European Journal of Operational Research 298 (2022) 611–626

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Decision Support

Multicriteria decision support for the evaluation of electricity supply resilience: Exploration of interacting criteria

Eleftherios Siskos*, Peter Burgherr

Laboratory for Energy Systems Analysis, Paul Scherrer Institute, PSI, Villigen, Switzerland

ARTICLE INFO

Article history:
Received 22 December 2020
Accepted 12 July 2021
Available online 20 July 2021

Keywords:
Multiple criteria analysis
Electricity supply
Resilience
Interacting criteria
Choquet integral

ABSTRACT

The resilience of an energy system and especially the national electricity supply is a complex and multidimensional concept, which is receiving growing attention at a European level. In particular, the increasing risks of extended electricity supply disruptions and/or severe electricity price fluctuations are stressing the need for an assessment of the European countries' electricity supply resilience. This paper proposes an elaborative multicriteria decision support methodological framework, based on three major resilience dimensions, namely: "resist", "restabilise" and "recover". In total, 35 European countries are evaluated and ranked according to their performance on 17 interacting evaluation criteria. The overall evaluation of the countries is established based on a synergy of two complementary multicriteria decision aid (MCDA) methods. Specifically, the Choquet Integral is approached and assessed as an importance indicator to properly accommodate and incorporate the interacting criteria into the value system, negating therefore their arbitrary effects on the final benchmarking. Simultaneously, a procedure based on the Simos method supports the robust elicitation of the Choquet capacities. All preferential information required for the implementation of the MCDA framework has been elicited from an expert, highly knowledgeable of the European energy system. This research work aims to support energy policymakers in Europe and provide guidelines and areas for improvement at a country level.

1. Introduction

Energy resilience is a multidimensional concept, increasingly establishing a prominent role in national and international policymaking. As such, it affects all dimensions of sustainability, namely the economy, the society, the environment and the governance, and assures the high quality of life and wellbeing of citizens (Gatto & Drago, 2020). In the scientific literature, the connection between resilience and sustainability has been emphasized and examined from different perspectives (Marchese et al., 2018; Gatto & Busato, 2020; McLellan et al., 2012). Furthermore, energy system resilience is also interwoven with the security of electricity supply (Gasser et al., 2019), and specifically with the ability of an energy system to retain, react and overcome potential disruptions, caused by endogenous or exogenous shocks in the economy, society, politics or the environment. Strong energy resilience of a system translates to a significant resistance to perturbations, fast recovery due to the learning capacity to adapt to change and a balancing to an improved and more efficient state (Hosseini, 2020; McCollum et al., 2020).

The multitude of benefits that a resilient electricity supply system offers to modern society, the economy and the political stability are unambiguous and therefore demand a concrete and diaphanous evaluation framework (Gillespie-Marthaler et al., 2019). Hence, resilience benchmarks are used to assess the progress of a country over a period of time and compare its performance against its peers (Gasser et al., 2020). Such focused assessments can have significant practical impact and drive socio-economic and political progress, influencing and driving the development of relative initiatives, policies and technological research (Siskos et al., 2014). Similarly, the results of benchmarks and studies in the broader area of energy policy, and particularly those issued by international organizations (WEF, 2020; IEA, 2020; WEC, 2020; REA, 2019), attract the interest of a variety of observers, including governments, energy agencies and citizens associations.

The multi-dimensionality of energy resilience and the conflicting viewpoints and interests of the different stakeholders on the topic demand a rigorous, yet transparent, benchmarking framework. Towards this direction, Multicriteria Decision Aid (MCDA) offers the appropriate theoretical background and principles, as well as a multitude of tools and techniques to perform such demand-

* Corresponding author.
E-mail addresses: eleftherios.siskos@psi.ch (E. Siskos), peter.burgherr@psi.ch (P. Burgherr).

https://doi.org/10.1016/j.ejor.2021.07.026

ing tasks. MCDA, in particular, has been extensively used to support complex decision making and successfully provide insight on multi-faceted and controversial problems. For a comprehensive review on the MCDA applications see Greco et al. (2016).

The problem of the evaluation of energy security, resilience and sustainability has been approached by several studies that have exploited the benefits of MCDA; some of which are selectively presented here. Recently, Resce and Schiltz (2020) evaluated sustainable development in Europe, using the Hierarchical SMAA (Stochastic Multicriteria Acceptability Analysis), whereas Shah et al. (2019) evaluated energy security and environmental sustainability in Asia, using Data Envelopment Analysis (DEA). Neofytou et al. (2020) evaluated energy transition readiness in Europe, through the synergy of the AHP and the PROMETHEE methods. Gasser (2020) published a review on the indices employed to evaluate energy security, within a resilience perspective, at a national level. Angilella and Pappalardo (2020) built an integrated multidimensional system to evaluate energy companies, while Kumar et al. (2017) presented a state-of-the-art on MCDA applications towards sustainable energy development. In the context of different methodological frameworks Matsumoto et al. (2018) evaluated energy security in Europe, using time-series clustering approaches and three energy security indicators based on the Shannon–Wiener diversity index, Neelawela et al. (2019) constructed a composite indicator, and Hirschberg and Burgherr (2015) implemented a portfolio of different analytical approaches to assess the sustainability of energy technologies.

Although, all the aforementioned approaches build comprehensive indices and composite indicators to perform a ranking of countries, none of them delves further into the specific subindicators and criteria to explore and consider their potential overlaps, redundancies and/or synergies. The analysis proposed through this paper falls in the recently studied context of interacting criteria (Grabisch & Roubens, 2000), which receives growing attention from researchers and practitioners in the field of MCDA (Figueira et al., 2009; Grabisch et al., 2008; Greco et al., 2014). The case of interacting evaluation criteria, although meaningful and promising for this scientific field, requires a strong cognitive burden for the stakeholder – decision maker (DM), who is required to articulate his/her preference input, framing the decision model (Grabisch & Roubens, 2000; Angilella et al., 2018). Hence, until now, a limited number of non-theoretical studies, addressing the issue of interacting criteria of an actual evaluation problem have been published. Most of these, in fact, consider either didactic examples or limited scale applications, without always demonstrating in a comprehensible way the decision processes and the actual interaction between the analyst and the DM, in order to elicit the preferences and the decision parameters, pertaining to the interacting criteria.

The main contribution of this paper is the implementation of a credible and comprehensive MCDA evaluation framework of the resilience of electricity supply in Europe, which considers the possible interactions between the evaluation criteria. The framework adds to the whole assessment the subjective nature of the preferences of a real energy expert, highly knowledgeable of the European energy status quo, which serves the paper's objectives to achieve a personalized resilience ranking. In terms of the methodological contribution of the paper to the respective literature, the paper proposes a synergy of preference elicitation techniques to support the application of the Choquet integral utility function. It is important to emphasize here that the Choquet integral is approached and assessed as an importance indicator. The proposed elicitation techniques include a new procedure, based on the rationale of the Simos method and a novel interactions identification and quantification framework, based on a direct pinpointing of the interactions and the inclusion of certain additional heuristic questions and pairwise comparisons. The Simos procedure, especially, has been selected, in order to facilitate the DM in confidently providing preferences on the highly diversified criteria family. On the other hand, the interactions are examined in pairs of criteria, since the consideration of more complex structures is barely conceivable and controllable by both the analyst and the DM.

In terms of the criteria modeling procedure for the electricity supply resilience evaluation, this paper extends the work of Gasser et al. (2020), building upon the 11 indices proposed in that study. In particular, six additional criteria are included in the evaluation framework, and one is modified to fit the European context, as pointed out by the DM. In the end, 17 evaluation criteria are modeled and categorized to the energy resilience dimensions, which have now been reduced to three, instead of four. In this way, an equal representation of the dimensions is achieved avoiding at the same time the simultaneous assignment of a criterion to more than one resilience dimensions. The criteria are quantified using the latest criteria data and form the framework to evaluate and rank 35 European countries in total.

The paper is organized as follows: Section 2 presents an overview of the methodological concepts used in the paper, whereas Section 3 describes the electricity supply resilience evaluation problem and the criteria modeling. Section 4 outlines the methodological framework pursued in the study, followed by its implementation in the European context in Section 5. Section 6 concludes the paper. The criteria data, referring to the countries under evaluation, are provided in the Appendix of the paper.

2. Basic concepts

The basic methodological concepts used in this study are introduced and elaborated in this section. Specifically, in Section 2.1 the Choquet integral preference model is presented, along with the 2-additive capacities that are mainly used in MCDA problems. Section 2.2 describes the Simos method, or the method of the cards, and its variations proposed later, i.e. the Revised Simos method and the Robust Simos method.

2.1. The Choquet integral preference model

Each evaluation problem, falling into the category of MCDA, comprises a specific number of evaluation criteria. Let $G = \{g_1, g_2, \dots g_n\}$ be the set of the n evaluation criteria and 2^G the set of all subsets of G. A capacity, the measure in conjunction with which Choquet can be applied, is a function $\mu : 2^G \to [0, 1]$, with $\mu(\emptyset) = 0$ and $\mu(G) = 1$, which constitute the normalization constraints. Additionally, the monotonicity constraints need to be respected, such that $\mu(T) \leq \mu(R)$ for all $T \subseteq R \subseteq G$. The Möbius representation of the capacity μ is the function $m : 2^G \to \mathbb{R}$, and for all $R \subseteq G$ is:

$$\mu(R) = \sum_{T \subseteq R} m(T) \tag{1}$$

If A is the set of actions/alternatives under evaluation, and $a \in A$, then the Choquet integral of a, using the Möbius representation of the capacity μ, is:

$$C_\mu(a) = \sum_{T \subseteq G} m(T) min_{i \in T} g_i(a) \tag{2}$$

where $g_i(a)$ is the evaluation of the action a on the criterion g_i. This general form of the Choquet integral considers not only the importance of the criteria as singletons but also their contributions to all coalitions with the rest of the criteria (see Grabisch & Roubens, 2000; Angilella et al., 2016, for more information). However, due to the cognitively hard inference of all these parameters, in real world applications, the simplified version of Choquet is used, which considers 2-additive capacities. Despite the simplification of the capacities from their general form, they are still flexible enough to model nonlinear interactions, such as positive and negative ones (Pelegrina et al., 2020).

This simplified mathematical expression considers only interactions between pairs of criteria and requires therefore the identification of $n + \binom{n}{2}$ parameters, namely m_i for each criterion and $m_{i,j}$ for each couple of criteria. The Choquet integral in that case, using the Möbius representation, takes the following form:

$$C_\mu(a) = \sum_{i \in G} m_i \, g_i(a) + \sum_{\{i,j\} \in G} m_{i,j} \, min\{g_i(a), g_j(a)\} \tag{3}$$

The normalization constraints take the form:

$$m(\emptyset) = 0, \; \sum_{i \in G} m_i + \sum_{\{i,j\} \in G} m_{i,j} = 1 \tag{4}$$

while the monotonicity constraints are:

$$\begin{cases} m_i \geq 0, \quad \forall \; i \in G \\ m_i + \sum\limits_{j \in T} m_{i,j} \; \geq 0, \; \forall \; i \in G \; and \; T \subseteq G \backslash i, \; T \neq \emptyset \end{cases} \tag{5}$$

In the framework of the Choquet integral, the m_i (single capacity from now on) corresponds to a value that is closely connected to the importance of the criterion i, hence being always positive (Pelegrina et al., 2020; Angilella et al., 2016). However the $m_{i,j}$ (dual capacities from now on), which correspond to the interaction between criteria i and j can be either positive, negative or zero (Angilella et al., 2016).

- A positive dual capacity, implies a complementary behavior between i and j. This means that the simultaneous satisfaction of both criteria by an alternative provides additional added value, and therefore this alternative is awarded with a bonus score.
- A negative dual capacity, implies a redundant behavior between i and j. This means that the satisfaction of either i or j is sufficient to have a significant effect on the global score. Therefore, an alternative that excels in both i and j, will receive a penalty, to compensate for the redundancy effect between the two criteria.
- A dual capacity that is equal to zero, signifies that there is no kind of interaction between i and j.

For the assessment and calculation of the Choquet capacities, several procedures have been proposed. One popular approach is the regression method, building upon certain DM's preference statements, by Marichal and Roubens (2000) and its extensions by Angilella et al. (2010 and 2015). In Grabisch and Labreuche (2016) and Grabisch (2016) the capacities are calculated using the MACBETH method (Bana e Costa et al., 2012). Other more analytical approaches include the least square method by Mori and Murofushi (1989), the minimum variance method by Kojadinovic (2007), the least squares method by Meyer and Roubens (2005) and the building of interval scales through the deck of cards method by Bottero et al. (2018).

In this paper, the Choquet value function (3)–(5) is interpreted and assessed as an importance indicator, through a carefully designed integrated methodological framework, which is described in Section 4.

2.2. Rationale of the Simos methods

The original Simos Method or method of cards (see Simos, 1990, Maystre et al., 1994, Pictet & Bollinger, 2008) consists of the following three information extraction steps:

1. The decision maker (DM) is provided with a set of cards, with the name of one criterion on each (n cards, each corresponding to a specific criterion of the criteria family G). A number of white cards are also provided to the DM.
2. The DM is asked to arrange the n criteria cards from the least to the most important. If multiple criteria have the same importance, the DM builds a subset (ex aequo criteria) by holding the corresponding cards together with a clip.
3. The DM is finally asked to introduce white cards between two successive cards (or subsets of ex aequo criteria), when he believes there exists a larger gap of importance. The gap of importance between the weights of the successive criteria (or the subsets of criteria) can increase linearly by adding several white cards.

For the calculation of the criteria weights, Simos (1990) proposed some basic mathematical procedures, based on the assignment of positions and calculation of non-normalized and normalized weights in [0, 100].

However, due to the significant lack of robustness in the results, Figueira and Roy (2002) proposed a revised Simos method, introducing a fourth step to the procedure, which requires the inference of a ratio z. This ratio signifies how many times is the last criterion more important than the first criterion, and it adds significantly to the stability of the results. More recently, Siskos and Tsotsolas (2015), in an attempt to control further the robustness of the weights of the Simos procedure and include the DM in the corresponding issue and the amendment actions, proposed a set of rules and measures that need to be followed, each time the Simos method is applied. Corrente et al. (2020) proposed a new version of the original Simos method by integrating additional kind of preference information.

3. Developing an electricity supply resilience evaluation framework

In this section, the electricity supply resilience in Europe is defined and a corresponding evaluation system is built, in order to perform a benchmark of the European countries. This evaluation system consists of specific criteria, assigned to the different resilience dimensions, and accompanied with their corresponding data and measurement units. For the purposes of this benchmark, 35 European countries have been selected, which altogether form the European Network of Transmission System Operators for Electricity (ENTSO-E). In this study, a Swiss energy expert with many years of professional experience in the European energy system plays the role of the Decision Maker (DM).

3.1. Criteria modeling

To achieve an overall assessment of electricity supply resilience (ESR) in Europe, a consistent family of criteria is constructed, following the classical multicriteria modeling principals, proposed by Roy (1985). According to this procedure, the multicriteria evaluation system should be composed, in close collaboration between the analyst and the DM.

Towards this direction, a hierarchical structure of criteria is modeled, based on the resilience dimensions introduced in the Introduction. This decomposition of the resilience problem into three dimensions helps further the analyst and the DM to model their objectives, achievement of objectives and values (Keeney, 1992). Specifically, the analyst and the DM agreed to reduce the often-used four resilience dimensions to three: “Resist”, “Restabilise” and “Recover”, by merging “Rebuild” and “Reconfigure” to the newly proposed “Recover”. Through this change, the DM wanted to treat evenly these two closely connected system-recovery phases, other-

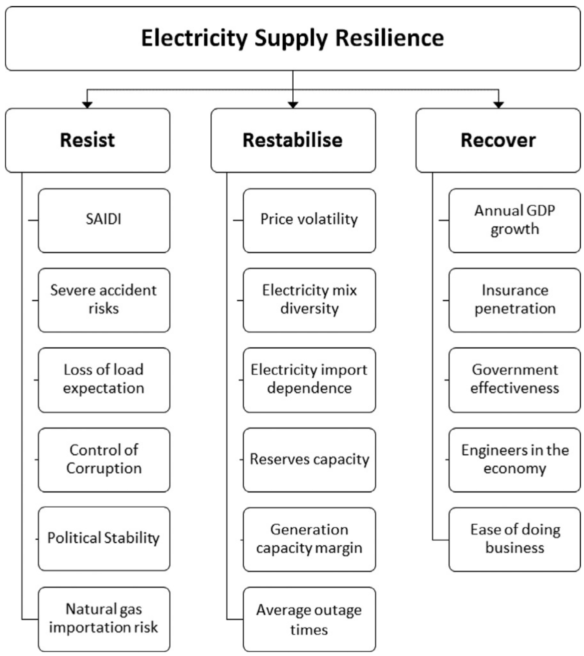


Fig. 1. The evaluation system of Electricity Supply Resilience.

wise it would pose modeling difficulties in specifying criteria that apply to each one separately.

As a next modeling step, a number of evaluation parameters is defined for each dimension, which form the final set of 17 evaluation criteria. The criteria that compose each resilience dimension have been proposed and assigned, with a view to guiding the decision making process in a controllable, complete, measurable, non-redundant and concise way. Additionally, an equal representation of the three resilience dimensions was achieved through an even allocation of the criteria to them. In the end, the three dimensions include six, six and five criteria, respectively (see Fig. 1).

The basis for the criteria selection procedure is the Resilience index proposed by Gasser et al. (2020), consisting of 12 indicators, categorized according to four distinct resilience dimensions. Particularly, 11 of these indicators were selected for utilization in this study, in agreement between the analyst and the DM, while the Equivalent Availability Factor was modified to the Generation Capacity Margin criterion. Five additional indicators were added in the final criteria family, in order to more adequately account for the major resilience aspects, such as the stability of the pricing of commodities, the reliability of the natural gas providers and the volume of reserves of each European country. The five new criteria are namely: Loss of load expectation, Natural gas importation risk, Price volatility, Reserves capacity, and Engineers in the economy. Fig. 1 presents the final evaluation system of Electricity Supply Resilience in Europe. The following paragraph describes the 17 evaluation criteria in detail.

3.2. Criteria description and analysis

This paragraph concisely presents the 17 selected criteria (g_1 to g_{17}). The primary data, feeding the criteria and the sub-criteria the former are composed of, are compiled from reliable and recognized sources, such as the Statistical Administration of the European Commission (Eurostat), the International Energy Agency, the World Bank, etc. The criteria descriptions are given hereafter, while the complete dataset is provided in the Tables A1 and A2 of the Appendix.

g_1 – System Average Interruption Duration Index - SAIDI: The SAIDI is a measure of the total duration of electricity supply interruptions per customer per year. It is a commonly used indicator and a direct representation of the quality and reliability of electricity supply. A high SAIDI value indicates that electricity supply disruptions are frequent and/or last long, meaning that the system does not perform satisfactorily and is susceptible to blackouts in the case of potential disturbances.

g_2 – Severe accident risks: This criterion quantifies the number of fatalities in severe accidents (≥ 5 fatalities) per unit of annual electricity produced (GWeyr[1]). The data on the European countries stem from the work of Burgherr et al. (2020). Initially, the indicator is quantified for each generation technology and then aggregated according to the production mix of each country. The fatalities do not only include events from the actual power production, but all stages of the production, transmission and transfer chain (Burgherr & Hirschberg, 2008). A high value indicates that severe accidents are frequent, resulting in a higher fatality rate, occurring in countries with lower safety standards or inadequate technological expertise.

g_3 – Loss of Load Expectation - LOLE: The LOLE represents the number of hours per year in which the supply will not meet the demand. It is a resilience indicator, derived from probabilistic market modeling tools, which attempts to forecast the reliability of the European energy systems in the coming years. The indicator data refer to the base case scenario of 2020 and were published in the Mid-term Adequacy Forecast report of the European Network of Transmission System Operators for Electicity, (2018).

g_4 – Control of Corruption: Control of corruption is a composite governance measure that captures to which extent public power is used for private gains. Hence, higher corruption is more likely to lead to disruptions within the system, because the individual sociopolitical components are less robust and there is usually a considerable lack of well-established processes, to prevent and/or address faster power failures, during critical situations (Wang & Zhou, 2017). Control of corruption is an aggregate indicator, measured as a percentile rank, indicating the rank of a country among all countries, provided by the (World Bank, 2018).

g_5 – Political stability and absence of violence/terrorism: A composite indicator that measures to what extent the political system is stable and not hindered by acts of violence and terrorism. Similar to the control of corruption, a higher political stability and absence of violence or terrorism leads to fewer disruptions in the electricity system (Ang et al., 2015). In fact, since political stability fosters long-term investments, the infrastructures in politically stable regions, including these related to the power sector, are of higher quality (Wang & Zhou, 2017). This criterion, like g_4, is an aggregate indicator, measured as a percentile rank, indicating the rank of a country among all countries, provided by the World Bank.

g_6 – Natural gas importation risk: This indicator quantifies the risk of natural gas (NG) importation from third countries. The indicator builds upon the political risk indicator of the exporting countries r_j and the diversification of the NG imports for the country under evaluation i. The NG imports data are provided by OECD (2019), while the political risk assessment stems from the monthly datasets, issued by the PRS Group (PRS, 2020). The political risk is a composite qualitative indicator, ranging in [0, 100], $r_j \in \mathbb{N}$, which considers subcomponents, such as socioeconomic conditions, the investment profile, internal and external conflict, government stability, religious and ethnic tensions, etc. (see PRS, 2020 for more information). The natural gas importation risk R_i for a country i is

[1] GWeyr stands for GigaWatt$_{\text{electric}}$year. It is a unit of electrical energy, where 1 GWeyr = 8760×10^6 kWh of electricity

calculated, based on the following expression:

$$R_i = 1 - \sum_j I_{ij} \cdot \frac{r_j}{100} \tag{6}$$

where I_{ij} is the import percentage of country i from country j. The expession is reversed, via the subtraction with 1, since the PRS political risk index is a decreasing index (the higher the r_j the lower the risk).

g_7 – Volatility of electricity prices: This criterion measures the volatility of electricity prices for households over the last decade. Electricity supply resilience and subsequently energy poverty, apart from the availability of electrical energy, are strictly linked with the affordability of it by the consumers. An effective way to measure the latter is the stability or volatility of electricity prices. To do so, this criterion measures the yearly percentagewise deviation of electricity prices (€/kWh) for households, during the last 12 years. The volatility of electricity prices is then calculated as the standard deviation of the previously defined yearly deviations. Electricity pricing data stem from Eurostat and concern the timeframe of 2008–2019.

g_8 – Electricity mix diversity: This criterion measures the diversification of the electricity mix of each country, to different electricity generation technologies. Diversity is one of the key features for the ability to restabilize a system. In the case of unforeseen supply disruptions, it allows an easier shift from one technology to another or to modify the supply routes (Kruyt et al., 2009). Hence, a diverse supply is a good way to hedge against unforeseen supply risks and mitigate the effects of potential future technology lock-ins (Molyneaux et al., 2012). It is calculated using electricity generation data, extracted from the International Energy Agency (IEA, 2018), and the popular mathematical expression of the normalized Shannon index (Spellerberg & Fedor, 2003):

$$H' = -\frac{1}{\ln N} \sum_i p_i \cdot \ln p_i \tag{7}$$

where p_i is the share of technology i in the generation mix and N denotes the total number of technologies. The different power generation technologies which were considered are: coal, oil, natural gas, biomass, nuclear, hydropower, geothermal, solar photovoltaic, wind and other sources (e.g. solar thermal, tides, waves, ocean). The Shannon index has been normalized between 0 and 1 by dividing by natural logarithm of N, meaning that when the technologies have roughly equal share in the electricity mix of a country the index converges to 1. On the other hand, the extreme case of 0 arises when electricity production relies only on a single technology.

g_9 – Electricity import dependence: This criterion defines the ratio between electricity consumption and production in each European country. A country with a value lower than 1 (production > consumption) has export capabilities and therefore presents more flexibility on the flows to better absorb disruptions, because of the higher ability to reroute flows (Sovacool & Mukherjee, 2011). In addition, in emergency cases, that country could use the production excess for its own consumption. On the other hand, a country with a value higher than 1 (consumption > production) has an import dependence, being thus vulnerable to shortages. In addition, a country reliant on imports is affected by the stability of the supplier, a fact that apparently increases the chances of non-delivery and heavy price fluctuations (Molyneaux et al., 2012).

g_{10} – Reserves capacity: The reserve capacity is the amount of power ready to be dispatched, in order to cover supply shortages. Specifically, each national transmission system operator procures ancillary services to ensure a balanced electricity grid, on the basis of agreements with certain producers and customers, to increase or decrease the production or demand of certain sites. The aim is to compensate for the unbalance that could be caused by unexpected loss of production or demand and renewable forecasting deviations. The reserve capacity is an accurate indicator to model the recovery shape of the resilience curve, as the larger the reserve capacities, the faster a system can recover from a disruption. The criterion is measured as a percentage of the total peak demand in a country and data are provided by ENTSO-E in its Mid-term Adequacy Forecast report, published in 2018.

g_{11} – Generation capacity margin: The average capacity margin is a measure indicating the margin of each country's actual electricity production compared to its total installed capacity. This margin in essence shows if the power plants are capable of increasing their operation time or if they are currently operating at their full capacity. The existence of a margin means that there is a possibility to switching electricity production between different power plants of the same or different technology in the case of a disruption. This resilience measure is only meaningful and applicable for the case of dispatchable electricity production technologies, and therefore not for the stochastic renewable energy sources.

The Generation Capacity Margin (GCM) of a country is calculated as follows:

1. The annual electricity production from each dispatchable technology is divided by the respective installed capacity and the 8,760 hours of a year. The electricity production data are measured in GWh and stem from the IEA, while the capacity data are measured in GW and are retrieved by ENTSO-E. All data refer to the year of 2018. The hydropower data do exclude run-of-river, since it is a non-dispatchable technology.
2. The capacity factors calculated in (1) are subtracted to the availability factors of each technology, in order to estimate the respective capacity margins. The availability factors have been estimated, based on data from Roth et al. (2009) and the US Energy Information Administration (EIA) (Energy Information Administration, 2020). The availability factors for each technology are summarized in Table 1.
3. The capacity shares are calculated by dividing the installed capacity of each technology with the total installed electricity production capacity. The resulting percentages represent the shares of each technology to the national electricity production mix.
4. The capacity margins of each technology of (2) are multiplied with the respective capacity shares of (3), resulting to the average capacity margin of each technology, hence the GCM.

g_{12} – Average outage time: The average outage time is the ratio between SAIDI and the System Average Interruption Frequency Index (SAIFI). Hence, it represents the average length of disruptions until their successful recovery. Countries with detailed emergency preparedness measures, defined processes, human and financial capabilities are expected to restore electricity supply faster (Finster et al., 2016).

g_{13} – Annual GDP growth: A country exhibiting an expansion to its Gross Domestic Product (GDP) is expected to foster long-term investments and economic growth, a fact that usually positively affects the improvement of the resilience of its electricity supply system. To this end, this criterion measures the evolution trend of each country's GDP by calculating its weighted average growth/shrinkage, during the last 6 years, namely between 2013–2018. To magnify the impact of the most recent years to the evolution trend of the country's GDP, each consecutive year is given an additional weighting point, compared to the preceding year. The criterion considered data since the year of 2013, in order to avoid the influence of the global economic crisis data, prior to 2012. The country data are extracted from the World Bank.

g_{14} – Insurance penetration: An economic composite indicator quantifying the access to financial resources, necessary to rebuild

Table 1
Availability factors per electricity production technology.

Coal	Oil	Natural Gas	Biofuels	Waste	Nuclear	Hydropower	Geothermal
0.85	0.85	0.85	0.85	0.85	0.98	0.80	0.90

a system. A framework of high insurance penetration is the fastest and most equitable mean of financing reconstruction (Asgary et al., 2015), additionally decreasing the workload for governments by shifting the administrative expenses to insurance companies in the private sector. Consequently, an adequately and properly insured system gains faster access to the financial resources necessary to overcome a disruption or crisis. Insurance penetration is an indicator that measures premiums as a percentage of the GDP and is provided by Sigma-Explorer of the Swiss Re Institute (2018).

g_{15} – Government effectiveness: Government effectiveness represents the quality of public services and the readiness of policy formulation and implementation. Consequently, since the restoration of damaged infrastructure is a complex and time-intensive process, involving many different bodies, an effective government, with clearly defined processes and governance, leads to faster and more effective recoveries (Heinimann & Hatfield, 2017, Martišauskas et al., 2018). Government effectiveness is an aggregate indicator, measured as a percentile rank, indicating the rank of a country among all countries. The indicator data are extracted from the World Bank.

g_{16} – Engineers in the economy: This criterion measures the annual influx of engineers in the country's workforce. This metric is useful to assess the available human resources in the context of "skilled personnel resources", who are highly relevant to the field of electricity production and supply. Engineers would provide the needed expertise, local system knowledge and ingenuity in rebuilding the electricity system's functionality after a disaster or a minor disturbance to the electricity supply system. The criterion includes the annual graduates, pertaining to the International Standard Classification of Education (ISCED 2011) Field of education and training F07 – Engineering, manufacturing and construction. The numbers of the graduates are then divided by the total population of the country, to switch to the percentagewise influx of engineers in the population. The data, extracted from the Eurostat database, refer to the year of 2017.

g_{17} – Ease of doing business: The ease of doing business index represents the conduciveness of the regulatory environment to start and operate businesses (World Bank, 2017). A country with a fast, simple and transparent investment regulatory framework is more competent to implement technological change and consequently upgrade its power system with more performant components, technologies and monitoring equipment. On the other hand, a country with an unfavorable investment environment hinders the involvement of the private sector (Laldjebaev et al., 2018), delaying therefore its adaptation to the new technological standards and reconfiguration capabilities. The ease of doing business score is the simple average of the scores for each of the Doing Business topics: starting a business, dealing with construction permits, getting electricity, registering property, getting credit, protecting minority investors, paying taxes, trading across borders, enforcing contracts and resolving insolvency.

The 17 criteria that form the evaluation system of the electricity supply resilience problem are summarized in Table 2, together with their resulting measurement units, data sources and date of data. The data on each criterion have been selected based on the most recent available data entries. Each criterion can be of Increasing or Decreasing type (I or D); an increase in the country score, or a decrease respectively, indicates a better country performance.

4. Methodological framework

The evaluation system, described in the previous section, due to its significant size and the intricate and heterogeneous nature of the criteria, needs rigorous planning and management. In addition, the existence of interacting pairs of criteria, some of which being identified by the DM, already since the modeling phase, render the evaluation even more delicate and complicated.

For this reason, the methodological framework for the benchmarking of the countries, proposed by the analyst and endorsed by the DM, is based on a carefully planned and designed synergy of MCDA methods and techniques. The core method of the framework is the Choquet Integral value system, which calculates a resilience score for each European country, based on which a ranking will be formed. The strong benefit of the Choquet Integral is the consideration and management of interacting criteria, which, as described in Section 2, is highly relevant to the context of this study. As part of this study, and due to the high cognitive effort that is required by the DM, the criteria interactions will be examined in pairs and not in triplets or other more complex structures. Moreover, two types of intra-criteria interactions are considered, namely the positive and the negative ones.

The methodological framework begins with the assignment on a common utility scale of performances of the countries on the criteria, as required for the implementation of the Choquet integral (Bottero et al., 2018). Besides, the Choquet integral is complemented by two additional MCDA techniques, for the acquisition of the required input by the DM. Specifically, for the elicitation of the single capacities for each criterion m_i, a procedure based on the rationale of the Simos method is used. Additionally, for the elicitation of the dual capacities m_{ij} for each pair of criteria, a heuristic framework, which identifies and then calculates the potential interactions, is applied in cooperation with the DM. An overall flowchart of the methodological framework is depicted in Fig. 2.

4.1. Assignment of performances on a common utility scale

The utility values of the Choquet integral are the levels of a common interval scale, in general, within the range [0, 1]. In order to translate the original criteria scales to a single common scale for all the criteria, a procedure that accounts for the intensity of preferences between consecutive intervals of the scale will be followed (Bottero et al., 2018). Hence, the definition of at least two references levels for each criterion, I_p and I_q, is required in order to build the interval scale and anchor within it the computations.

In the context of the resilience evaluation system, the DM decided, after dialogue with the analyst, to build a continuous linear common scale [0, 1] for all the criteria, since he assumed for all a linear increase in the intensity of the utility of the countries, throughout the scales of the criteria.

The translation to a common interval scale will be therefore performed, using a linear normalization of the performances of the countries in [0, 1], guided in each criterion by two reference levels. The two reference levels will be assigned by the DM, based on his experience, preferences and the guidance of the dataset. The reference levels will therefore follow one of the following three schemes:

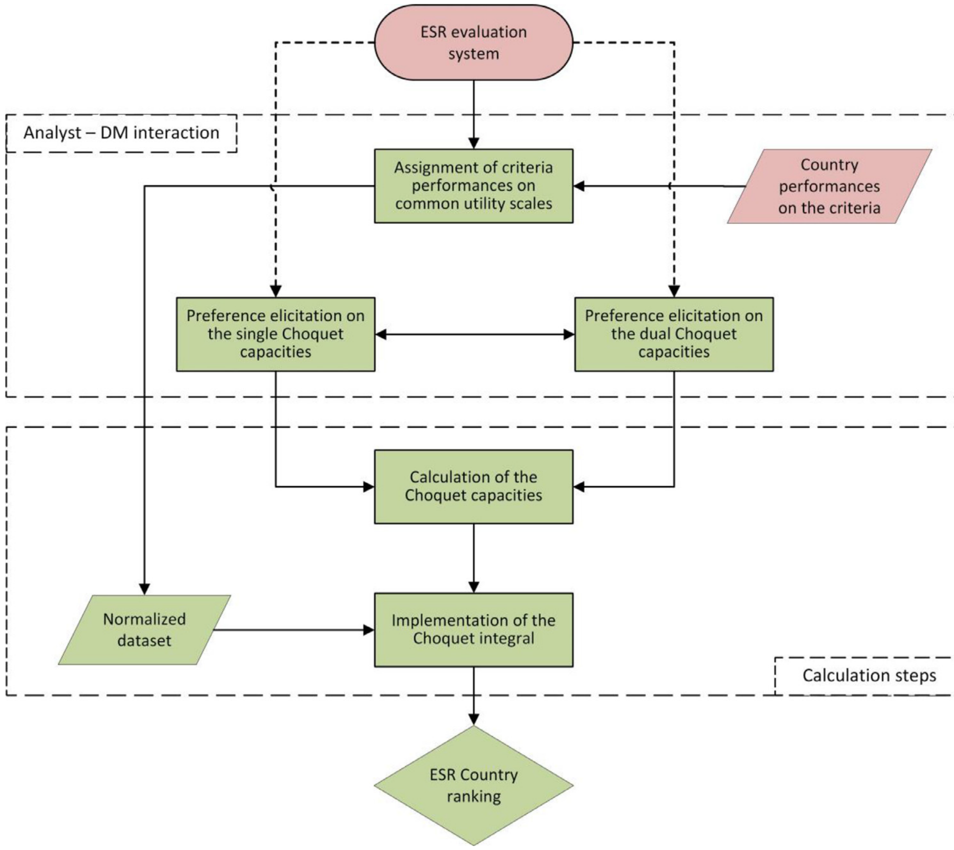


Fig. 2. Flowchart of the methodological framework.

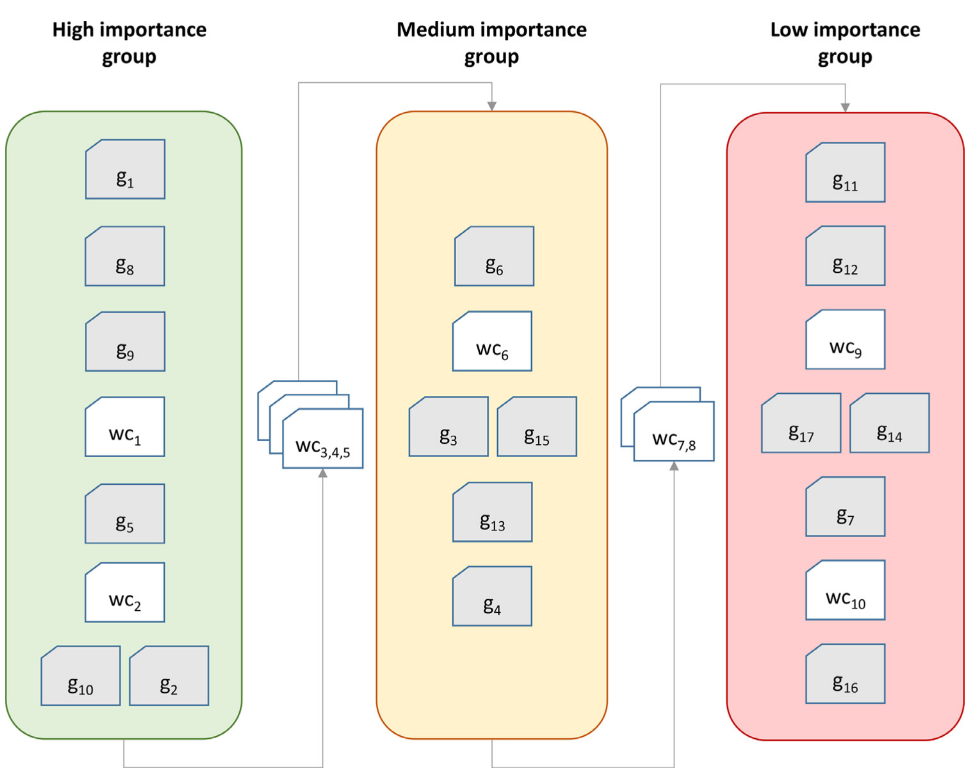


Fig. 3. Complete prioritization of the criteria, as given by the DM.

Table 2
Measurements units and data sources of the ESR criteria system.

#	Criterion	Measurement unit	Criterion type	Data source	Date of Data
g_1	SAIDI	h/year	D	Doingbusi-ness.org	2019
g_2	Severe accident risks	# of fatalities / GWeyr	D	Burgherr et al (2020)	2020
g_3	Loss of Load expectation	h/year	D	Entso-e	2020
g_4	Control of Corruption	Percentile Rank	I	World Bank	2018
g_5	Political stability	Percentile Rank	I	World Bank	2018
g_6	Natural gas importation risk	0-1 indicator	D	PRS Group, OCED	Imports: 2019 Risk indicators: 2020
g_7	Volatility of prices	% index	D	Eurostat	2008-2019
g_8	Electricity mix diversity	0-1 indicator	I	IEA	2018
g_9	Electricity import dependence	dimensionless ratio	D	IEA	2018
g_{10}	Reserves capacity	% index	I	Entso-e	2018
g_{11}	Generation capacity margin	% index	I	Entso-e, Eurostat, IRENA	2018
g_{12}	Average outage time	hours	D	Doingbusiness.org	2019
g_{13}	Annual GDP growth	% index	I	World Bank	2013-2018
g_{14}	Insurance penetration	% of GDP	I	Sigma-EXPLORER	2018
g_{15}	Government effectiveness	Percentile Rank	I	World Bank	2018
g_{16}	Engineers in the economy	% index	I	Eurostat	2017
g_{17}	Ease of doing business	Composite indicator	I	Doingbusiness.org	2020

- Perfect match of the reference levels with the best and worst country performances; all country performances are therefore normalized in the utility scale [0, 1].
- Reference levels within the best and worst country performances; country performances within the levels are as usual normalized in [0, 1], while outperforming countries are given the extreme utilities of 0 or 1.
- Reference levels beyond the best and worst country performances; all country performances within the levels are as usual normalized in [0, 1]. However, no country is assigned the extreme utilities of 0 or 1. The common interval scale has the capability margin of accommodating more extreme country performances, when new data arise or new countries, other than the 35 at hand, are integrated into the evaluation system.

4.2. Preference elicitation on the single Choquet capacities

For the sake of facilitating the DM in articulating his preferences on the extensively heterogeneous and complicated set of criteria, the Choquet single capacities are assumed to correspond to the criteria importance weights. For the determination of the single capacities m_i, a procedure based on the Simos method is proposed. In particular, the rationale of the Simos preference elicitation framework is followed, but with certain diversifications, as shown below, due to the complexity of the problem. In the end, the preference information on the single capacities is obtained in the form of the complete criteria ranking.

It must be noted, that this criteria ranking also incorporates and reflects information on the potential interactions between criteria pairs. Consequently, the DM is instructed by the analyst to account for them and accordingly include this information when externalizing his preferences. This input will be considered in 4.4, during the quantification of the Choquet capacities.

Specifically, the steps for the explicit elicitation of the preference information by the DM on the single capacities are as follows:

1. The procedure begins with the assignment of the criteria to three categories: low importance, medium importance and high importance. The analyst provides the DM with the criteria, in the form of cards, and asks him to split them in the three importance categories.
2. The DM, after confirming his categorization, focuses on each importance group and rank-orders the criteria from the most to the least important one. When two or more criteria are of equal importance, he clips the corresponding cards with a clipper. In the end of the rank-ordering, he can insert white cards between consecutive criteria or subsets of ex-aequo criteria to indicate a greater importance gap.
3. The DM indicates a potential number of white cards to be inserted between the high and medium importance groups, as well as the medium and the low importance groups. In this way, the three importance categories are merged and a complete ranking of the criteria is obtained.

For the quantification of the single capacities, a process like the one integrated in the Simos method (Simos, 1990), the one proposed in the Revised Simos method (Figueira & Roy, 2002) or the robust recommendations suggested by Siskos and Tsotsolas (2015) can be alternatively used. This depends on the needs of the methodology and especially on the necessity to account for and control the robustness of the model and the results.

4.3. Preference elicitation on the dual Choquet capacities

For the determination of the dual Choquet capacities $m_{i,j}$, a heuristic elicitation framework is applied. The dual capacities are assumed as the intensity of the interactions and the DM is asked to provide relevant preference information. This framework considers only the case of pairs of criteria, which exhibit either a positive or a negative interaction between them.

The framework is divided into three preference elicitation steps, beginning with the identification of the criteria pairs and continuing with the acquisition of information, required for the quantification of the respective interactions. The three steps are described as follows:

1. The DM is given an empty interactions table and asked to pinpoint the pairs of criteria that exhibit some sort of interaction between them. The criteria pairs that exhibit a positive or negative interaction are signified with a plus (+) or minus (-) sign, respectively. The DM identifies the interacting pairs, through his experience and by revisiting the criteria descriptions, measurement scales and datasets. He has also the possibility to consult

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3	+																
4		+															
5																	
6																	
7																	
8						-											
9								-									
10																	
11									-	+							
12																	
13																	
14																	
15				+													
16																	
17															+		

Fig. 4. Criteria interactions chart, as filled by the DM.

the data correlations table, since a positive correlation between two criteria can imply a negative interaction and vice versa.

2. The DM is asked to group the identified criteria pairs, based on the intensity of their interaction. Specifically, he categorizes the interacting pairs into two categories, i.e. strong and weak interactions. The kind of the interaction (positive or negative) does not play any role here.
3. The analyst asks for additional information on the identified interacting pairs of criteria. This can take the form of pairwise comparisons, most and least intense interactions, comparisons of triplets of criteria pairs, specific ratio or a ratio interval between the most and least intense interactions, etc. This input will be considered for the formulation of the linear problem in 4.4, the execution of which will give the Choquet capacities.

4.4. Determination of the capacities and implementation of the Choquet integral

The last part of the methodological framework concerns the quantification of the single and dual capacities, based on the preference information acquired in 4.2 and 4.3. The intervention of the DM is completed and the analyst is required to work on the information at hand, in order to estimate the capacities.

At this point, the preference information is considered altogether by the analyst, since the single capacities can only be obtained simultaneously and in conjunction with the dual capacities. To do so, the criteria ranking, obtained in 4.2, is translated into a system of mathematical equations and inequalities. Each mathematical expression, apart from solely considering the single capacities of the consecutive criteria in the ranking, also includes all the dual capacities, related to the interactions of the considered criteria with the rest of the criteria (1st step of 4.3). The mathematical expression (8) is built between g_k and g_r, which are two consecutive criteria in the ranking.

$$m_k + \sum_{j\,\in\,G} m_{k,j} - \left(m_r + \sum_{j\,\in\,G} m_{r,j} \right) \geq \delta \tag{8}$$

where δ is a positive number, which denotes the preference threshold between two criteria. δ is defined by the analyst. It should be neither too low (to a degree that it does not correspond to the preference threshold that a human being can assign) nor too high, a fact that can lead the linear problem to infeasibility. In any case, the value of the delta parameter (when different than zero) has been experimentally proven to have very limited effect on the results of the model (Greco et al. 2016).

The mathematical system of the expressions of type (8) is additionally complemented with the set of equations and inequalities on the interactions, as translated by the input of the DM in the 2nd and 3rd steps of 4.3. The complete preference mathematical system is from now on denoted with A_R.

Prior to solving A_R to calculate the Choquet capacities, the analyst should also consider the normalization and monotonicity constraints of the Choquet integral, Eqs. 4 and 5, respectively. For the actual calculation of the Choquet capacities, the analyst should solve the following linear programming model:

$$\begin{aligned} &\textit{Minimize/maximize } m_i \\ &\text{s.t.} \\ &\begin{cases} \sum\limits_{i\,\in\,G} m_i + \sum\limits_{\{i,j\}\in\,G}^{A_R} m_{i,j} = 1 \\ m_i \geq 0,\ \forall\, i \in G \\ m_i + \sum\limits_{j\,\in\,T} m_{i,j}\ \geq 0,\ \forall\, i \in G \textit{ and } T \subseteq G \backslash i,\ T \neq \emptyset \end{cases} \end{aligned} \tag{9}$$

The above linear programming problem should be consecutively solved for each single capacity m_i, as well as each dual capacity $m_{i,j}$. The problem is solved twice for each capacity, one maximizing and one minimizing it. Each execution, apart from the optimal value of the capacity, set as an objective function, calculates also the values of the rest of the capacities. This iterative procedure is performed, in order to end up with the average values of all the capacities and avoid extreme feasible values. The average values are the ones to be set as input to the Choquet integral.

After the average values of the Choquet capacities have been retrieved, they are incorporated, together with the criteria performances, to the mathematical expression (3) of the Choquet integral. The Choquet integral is then calculated separately for each country, assigning to it a score. In the end, the countries are rank-ordered, based on their Choquet value, in descending overall performance.

5. ESR evaluation in Europe

This Section applies the methodological steps proposed in Section 4 to the electricity supply resilience problem, modeled in Section 3. The methodological steps are carefully followed and the resilience results are presented at the end of the Section.

5.1. Assignment of the performances in a common utility scale

The procedure for the evaluation of the ESR in Europe begins with the assignment of the country performances on the criteria on a common interval scale, as required for the implementation of the Choquet integral. The criteria values are therefore linearly normalized in [0, 1], based on two reference points (lower and upper thresholds), defined by the DM. All three different schemes for the assignment of the reference points (described in 4.1) were followed and can be seen in Table 3.

Following, the normalization of the criteria scores, the procedure is broken down in two distinct stages, in which the analyst is required to elicit information by the DM on the criteria importance (single capacities) and the criteria interactions (dual capacities), outlined in the next paragraphs.

Table 3
Normalization ranges of the criteria, best and worst country performances.

Criteria	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9
Worst country performance	40.3	4.92	76.5	-0.6	-0.39	0.43	0.187	0	3.67
Best country performance	0.1	0.008	0	2.2	1.41	0	0.024	0.84	0.79
Normalization range	[5, 0]	[2, 0]	[5, 0]	[-0.6, 2.3]	[-0.40, 1.42]	[1, 0]	[0.2, 0.0]	[0, 1]	[2, 0.5]
Criteria	g_{10}	g_{11}	g_{12}	g_{13}	g_{14}	g_{15}	g_{16}	g_{17}	
Worst country performance	2	0.04	4.4	0.73	0.7	-0.62	0.06	65.4	
Best country performance	20	0.76	0.33	9.45	7.5	2.04	0.32	85.3	
Normalization range	[2, 20]	[0, 1]	[4, 0]	[-1, 5]	[0, 5]	[-0.6, 2.0]	[0, 0.3]	[60, 100]	

Table 4
Categorization of the criteria in three importance categories.

High Importance	Medium Importance	Low Importance
g_1. SAIDI	g_3. Loss of load expectation	g_7. Volatility of electricity prices
g_2. Severe accident risks	g_4. Control of corruption	g_{11}. Generation capacity margin
g_5. Political stability and absence of violence/ terrorism	g_6. Natural gas importation risk	g_{12}. Average outage times
g_8. Electricity mix diversity	g_{13}. Average GDP growth	g_{14}. Insurance penetration
g_9. Electricity import dependence	g_{15}. Government effectiveness	g_{16}. Engineers in the economy
g_{10}. Reserves capacity		g_{17}. Ease of doing business

5.2. Elicitation of preference information on the single capacities

For the estimation of the single capacities m_i, a procedure based on the rationale of the Simos method is followed, with some adjustments, due to the big number of criteria (see paragraph 4.2). Throughout this procedure, the DM is explicitly instructed by the analyst to thoroughly consider the potential complementarities or redundancies of the criteria and account them in his provision of preference information.

The elicitation of the preferential information by the DM is described in a three-step procedure below, while the calculation of the single capacities by the analyst, together with the dual capacities, is illustrated in 5.4.

1. The procedure begins with the categorization of the 17 criteria to three categories/priorities; high importance, medium importance and low importance, so that the DM is gradually guided to form a complete ranking of the criteria. Specifically, the DM is provided with the 17 criteria, in the form of cards, and groups them into the three categories, as in Table 4.

   The ordering of the criteria within each category of Table 4 is given, based on the numbering of the criteria, and does not reflect at this point any preference.
2. The DM, after confirming the categorization of Table 2, focuses then on each group separately and rank-orders the criteria from the most important to the least important one. For the case of equally important criteria, he clips the corresponding cards with a paper clip. In the end of the rank-ordering, he is asked to insert white cards between consecutive criteria to indicate a greater importance gap. Table 5 depicts the criteria rank-ordered by the DM in each importance group.
3. For the finalization of the preference elicitation procedure, the three importance groups need to be merged through the identification of importance gaps between them, resulting therefore to a complete hierarchy of all the criteria. Hence, the DM is asked to indicate the number of white cards to be inserted between the high and medium importance groups, as well as the medium and the low importance groups. After examining the categories and through dialogue with the analyst, the DM decided to insert three white cards between the high and medium importance categories and two white cards between the medium and low importance categories.

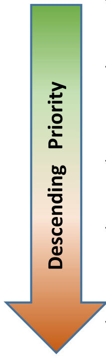
   The complete prioritization of the criteria, including the insertion of white cards between subsequent criteria or subgroups of criteria (Step 2) and between the three importance groups (Step 3), is illustrated in Fig. 3. The criteria are now denoted as g_i, without their description, for legibility reasons, while the white cards are denoted as w_{cj}.

5.3. Elicitation of preference information on the dual capacities

For the elicitation of the dual capacities, which correspond to the interactions between pairs of criteria, direct assessment procedures are implemented. The correlation analysis that is performed after the data validation has also been presented to the DM and plays a significant guiding role for the definition and quantification of the interactions. The steps that have been followed are:

1. The procedure begins with a mapping of the correlations by the analyst, a definition of high and medium interactions thresholds for the Spearman values and the identification of the criteria that mostly correlate with others. Next, the DM has been given an empty interactions chart, which, in the end, after elaboration, dialogue and guidance, is completed with "pluses" and "minuses", as shown in Fig. 4. The pluses and the minuses indicate the positively and negatively interacting criteria pairs, respectively.
2. After the identification of interacting pairs of criteria, the analyst asks for questions to quantify the intensity of these interactions. To do so, the DM is first required to categorize the pairs into two categories (weak and strong interactions). At this stage, all the interaction intensities (positive and negative) are treated as absolute values, therefore, in the same way.
   The categorization of the interacting pairs by the DM in the two intensity categories, without any hierarchy information, is shown in Table 6:
3. Subsequently, the DM is asked heuristic questions by the analyst, regarding the intensity of the interactions. These questions have the form of pairwise comparisons, specific ratio or a ratio interval between certain interactions, etc. (see paragraph 4.3). This additional information will feed the LP of 5.4, enriching the set of constraints A_R and helping to better quantify the intensity of these interactions. The preference statements be-

Table 5
Criteria ordering in descending importance.



High Importance	Medium Importance	Low Importance
g_1. SAIDI	g_6. Natural gas importation risk	g_{11}. Generation capacity margin
g_8. Electricity mix diversity	g_3. Loss of load expectation, g_{15}. Government effectiveness	g_{12}. Average outage times
g_9. Electricity import dependence	g_{13}. Average GDP growth	g_{17}. Ease of doing business, g_{14}. Insurance penetration
g_5. Political stability and absence of violence/ terrorism	g_4. Control of corruption	g_7. Volatility of electricity prices
g_{10}. Reserves capacity, g_2. Severe accident risks		g_{16}. Engineers in the economy

Table 6
Categorization of the interactions based on their intensity.

	Strong interactions		Weak interactions
$m_{4,\ 15}$	g_4 & g_{15} Control of Corruption & Government effectiveness	$m_{2,\ 4}$	g_2 & g_4 Severe accident risks & Control of Corruption
$m_{1,\ 3}$	g_1 & g_3 SAIDI & Loss of Load expectation	$m_{10,\ 11}$	g_{10} & g_{11} Reserves capacity & Generation capacity margin
$m_{15,\ 17}$	g_{15} & g_{17} Government effectiveness & Ease of doing business	$m_{8,\ 9}$	g_8 & g_9 Electricity mix diversity & Electricity import dependence
$m_{6,\ 8}$	g_6 & g_8 Natural gas importation risk & Electricity mix diversity		
$m_{9,\ 11}$	g_9 & g_{11} Electricity import dependence & Generation capacity margin		

low summarize the actual information, given by the DM at this step:

- $m_{4,\ 15}$ is the most intense interaction of all eight
- $m_{15,\ 17}$ is the second most intense interaction
- $m_{2,\ 4}$ is the least intense interaction of all eight
- $m_{10,\ 11}$ is the second least intense interaction
- $m_{4,\ 15}$ is 4 to 5 times more intense than $m_{2,4}$

5.4. Determination of the Choquet capacities

Following the preference information elicitation procedure, the DM's involvement to the development of the evaluation model is complete. The analyst, based on the criteria hierarchy composed in 5.2, builds the underlying mathematical constraints, according to the procedure described in 4.4. These mathematical constraints blend the single with the dual capacities (where applicable) and together with the additional constraints on the dual capacities given by the DM in 5.3, form the system A_R. This system of constraints does not solve to a single solution but, due to the inequalities, to a feasible space $\boldsymbol{P}$. For the Simos inequalities, the analyst defined a preference threshold of 0.5% between two successive criteria in the hierarchy ($\delta = 0.005$). On the other hand, a preference threshold of 0.2% is selected for the interactions, due to their smaller absolute values, compared to the single capacities ($\delta = 0.002$).

In the end, the A_R system amounts to 35 constraints, 26 of them, stemming from the Simos procedure, including both single and dual capacities (one less than the number of criteria cards and white cards in the DM's ranking) and 9 emerging from the preference information on the interactions, including only dual capacities. The incorporation of the Choquet normalization and monotonicity constraints to A_R, finalized the linear problem (LP) of (8).

The iterative execution of the LP, minimizing and maximizing successively all the Choquet capacities, yielded the following average capacities:

Single capacities

$m_1 = 0.133,\ m_2 = 0.098,\ m_3 = 0.057,\ m_4 = 0.033,\ m_5 = 0.114,\ m_6 = 0.068,\ m_7 = 0.012,\ m_8 = 0.112,\ m_9 = 0.104,\ m_{10} = 0.094,\ m_{11} = 0.019,\ m_{12} = 0.034,\ m_{13} = 0.062,\ m_{14} = 0.029,\ m_{15} = 0.036,\ m_{16} = 0.001,\ m_{17} = 0.015$

Dual capacities

$m_{9,11} = 0.012,\ m_{6,8} = 0.012,\ m_{8,9} = 0.010$

$m_{4,15} = -0.019,\ m_{1,3} = -0.012,\ m_{15,17} = -0.014,\ m_{2,4} = -0.004,\ m_{10,11} = -0.008$

All the modeling work and the respective executions of the LPs were performed in GAMS (GAMS, 2020).

5.5. Implementation of the Choquet integral

In order to evaluate the 35 countries, The Choquet integral is calculated, for each specific country, in order to assign an importance score to it, which translates to its electricity supply resilience. The 2-additive capacities version of the Choquet integral (Eq. (3)) is applied and receives as input the single capacities on the criteria and the dual capacities between certain pairs of criteria, calculated in the previous paragraph. In addition, it accommo-

Table 7
Ranking of the 35 ENTSO-E countries on their electricity supply resilience.

Rank	Countries	Score	Rank	Countries	Score
1	Denmark	0.728	19	Luxembourg	0.605
2	Switzerland	0.720	20	Latvia	0.603
3	Iceland	0.718	21	Romania	0.601
4	Sweden	0.713	22	Norway	0.596
5	Slovak Republic	0.695	23	United Kingdom	0.593
6	Slovenia	0.695	24	Hungary	0.584
7	Czech Republic	0.694	25	Poland	0.583
8	Germany	0.686	26	France	0.578
9	Ireland	0.680	27	Croatia	0.562
10	Netherlands	0.673	28	Italy	0.532
11	Lithuania	0.666	29	Greece	0.501
12	Estonia	0.666	30	Bosnia and Herzegovina	0.465
13	Portugal	0.664	31	Bulgaria	0.453
14	Finland	0.653	32	Montenegro	0.430
15	Austria	0.647	33	Serbia	0.398
16	Cyprus	0.636	34	North Macedonia	0.381
17	Spain	0.627	35	Albania	0.329
18	Belgium	0.620			

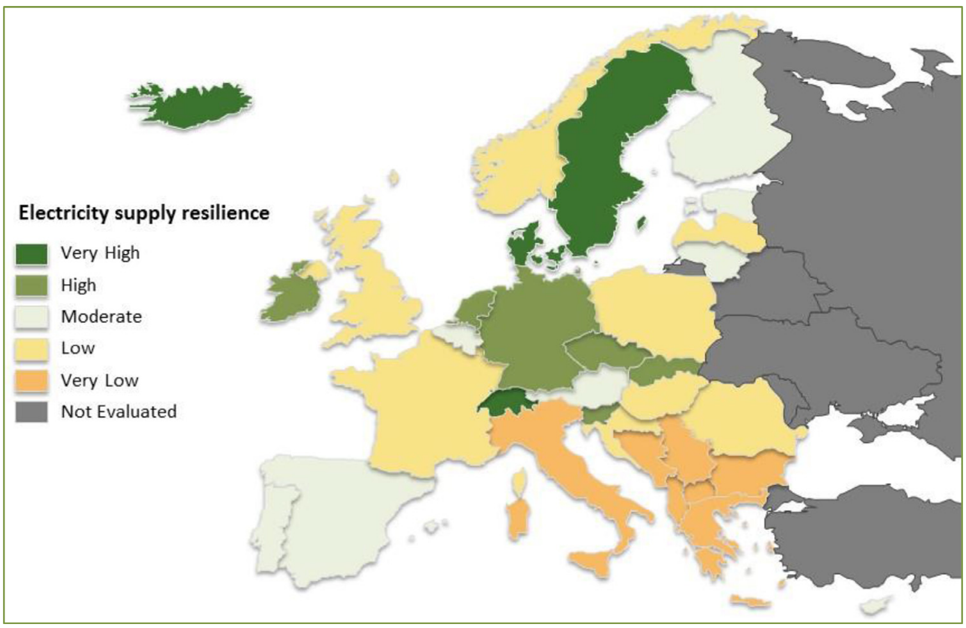


Fig. 5. European map of electricity supply resilience.

dates the normalized values of the performance of the country on the 17 criteria. The complete ranking of the 35 ENTSO-E countries, as resulted by the calculation of the Choquet integral is depicted in Table 7.

An illustration of the European status quo of electricity supply resilience is provided in Fig. 5. The countries have been empirically classified, for visualization purposes, into five resilience performance categories, based on the implementation results of Table 7. It should be noted, that no specific formal methodology was followed for the classification of the countries in Fig. 5. Instead, the countries were categorized, according to a heuristic process, which considered gaps of performance between consecutive countries in the ranking and aimed for a roughly equal distribution of the countries into the categories. At the same time, there was no specific reason for choosing five performance categories, instead of four or six.

5.6. Discussion

This application contributes to the advancement of two different research areas, namely the theoretical developments in the field of criteria interactions in MCDA, and the actual electricity supply resilience results and their implications for the European status quo.

5.6.1. Theoretical development in criteria interactions

The innovative implementation of the Choquet integral in a real large-scale context, in close collaboration with the DM, offers some valuable lessons learnt and interesting feedback on the criteria interactions. The actual cooperation of the authors with the DM unveiled a significant cognitive burden for the latter, which should be overcome, if meaningful results on the criteria interactions are to be extracted. The DM, although familiar with the concepts of MCDA in this case, he initially expressed his reluctance and worries on criteria interactions. Only after the careful provision of information and guidance by the analyst could he confidently identify interacting pairs of criteria and articulate preferences on the intensity of the interactions. However, although the role of the analyst in such applications is supportive and informative to the DM, his/her position remains delicate, so as not to influence and non-deliberately manipulate the preference elicitation procedure. In the end, the DM admitted that, albeit the analyst's guidance, still he would not comprehend criteria interactions for criteria triplets or more complex structures of interactions. However, he acknowledged the value of the criteria interactions chart and the degree that it helped him structurally organize the interacting pairs of criteria in his head and eventually pinpoint them on paper.

On the other hand, evidence showed that the careful and filtered consultation of the data correlations between the criteria could offer a helpful overview of the intra-criteria relationships. The potential high correlation between a pair of criteria can be a sign of a possible interaction, and should be therefore examined. Indeed, careful and productive thinking over the ESR dataset by the DM, showed that a positive correlation, in particular, can signify a negative correlation (overlap/redundancy) between the criteria. The opposite seems to apply to a lesser extent for the case of positive interactions, since the context of synergistic criteria is harder to conceive and prove in a numerical way. Indeed, a negative correlation between the performances of the alternatives in two criteria is difficult to be attributed to a synergy between them, and accordingly justified and proved. In any case, the causality concept of interactions and correlations needs to be further researched both theoretically and practically, to draw more solid conclusions.

Concerning the actual impact of the criteria interactions on the resilience results, a rough analysis shows that both positive and negative interactions can equally influence the final resilience score of a country. However, it is obvious from the Eq. (3) that the greater the number of interacting pairs is, the stronger this influence gets. In the context of this study, where five negative and three positive interactions were identified, the contribution of the weighting linear part of the Choquet to the final resilience score amounts to more than 90%. Accordingly, the negative interactions partake roughly to 5% of the resilience score of a country with a high/very high resilience score, while the positive interactions to less than 2%. Of course, the actual degree of contribution of the interactions is highly dependable on the total number of identified interactions, their distribution to positive and negative ones and the number of evaluation criteria. All these assumptions need to be further justified, explained and quantified through experimentation in multiple pilot and real decision problems.

5.6.2. Discussion on the benchmarking results

An analysis of the electricity supply resilience (ESR) results for the 35 European countries does not reveal any solid geographical pattern (i.e. from the north to the south or west to east), except for the Balkan countries, which are to their majority assigned to the “very low” category. This can be mostly attributed to their older energy production and electricity-transmitting infrastructures, which are rather prone to electrification disruptions, and partly to their inadequately diversified energy mixes. Neighboring countries to this Southeastern group (i.e. Italy, Croatia, Hungary and Romania) perform already better, as reflected by their moderate ESR scores.

On the other hand, there is a tendency for higher resilience in the center of Europe, with countries such as Denmark, Sweden, Switzerland, Germany, Austria, and Czech Republic, belonging to the leading positions of the ranking. This is mostly due to the diversified energy mix, the existing interconnections between the countries, as well as their high scoring on the purely political criteria. Certain exceptions to this trend comprise France, Italy, Latvia, Luxembourg, Norway, Poland and the UK, which all exhibit a moderate ESR score and are ranked in the second half of the ranking. These countries generally have indicator values representing a low or moderate performance on several criteria, which are considered to be of high importance, namely SAIDI, electricity mix diversity, electricity import dependence, political stability and reserves capacity (see Table 7, Fig. 5 and Tables A1 and A2 of the Appendix), thus degrading their overall ESR score. For example, the ranking of Norway is primarily affected by its very low electricity mix diversity and reserves capacity, although abundant hydropower accounts for 96% of electricity generation and three quarters of it are dispatchable. Similarly, the other countries mentioned perform particularly low on certain of the most important indicators. For example, France lacks on political stability and reserves capacity; Poland and Latvia exhibit low scores on SAIDI, electricity mix diversity and import dependence, whereas Italy has moderate performance on four out of the five aforementioned criteria.

From a broader perspective, it should be herein clarified that the individual country scores should not be interpreted in a superficial and narrow perspective, with regard to their ranking positon, but it is important to deepen the analysis by establishing a feedback loop to the raw indicator data and the actual subjective preferences, elicited by the DM. These help further setting the basis for understanding a country’s rank and subsequently focusing on identifying the weak points and the potential measures for improvement.

Reciprocally, the resilience results, obtained from the application of the proposed decision model, can form the basis of a benchmarking framework. This framework, with the aid of its multidimensional nature can dynamically monitor the performance and progress by individual countries and identify areas for further improvement. In addition, the incorporation of the modeling work to a decision support system can support energy researchers, various stakeholders and policy makers in forming their own evaluation system and receiving personalized assessment results. Such results can have a significant practical impact, both political and economic, therefore influencing the development of initiatives and policies, targeting the upgrading of the electricity infrastructures, and attracting considerable interest from a variety of observers, including governments.

6. Conclusions

The study, presented in this paper, addresses the highly complicated and controversial problem of evaluating national electricity supply resilience. The provision of decision support to a decision maker, throughout the whole procedural chain from problem modeling to acquisition of meaningful results, frames the core objective of this application. The study ultimately evaluates and ranks all the 35 European ENTSO-E countries, in the form of a benchmark, based on their performance on 17 evaluation criteria.

However, the potential interdependences, synergistic effects and redundancies between some of the evaluation criteria, as well as their great heterogeneity, could potentially compromise the validity and consistency of the family of criteria, according to the theoretical MCDA foundations, laid by Roy (1985). This fact urged the authors of this paper to consider the case of interacting criteria, in the modeling and decision support procedure, through the consideration and application of the Choquet integral. In this way, the decision model addresses the potential synergies and redundancies between certain pairs of criteria, which are pointed out by the decision maker.

In summary, the most important features of the proposed approach are conveyed below:

- The electricity supply resilience at a national level is an independent procedure, enabling each individual to specify the relevant evaluation criteria, as well as unique preferences on the importance, value functions and potential interrelations of these criteria. Hence, each evaluator has control over the assessment of her/his personalized evaluation model.
- The constructed model can be easily implemented on different data or when new countries enter the evaluation system. That

gives the possibility to schedule a new national resilience assessment, when new data on the criteria are available, measuring therefore dynamically the progress made by the countries.
- The application of the Choquet integral, along with its supplementary techniques and methods to elicit and quantify the capacities, is a feasible and beneficial operation when it comes to real large-scale decision problems. This study proves that the Choquet integral can significantly aid the modeling of complex problems, without compromising the results through the exclusion of the “problematic” criteria from the decision process or through their mandatory modification/simplification.

This study offers some interesting perspectives for future research both to a theoretical and practical level. Specifically, the use of the Choquet integral to model and solve real decision problems is still at an early stage, mostly due to the high cognitive burden that it poses on the DM and the strict theoretical principals that need to be respected. However, the development of new sound elicitation techniques and communication protocols can greatly support the DM in conceiving the concept of criteria interactions and adequately provide her/his preferences. These tools, when implemented by the analyst, in close cooperation with the DM, can increase the confidence of the latter to articulate preferences.

From a methodological point of view, the preference elicitation procedure for the identification and estimation of the Choquet capacities is in most proposed frameworks an indirect procedure, which builds upon preference statements of the DM. This implicit provision of information (UTA and ROR, Simos framework, heuristical pairwise comparisons, etc), albeit helpful and facilitative, adds to the instability of the model and the results. The coupling of the Choquet integral with a robustness analysis framework is hence of great merit. Such a coalition of frameworks will enable the analyst to measure the stability of the model under development and its results and proceed to the pursuit of additional preference information, when the robustness indices demand it.

Finally, a new prospect that arises after the actual implementation of the Choquet integral to a real benchmarking problem is the further analysis of the impact of the interactions on the obtained results. Specifically, the iterative calculation of the Choquet integral, using more and different combinations of interacting criteria, different kinds of interactions and different intensities of interactions will unveil further their effect on the results. In addition, it is necessary to analyze how more and/or different kinds of interactions benefit or harm the robustness of the model and to

Table A1
Country data on criteria g_1 to g_8.

Countries	System Average Interruption Duration Index (SAIDI)	Severe accident risks	Loss of Load Expectation (LOLE)	Control of corruption	Political stability and absence of violence/ terrorism	Natural Gas importation risk	Volatility of electricity prices (households)	Electricity mix diversity
Albania	33.5	4.923	0.43	-0.52	0.38	0.000	0.125	0.00
Austria	0.6	0.028	0.00	1.60	0.92	0.284	0.034	0.56
Belgium	0.4	0.033	0.07	1.51	0.41	0.170	0.081	0.68
Bosnia and Herzegovina	2.2	1.591	0.00	-0.57	-0.39	0.405	0.024	0.26
Bulgaria	6.2	0.066	20.71	-0.15	0.42	0.405	0.071	0.59
Croatia	3.3	0.040	0.00	0.13	0.77	0.222	0.077	0.62
Cyprus	0.6	0.073	76.50	0.64	0.54	0.000	0.187	0.16
Czech Republic	0.5	0.072	0.00	0.50	1.04	0.404	0.078	0.55
Denmark	0.5	0.047	0.02	2.15	0.96	0.146	0.033	0.58
Estonia	0.3	0.112	0.06	1.51	0.60	0.405	0.090	0.28
Finland	0.2	0.038	3.56	2.21	0.92	0.404	0.051	0.74
France	0.4	0.014	1.96	1.32	0.11	0.263	0.034	0.47
Germany	0.3	0.063	0.00	1.95	0.60	0.304	0.040	0.77
Greece	1.6	0.069	61.46	-0.07	0.09	0.415	0.063	0.72
Hungary	2.6	0.042	0.00	0.05	0.76	0.399	0.074	0.61
Iceland	0.6	0.008	0.00	1.84	1.41	0.000	0.106	0.27
Ireland	0.8	0.053	0.01	1.55	1.03	0.170	0.073	0.53
Italy	1.3	0.051	3.71	0.24	0.31	0.393	0.065	0.73
Latvia	1.0	0.043	0.18	0.33	0.42	0.405	0.103	0.47
Lithuania	0.4	0.023	0.21	0.50	0.75	0.283	0.093	0.71
Luxembourg	0.4	0.020	2.98	2.09	1.37	0.221	0.064	0.51
Montenegro	40.3	2.411	0.00	0.02	0.11	0.000	0.027	0.30
Netherlands	0.8	0.071	0.00	2.01	0.87	0.214	0.107	0.60
North Macedonia	7.5	1.326	0.00	-0.36	-0.20	0.405	0.034	0.49
Norway	1.5	0.011	0.81	2.09	1.15	0.000	0.119	0.11
Poland	1.1	0.108	0.03	0.64	0.55	0.327	0.086	0.36
Portugal	0.5	0.050	0.00	0.85	1.14	0.430	0.065	0.72
Romania	3.1	0.049	0.00	-0.12	0.06	0.383	0.095	0.75
Serbia	3.9	1.674	0.00	-0.37	0.08	0.405	0.059	0.30
Slovak Republic	0.9	0.028	0.00	0.36	0.75	0.405	0.065	0.58
Slovenia	0.1	0.045	0.00	0.87	0.91	0.233	0.053	0.58
Spain	0.5	0.040	0.00	0.61	0.25	0.400	0.067	0.84
Sweden	0.6	0.014	0.11	2.14	0.91	0.180	0.075	0.55
Switzerland	0.2	0.012	0.01	2.01	1.34	0.186	0.043[1]	0.43
United Kingdom	0.3	0.042	4.09	1.83	0.05	0.172	0.088	0.71

[1] Average value of its neighboring countries

Table A2
Country data on criteria g_9 to g_{17}.

Countries	Electricity import dependence	Reserves capacity	Generation Capacity Margin	Average outage time	Annual GDP growth	Insurance penetration	Government effectiveness	Engineers in the economy	Ease of doing business
Albania	1.33	6%	0.55	1.52	3.26	1.00	0.11	0.176%[5]	67.7
Austria	1.14	4%	0.43	1.00	1.89	3.00	1.45	0.286%	78.7
Belgium	1.23	3%	0.45	1.00	1.63	2.60	1.17	0.188%	75.0
Bosnia and Herzegovina	0.79	12%	0.37	4.40	2.80	2.70	-0.62	0.176%[5]	65.4
Bulgaria	0.81	4%	0.42	1.24	3.23	2.00	0.27	0.088%	72.0
Croatia	1.42	6%	0.54	2.06	2.47	1.80	0.46	0.280%	73.6
Cyprus	1.00	18%	0.50	3.00	3.48	2.40	0.92	0.061%	73.4
Czech Republic	0.84	11%	0.34	1.25	3.34	1.80	0.92	0.213%	76.3
Denmark	1.17	15%	0.65	1.00	2.32	2.80	1.87	0.149%	85.3
Estonia	0.81	14%[2]	0.28	1.50	3.84	1.90	1.19	0.097%	80.6
Finland	1.29	10%	0.38	1.00	1.71	1.80	1.98	0.323%	80.2
France	0.89	2%	0.36	1.33	1.52	3.10	1.48	0.306%	76.8
Germany	0.92	6%	0.36	1.00	1.93	3.60	1.62	0.131%	79.7
Greece	1.12	7%	0.47	1.14	0.73	1.20	0.34	0.115%	68.4
Hungary	1.44	8%	0.45	2.17	3.95	1.30	0.49	0.101%	73.4
Iceland	1.01	10%[3]	0.04	1.50	4.85	2.20	1.47	0.233%	79.0
Ireland	1.00	3%	0.51	1.33	9.45	1.20	1.42	0.092%[6]	79.6
Italy	1.15	5%	0.50	0.59	0.90	2.20	0.41	0.097%	72.9
Latvia	1.19	7%	0.55	2.50	3.32	1.50	1.04	0.077%	80.3
Lithuania	3.70	20%	0.76	1.00	3.33	0.70	1.07	0.083%	81.6
Luxembourg	3.67	4%[4]	0.66	1.33	3.39	1.70	1.78	0.132%	69.6
Montenegro	1.26	16%	0.57	1.56	3.96	1.50	0.13	0.191%	73.8
Netherlands	1.08	4%	0.40	1.60	2.26	7.50	1.85	0.152%	76.1
North Macedonia	1.25	10%	0.47	0.53	2.40	1.20	0.09	0.208%	80.7
Norway	0.93	4%	0.23	1.15	1.64	1.70	1.89	0.216%	82.6
Poland	1.04	4%	0.33	1.00	4.16	2.10	0.66	0.163%	76.4
Portugal	0.97	2%	0.48	0.83	2.20	2.40	1.21	0.064%	76.5
Romania	0.84	13%	0.51	0.91	4.78	0.90	-0.25	0.232%	73.3
Serbia	0.89	7%	0.36	1.26	2.62	1.50	0.11	0.176%[5]	75.7
Slovak Republic	1.14	20%	0.44	1.29	3.26	1.40	0.71	0.216%	75.6
Slovenia	0.98	8%	0.32	0.33	3.45	3.40	1.13	0.231%	76.5
Spain	1.04	3%	0.53	0.71	2.55	2.80	1.00	0.064%	77.9
Sweden	0.89	13%	0.34	0.86	2.61	1.80	1.83	0.120%	82.0
Switzerland	0.98	8%	0.38	1.00	2.05	4.10	2.04	0.253%	76.6
United Kingdom	1.06	2%	0.38	3.00	1.90	2.30	1.34	0.092%	83.5

[2] Average value of Latvia and Lithuania
[3] Average value of Norway, Sweden, Finland and Denmark
[4] Average value of Belgium, Netherland, France and Germany
[5] Average value of Greece, Bulgaria, Montenegro, N. Macedonia and Croatia
[6] Assumed the same as of the United Kingdom

what degree. It is also meaningful to investigate the role of more complex interactions in this post-analysis, such as the positive, negative or antagonistic interactions among triplets, quadruplets, etc. of criteria.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 701647 and Innosuisse through the Swiss Competence Center on Energy Research (SCCER) Supply of Electricity (SoE). The authors would also like to sincerely thank Dr. Matteo Spada, Dr. Marco Cinelli and Dr. Patrick Gasser for their valuable recommendations for the development of the resilience evaluation model.

Appendix

References

Ang, B. W., Choong, W. L., & Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews, 42*, 1077–1093.
Angilella, S., Greco, S., & Matarazzo, B. (2010). Non-additive robust ordinal regression: A multiple criteria decision model based on the Choquet integral. *European Journal of Operational Research, 201*, 277–288.
Angilella, S., Corrente, S., & Greco, S. (2015). Stochastic multiobjective acceptability analysis for the Choquet integral preference model and the scale construction problem. *European Journal of Operational Research, 240*, 172–182.
Angilella, S., Corrente, S., Greco, S., & Słowiński, R. (2016). Robust ordinal regression and stochastic multiobjective acceptability analysis in multiple criteria hierarchy process for the Choquet integral preference model. *Omega, 63*, 154–169.
Angilella, S., Catalfo, P., Corrente, S., Giarlotta, A., Greco, S., & Rizzo, M. (2018). Robust sustainable development assessment with composite indices aggregating interacting dimensions: the hierarchical-SMAA-Choquet integral approach. *Knowledge-Based Systems, 158*, 136–153.
Angilella, S., & Pappalardo, M. R. (2020). Performance assessment of energy companies employing hierarchy stochastic multi-attribute acceptability analysis. *Operational Research: An International Journal* In press.
Asgary, A., Ozdemir, A. I., & Gentles, C. (2015). Does insurance delay or speed up the recovery and reconstruction process? Evidences from Canada. *Reconstruction and Recovery in Urban Contexts* UCL: London, UK.
Bana e Costa, C., De Corte, J. M., & Vansnick, J. C. (2012). MACBETH. *International Journal of Information Technology & Decision Making, 11*, 359–387.
Bottero, M., Ferretti, V., Figueira, J. R., Greco, S., & Roy, B. (2018). On the Choquet multiple criteria preference aggregation model: Theoretical and practical insights from a real-world application. *European Journal of Operational Research, 271*(1), 120–140.
Burgherr, P., & Hirschberg, S. (2008). A comparative analysis of accident risks in fossil, hydro, and nuclear energy chains. *Human and Ecological Risk Assessment, 14*(5), 947–973.
Burgherr, P., Spada, M., Kalinina, A., Vandepaer, L., Lustenberger, P., Kim, W. (2020). Comparative risk assessment of accidents in the energy sector within different long-term scenarios and marginal electricity supply mixes, pp. 1525-1532.
Corrente, S., Figueira, J. R., & Greco, S. (2020). Pairwise comparison tables within the deck of cards method in multiple criteria decision aiding. *European Journal of Operational Research* In press.

Energy Information Association (2020). *Electric Power Monthly* Retrieved November 13, 2020, from: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b .

European Network of Transmission System Operators for Electicity (2018). *Mid-term Adequacy Forecast 2018* Retrieved December 2, 2020, from https://eepublicdownloads.entsoe.eu/clean-documents/sdc-documents/MAF/2018/MAF%202018%20Methodology%20and%20Detailed%20Results.pdf .

Finster, M., Phillips, J., & Wallace, K. (2016). *Front-Line Resilience Perspectives: The Electric Grid, United States: N* p. 2016 Web. https://doi.org/10.2172/1344876.

Figueira, J., & Roy, R. (2002). Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. *European Journal of Operational Research, 139*, 317–326.

Figueira, J. R., Greco, S., & Roy, B. (2009). ELECTRE methods with interaction between criteria: An extension of the concordance index. *European Journal of Operational Research, 199*(2), 478–495.

GAMS Development Corporation (2020). General Algebraic Modeling System (GAMS), Release 31.1.1 Washington, DC, USA.

Gasser, P. (2020). A review on energy security indices to compare country performances. *Energy Policy, 139*, Article 111339.

Gasser, P., Lustenberger, P., Cinelli, M., Kim, W., Spada, M., Burgherr, P., Hirschberg, S., Stojadinovic, B., & Sun, T. J. (2019). A review on resilience assessment of energy systems. *Sustainable and Resilient Infrastructure*. https://doi.org/10.1080/23789689.2019.1610600.

Gasser, P., Suter, J., Cinelli, M., Spada, M., Burgherr, P., Hirschberg, S., Kadziński, M., & Stojadinović, B. (2020). Comprehensive resilience assessment of electricity supply security for 140 countries. *Ecological Indicators, 110*, Article 105731.

Gatto, A., & Drago, C. (2020). Measuring and modeling energy resilience. *Ecological Economics, 172*(106527).

Gatto, A., & Busato, F. (2020). Energy vulnerability around the world: The global energy vulnerability index (GEVI). *Journal of Cleaner Production, 253*, Article 118691.

Gillespie-Marthaler, L., Nelson, K. S., Baroud, H., Kosson, D. S., & Abkowitz, M. (2019). An integrative approach to conceptualizing sustainable resilience. *Sustainable and Resilient Infrastructure, 4*(2), 66–81.

Grabisch, M., & Roubens, M. (2000). Application of the Choquet integral in multicriteria decision making. *Fuzzy Measures and Integrals*, 348–374.

Grabisch, M., Kojadinovic, I., & Meyer, P. (2008). A review of methods for capacity identification in Choquet integral based multi-attribute utility theory. Applications of the Kappalab R package. *European Journal of Operational Research, 186*(2), 766–785.

Grabisch, M. (2016). *Set functions, games and capacities in decision making*. Berlin, Germany: Springer-Verlag.

Grabisch, M., & Labreuche, C. (2016). Fuzzy measures and integrals in MCDA. In S. Greco, M. Ehrgott, & J. R. Figueira (Eds.), *Multiple criteria decision analysis: State of the art surveys* (pp. 553–603). New York, NY, USA: Springer Science + Business Media Inc.

Greco, S., Ehrgott, M., & Figueira, J. (2016). *Multiple Criteria decision analysis: State of the art surveys* (Second Edition). New York: Springer Volumes 1 & 2.

Greco, S., Mousseau, V., & Slowinski, R. (2014). Robust ordinal regression for value functions handling interacting criteria. *European Journal of Operational Research, 239*(3), 711–730.

Heinimann, H. R., & Hatfield, K. (2017). Infrastructure resilience assessment, management and governance-state and perspectives. *Resilience and Risk*, 147–187.

Hirschberg, S., & Burgherr, P. (2015). Sustainability assessment for energy technologies. In J. Yan (Ed.), *Handbook of clean energy systems*. Hoboken, NJ, USA: John Wiley & Sons, Ltd.

Hosseini, S. E. (2020). An outlook on the global development of renewable and sustainable energy at the time of covid-19. *Energy Research & Social Science, 68*, Article 101633.

International Energy Agency (2020). *Power systems in transition, Challenges and opportunities ahead for electricity security* Retrieved December 2, 2020 fromhttps://www.iea.org/reports/power-systems-in-transition.

International Energy Agency (2018). *Data and statistics Retrieved* December 2, 2020 fromhttps://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource.

Keeney, R. L. (1992). *Value-focused thinking: A path to creative decision making*. Cambridge, MA: Harvard University Press.

Kojadinovic, I. (2007). Minimum variance capacity identification. *European Journal of Operational Research, 177*, 498–514.

Kruyt, B., van Vuuren, D. P., de Vries, H. J. M., & Groenenberg, H. (2009). Indicators for energy security. *Energy Policy, 37*(6), 2166–2181.

Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., & Bansal, R. C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development. *Renewable and Sustainable Energy Reviews, 69*, 596–609.

Laldjebaev, M., Morreale, S. J., Sovacool, B. K., & Kassam, K. A. S. (2018). Rethinking energy security and services in practice: National vulnerability and three energy pathways in Tajikistan. *Energy Policy, 114*, 39–50.

Marchese, D., Reynolds, E., Bates, M. E., Morgan, H., Clark, S. S., & Linkov, I. (2018). Resilience and sustainability: Similarities and differences in environmental management applications. *Science of The Total Environment, 613-614*, 1275–1283.

Marichal, J. L., & Roubens, M. (2000). Determination of weights of interacting criteria from a reference set. *European Journal of Operational Research, 124*, 641–650.

Martišauskas, L., Augutis, J., & Krikštolaitis, R. (2018). Methodology for energy security assessment considering energy system resilience to disruptions. *Energy Strategy Reviews, 22*, 106–118.

Matsumoto, K., Doumpos, M., & Andriosopoulos, K. (2018). Historical energy security performance in EU countries. *Renewable and Sustainable Energy Reviews, 82*, 1737–1748.

Maystre, L., Pictet, J., & Simos, J. (1994). Methodes multicriteres ELECTRE – Description, conseils pratiques et cas d'application a la gestion environnementale. *Presses Polytechniques et Universitaires Romandes*. Lausanne.

McCollum, D. L., Gambhir, A., Rogelj, J., & Wilson, C. (2020). Energy modelers should explore extremes more systematically in scenarios. *Nature Energy, 5*(2), 104–107.

McLellan, B., Zhang, Q., Farzaneh, H., Utama, N. A., & Ishihara, K. N. (2012). Resilience, sustainability and risk management: a focus on energy. *Challenges, 3*(2), 153–182.

Meyer, P., & Roubens, M. (2005). Choice, ranking and sorting in fuzzy multiple criteria decision aid. In J.-R. Figueira, S. Greco, & M. Ehrgott (Eds.), *Multiple criteria decision analysis: State of the art surveys* (pp. 471–506). New York, NY, USA: Springer Science + Business Media Inc.

Molyneaux, L., Wagner, L., Froome, C., & Foster, J. (2012). Resilience and electricity systems: A comparative analysis. *Energy Policy, 47*, 188–201.

Mori, T., & Murofushi, T. (1989). An analysis of evaluation model using fuzzy measure and the Choquet integral. In Proceedings of the 5-th fuzzy system symposium, *Kobe, Japan* (pp. 207–212).

Neelawela, U. D., Selvanathan, E. A., & Wagner, L. D. (2019). Global measure of electricity security: A composite index approach. *Energy Economics, 81*, 433–453.

Neofytou, H., Nikas, A., & Doukas, H. (2020). Sustainable energy transition readiness: A multicriteria assessment index. *Renewable and Sustainable Energy Reviews, 131*, Article 109988.

OECD (2019). *World – Natural Gas imports by origin* Retrieved December 2, 2020 fromhttps://www.oecd-ilibrary.org/energy/data/iea-natural-gas-information-statistics/world-natural-gas-imports-by-origin_data-00555-en.

Pelegrina, G. D., Duarte, L. T., Grabisch, M., & Romano, J. M. T. (2020). The multilinear model in multicriteria decision making: the case of 2-additive capacities and contributions to parameter identification. *European Journal of Operational Research, 282*(3), 945–956.

Pictet, J., & Bollinger, D. (2008). Extended use of the cards procedure as a simple elicitation technique for MAVT. Application to public procurement in Switzerland. *European Journal of Operational Research, 185*(3), 1300–1307.

PRS (2020). *The international country risk guide methodology* Retrieved November 13, 2020, from:https://www.prsgroup.com/wp-content/uploads/2012/11/icrgmethodology.pdf.

Resce, G., & Schiltz, F. (2020). Sustainable development in Europe: A multicriteria decision analysis. *Review of Income and Wealth*. https://doi.org/10.1111/roiw.12475.

Roth, S., Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Heck, T., & Schenler, W. (2009). Sustainability of electricity supply technology portfolio. *Annals of Nuclear Energy, 36*(3), 409–416.

Roy, B. (1985). Méthodologie multicritère d'aide à la décision. *Economica, Paris*.

The Association for Renewable Energy & Clean Technology (REA) (2019). *Energy transition readiness index* Retrieved December 2, 2020, from https://www.r-e-a.net/wp-content/uploads/2019/11/Energy-Transition-Readiness-Index-2019.pdf .

Shah, S. A. A., Zhou, P., Walasai, G. D., & Mohsin, M. (2019). Energy security and environmental sustainability index of South Asian countries: A composite index approach. *Ecological Indicators, 106*, Article 105507.

Simos, J. (1990). *L'évaluation environnementale: Un processus cognitif négocié*. Lausanne: DGF EPFL Thèse de doctorat.

Siskos, E., Askounis, D., & Psarras, J. (2014). Multicriteria decision support for global e-government evaluation. *Omega, 46*, 51–63.

Siskos, E., & Tsotsolas, N. (2015). Elicitation of criteria importance weights through the Simos method: A robustness concern. *European Journal of Operational Research, 246*(2), 543–553.

Sovacool, B. K., & Mukherjee, I. (2011). Conceptualizing and measuring energy security: A synthesized approach. *Energy, 36*(8), 5343–5355.

Spellerberg, I. F., & Fedor, P. J. (2003). A tribute to Claude Shannon (1916-2001) and a plea for more rigorous use of species richness, species diversity and the 'Shannon–Wiener' Index. *Global Ecology and Biogeography, 12*(3), 177–179.

Swiss Re Institute (2018). *Sigma Explorer - Catastrophe and Insurance Market Data* Retrieved December 2, 2020, from http://www.sigma-explorer.com .

Wang, Q., & Zhou, K. (2017). A framework for evaluating global national energy security. *Applied Energy, 188*, 19–31.

World Economic Forum (2020). *Fostering effective energy transition, Insight Report* Retrived December 2, 2020, fromhttp://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2020_Edition.pdf.

World Energy Council (2020). *World energy trilemma index* Retrived December 2, 2020, fromhttps://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2020_-_REPORT.pdf.

World Bank (2017). *Distance to Frontier and Ease of Doing Business Ranking, 2017* Retrieved December 2, 2020 fromhttp://www.doingbusiness.org/~/media/WBG/DoingBusiness/Documents/Annual-Reports/English/DB17-Chapters/DB17-DTF-and-DBRankings.pdf.

World Bank (2018). *World Governance Indicators, 2018* Retrieved December 2, 2020 fromhttp://databank.worldbank.org/data/reports.aspx?source=worldwide-governance-indicators.