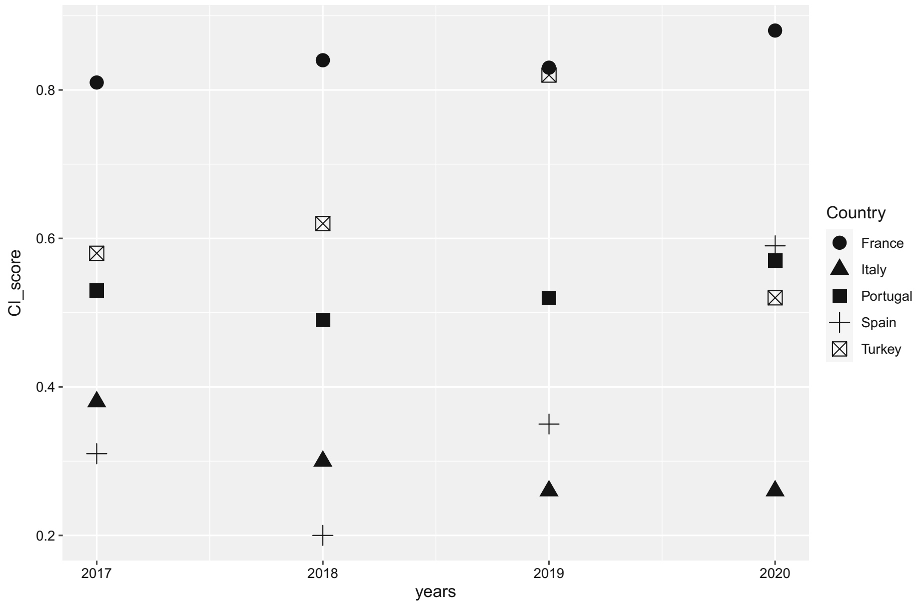

Fig. 6 Results for Energy Security using the UNS&S Choquet Integral

A graphic summary of the results obtained can be seen in Fig. 6. The predominance of France is clear, and the inferiority of Spain and Italy is also notable. However, Spain has improved substantially in the last year of the database.

5 Conclusions

The modelling of the Energy Security assessment of the countries is an appealing research question that we have addressed by applying a new hybrid methodology, UNS&S-CI, which introduces preferential/expert information into a multi-criteria technique. In addition, this hybrid methodology allows modelling the interaction between criteria which is a very interesting research issue where not only the importance of each criterion but also the importance of each subset of criteria is taken into account. In this context, the Choquet Integral is an alternative tool to the weighted arithmetic mean that incorporates the preferential priority of each subset of criteria. The methodology based on Choquet Integral runs in two phases. Firstly, a capacity is identified according to data behaviour; secondly, a distance minimisation process is applied in order to find a capacity close to the one found early, verifying several constraints established by the expert on the importance of the indicators and interactions among them.

The proposed methodology is applied to the five countries for the period 2017–2020. Results show the special situation of the Iberian Peninsula, rated in the worst positions in Affordability. It is worth highlighting the improvement of Spain in Acceptability (from the last position in 2017 to the second one in 2020). France consistently performs well in both climate resilience and risk poverty rate. When Energy Security is evaluated using the Choquet aggregation of the 4As over several years, France consistently ranks first. However, Italy and Spain have consistently ranked low in Energy Security during this time period.

The governments of Spain and Portugal have proposed National Energy and Climate Plans for the period 2023-2030, PNIEC and PNEC, respectively, in compliance with Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the governance of the Energy Union and Climate Action. Both plans aim to fulfil the commitments made under the EU framework and the Paris Agreement, as well as to contribute to the transition to a low-carbon and climate-resilient economy.

It was noted that only France had opted for electricity generation from nuclear power plants, which is why its current energy dependency rate (44.4) is below the European average and much lower than that of Spain and Portugal. This may explain France's objections to building the MidCat gas pipeline (gas interconnection between Spain and France through the Pyrenees), considering it "useless to confront the current crisis and harmful to the environment." However, Spain and Germany see the construction as useful and beneficial. The same context explains that "France and around twenty OECD countries are promoting an alliance to relaunch nuclear power."

The main conclusion of the empirical study is that the energy independence of these countries can only be achieved with the use of renewable energy or nuclear energy due to the scarcity of fossil energy resources. However, the availability that renewable energies can offer may come at a high price, worsening affordability. Renewables can be expensive and, in most cases, produce non-dispatchable energy that has to be supported by traditional dispatchable energy. Strong innovation would be needed to improve some issues in the application of renewables. Furthermore, the acceptance of renewable energies should be thoroughly analysed by broadening the criteria for the social acceptance of such energies. In addition, each country's idiosyncrasy should be considered when choosing which type of renewable energy is most comfortable for the population. In-depth research should be carried out to include more criteria in the Acceptability dimension that take into account the well-being of citizens, public concerns on climate change, inequality, depopulation, among others.

Taking into account (and being able to take into account) these "peculiarities" when modelling Energy Security would undoubtedly bring advantages in planning. The citizens' knowledge of the criteria of the decision-makers, their constraints, collisions of interests, and imbalances will guarantee fair Energy Security for all stakeholders.

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Declarations

Conflict of interest Amelia Bilbao-Terol declares that she has no conflict of interest. Verónica Cañal-Fernández declares that she has no conflict of interest. Carmen Gónzalez-Pérez declares that she has no conflict of interest.

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