A multicriteria classification approach for assessing energy security in Europe

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Europe has been subject to a multitude of adversities regarding energy security in recent years. This dissertation focuses on the assessment of 27 European nations’ energy security in 2013 and 2018, using the ELECTRE TRI-nC method implemented in the MCDA U-Laval software. This allows for the categorization of nation’s level of energy security, to aid further research in this field. Through studying these two years, the influence of the annexation of Crimean territory, and rising climatic tensions, can be better established. 8 indicators were chosen encapsulating all dimensions of energy security, as per a comprehensive framework. The use of the Shannon index to quantify the security of supply of oil and natural gas suppliers was included, revealing varying degrees of diversification efforts in response to ongoing political conflicts. Existing literature lacks sensitivity and robustness analysis, thus hindering the ability to attain valid results. The results of this study validate the results of existing literature, with the discussion uncovering areas of divergence. The United Kingdom and France emerge as the best-performing nations, consistently scoring high across all indicators, while Czechia, Estonia, Hungary, Poland, and Slovenia are identified as the worst performers. Norway’s results were ambiguous, owing in large part to incomplete datasets and the nature of the Shannon index formulation. All other nations within this analysis were assigned moderate to good energy performance levels. The dissertation's findings provide insights into the complex landscape of European energy security, highlighting the challenge of capturing the multifaceted concept of energy security with limited indicators.

KEYWORDS: Energy Security, ELECTRE TRI-nC, Multiple Criteria Decision Analysis, Europe

Resumo

A Europa tem estado sujeita a uma série de adversidades no que respeita à segurança energética nos últimos anos. Esta dissertação foca-se na avaliação da segurança energética de 27 nações europeias em 2013 e 2018, utilizando o método ELECTRE TRI-nC implementado no software MCDA U-Laval. Isto permite a classificação do nível de segurança energética da nação, para ajudar futuras investigações neste domínio. Através do estudo destes dois anos, é possível determinar melhor a influência da anexação do território da Crimeia e das crescentes tensões climáticas. Foram selecionados 8 indicadores que englobam todas as dimensões da segurança energética, de acordo com um quadro abrangente. A utilização do índice de Shannon para quantificar a segurança do abastecimento dos fornecedores de petróleo e gás natural foi incluída, mostrando diferentes graus de esforços de diversificação em resposta aos actuais conflitos políticos. Os resultados deste estudo validam os resultados da literatura existente, com a discussão a revelar áreas de divergência. O Reino Unido e a França emergem como os países com melhor desempenho, com pontuações constantemente elevadas em todos os indicadores, enquanto a República Checa, a Estónia, a Hungria, a Polónia e a Eslovénia são identificadas como os países com pior o desempenho. Os resultados da Noruega foram ambíguos, devido, em grande parte, a conjuntos de dados incompletos e à natureza da formulação do índice de Shannon. As conclusões da dissertação fornecem informações sobre a complexa paisagem da segurança energética europeia, salientando o desafio de captar o conceito multifacetado de segurança energética com indicadores limitados.

PALAVRAS-CHAVE: Segurança energética, ELECTRE TRI-nC, Análise de decisão com critérios múltiplos, Europa

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1. Introduction

Energies ubiquitous nature in modern living imposes the need for its constant and growing supply to be secure. One late British-German economist, Schumacher (1982), once stated energy to be "not just another commodity, but the precondition of all commodities, a basic factor equal with air, water and earth". As such, the benefits of improved energy security are unmatched. The very definition of energy security is multi-faceted and has experienced an evolution in its very meaning as nations have developed. A 2010 review identified 45 distinct definitions of the concept in practice (Sovacool and Mukherjee, 2011). A core duality principle that underpins most definitions of energy security is having "reliable supplies at a reasonable price", however when you delve into what a secure supply constitutes, its complexity becomes apparent (Baumann, 2008). A comprehensive study of energy security posits that the construct of energy security should comprise a quintet of dimensions namely: availability, affordability, technological advancement, sustainability and regulatory frameworks (Sovacool and Mukherjee, 2011). These five dimensions are further broken down into a total of 320 simple and 52 complex indicators which can provide a base for a multicriteria analysis (Sovacool and Mukherjee, 2011). Paravantis (2019) comprehensively reviewed the different frameworks constructed to define the different dimensions of energy security. Often deployed are the "five S's", the "four A's" or the "4 R's". (Kleber, 2009) (APERC, 2007) (Hughes, 2009). These definitive disparities of energy security allow for dynamic analysis which can focus on specific influential events on levels of energy security such as the Russia-Ukraine conflict or COVID-19.

The annexation of Ukraine's territory Crimea in March 2014 by the Russian Federation has emerged concern globally, whereby the post-World War 2 norm of respecting the territorial integrity of nations was overturned. The conflict has, and continues to, compromise Energy Security in Europe with disruptions to the flows of natural gas and concerns over Russia's control over essential energy infrastructure throughout Europe[1]. Europe's dependence on Russian fossil fuels has been prevalent since the beginning of international trade of energy. In 2021, the EUs energy imports from Russia contributed a significant portion of its total import expenditure, surmounting to 62% or €99 billion. Specifically, 46% of its coal, 40% of its total gas consumption and 27% of its oil. Despite this being a significant drop from 2011, whereby energy represented just shy of 77% or €148 billion of total EU import expenditure from Russia, the EU is taking further action to cut off its dependence completely from Russian energy imports[2]. REPowerEU is the European Commission's recent plan to make Europe independent from Russian fossil fuels well before 2030, in response to the Crimea invasion[3]. From IEA's data, it can be seen that from 2021 to 2022 Europe has already made progress with oil, reducing its dependency to 18%[4].

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[1] https://www.eeas.europa.eu/eeas/seven-years-russia%E2%80%99s-illegal-annexation-crimea_en

[2] https://commission.europa.eu/news/focus-reducing-eus-dependence-imported-fossil-fuels-2022-04-20_en

[3] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

[4] https://www.iea.org/data-and-statistics

The influence of climate change on the evolution of energy security is another area which also requires rapid yet cautious consideration. The Crimea conflict has been catalytic in decarbonizing the energy mix in Europe. The REPowerEU goal, as previously mentioned, has resulted in rapid efforts to increase the rollout of renewable energy sources, energy efficiency improvements and other low carbon technologies[3]. REPowerEU is a building block amongst a number of other EU plans and directives with the same goal; improving energy security and reducing fossil fuel dependence. Table 1 depicts, chronologically, the key directives and initiatives the EU has installed since the Crimea conflict.

Directive	Description
EU Energy Security Strategy[5]	Set out in 2014 in large part due to the Russia-Ukraine conflict Main Goals: Address the Launched in May 2014, mainly due to the Russian annexation of Crimea. Main goals: Address the risks associated with a heavy dependence on unstable energy suppliers Increase domestic energy production and diversify energy suppliers
The Paris Agreement[6]	Rolled out in 2015 as a global agreement aimed at tackling climate change. Key objectives: To limit global warming to below 2°C above pre-industrial levels. The EU committed to reducing GHG's by at least 40% by 2030 relative to 1990 levels and to become climate-neutral by 2050.
Energy Union Package[7]	Formulated in 2015 with the aim of ensuring an affordable, secure and sustainable energy supply for the EU. Main objectives: Upgrade energy security, energy efficiency, renewable energy capacity and energy market integration.
Clean Energy for all Europeans Package[8]	Proposed in 2016 with the aim of speeding up the EU's transition to clean energy sources and enhancing energy efficiency. The package revised Governance Regulation, the Energy Efficiency Directive and the Renewable Energy Directive. Main objectives: Improve energy efficiency, renewable energy share and develop integrated national energy and climate plans
Renewable Energy Directive (RED II)[9]	The revised Renewable Energy Directive (RED II) was enforced in 2018 Main goals: To increase the share of renewable energy in the EU's final energy consumption to at least 32% by 2030

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[5] https://eur-lex.europa.eu
[6] https://unfccc.int/process-and-meetings/the-paris-agreement
[7] https://www.europarl.europa.eu
[8] https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en
[9] https://joint-research-centre.ec.europa.eu

Directive	Description
Energy Efficiency Directive[10]	The revised Energy Efficiency Directive was executed in 2018 Main goals: To improve energy efficiency by 32.5% by 2030

Table 1 - Key directives to stipulate energy security in Europe

Behind directives and initiatives exist academics and researchers that evaluate the different elements of energy security. Multi Criteria Decision Aiding (MCDA) is a scientific approach used to compare and evaluate different alternatives based on a set of different criteria. The aim of such a technique is to provide decision makers with a structured and transparent system which can determine the best solution taking into account the indicators that are most important to them (Cabeça et al., 2021). MCDA can provide valid outputs for three core types of decision problems:

- Ranking, which involves ranking all alternatives (in this case countries) from best to worst considering their performance on the defined criteria.
- Sorting or ordinal classification, whereby the aim is to assign a set of alternatives into a set of classes. For example: Excellent, Good, Satisfactory, Poor.
- Choice, whereby the task is to define which subset of alternatives are considered the best (Figueira et al., 2016).

In the context of assessing different nations' energy securities, MCDA is deemed suitable. A single indicator system would be incapable of capturing the complexity and trade-offs inherent to energy security. Performing this evaluation under MCDA allows for the integration of qualitative and quantitative information, which is to be weighted under the influence of a stakeholder's preferences. The potential decision-maker (DM), who works as a Green Hydrogen engineer for Shell, contributed with her expert opinion to the weighting process. This study will therefore generate a robust assessment of energy security in each nation of Europe as comprehensively as possible. The method will be performed years 2013 and 2018, providing an insight into how EU nations' energy security evolves in conjunction with intensifying climatic and geopolitical issues.

When assessing energy security, we are interested in decision aiding whereby the alternatives (countries) must be sorted, or assigned to a set of categories which indicate the level of energy security of each nation. The ELECTRE TRI-nC method is deemed well suited for this assessment. With its nature being that of a sorting method, it is appropriate for dealing with decision aiding contexts and involves constructing a preference model. It abides by the following fundamental properties: conformity, homogeneity, monotonicity and stability (Dias et al., 2010). By having such fundamentals, ELECTRE TRI-nC is considered a sound and reliable method which can be trusted by DMs. The execution of the method in MCDA U-Laval also facilitates sensitivity and robustness analysis.

This work therefore will be applying the ELECTRE TRI-nC method to contribute, and build, on existing literature to help provide decision makers improve and innovate their energy security strategies. The criteria set (indicators)

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[10] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en

used will therefore comply with those found in existing literature, but with the inclusion of additional indicators that address the energy security risks associated with climate change and the Crimea conflict, which are not thoroughly covered in the literature.

Overall, this assessment aims at addressing the following research questions:

Are the results obtained robust?
What are the key indicators that contribute to energy security in Europe?
Which nations had the best and worst energy security assignments?
How has the Crimea conflict and the global focus on climate change impacted the energy security strategies of European countries?

The present work is divided into 8 sections which are structured as follows:
This first section provides context to the topic of energy security, its definitions and the defined dimensional framework followed in this paper. The second section consists of a literature review whereby the key studies performed, primarily using MCDA methods on the topic of energy security, are outlined. The third section displays the theoretical underpinning assumptions of the ELECTRE TRI-nC methodology. The fourth section outlines the practical methodology undertaken to obtain, process and formulate the data in MCDA U-Laval. The fifth section displays the results, along with complimentary sensitivity, robustness and statistical analysis. In Section 6, the results are discussed in 2 subsections with the following objectives: exploring what they imply and making comparisons with another study. Section 7 provides the conclusions, highlighting the key findings and remarks upon completing the energy security assessment. Finally, section 8 provides recommendations for future work to build on and improve the existing literature regarding energy security assessments.

2. Literature Review

A multitude of literature has been published with the aim of identifying and assessing the risk factors and strategies influencing energy security. In order to conduct research into the topic of energy security, Harzing's Publish or Perish software was used[11]. Keywords used for the search were 'energy security', 'multi criteria decision aiding' and 'Europe'. Further relevant studies were obtained through ResearchGate and ScienceDirect.

Noteworthy is the work by Sovacool and Mukherjee (2011). They identified, most comprehensively in the literature, the indicators related to energy security, with 320 simple and 52 complex indicators. Such a diverse list optimizes researchers' ability to fine tune their analysis relative to each unique energy environment. The paper also distinguishes between quantitative and qualitative metrics, emphasizing the significance of integrating a combination when performing an assessment of energy security. Three fundamental questions are defined when assessing energy:

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[11] https://harzing.com/resources/publish-or-perish

- Which dimensions of energy security are most important?
- What metrics best capture these dimensions?
- How might these metrics be used to create a common index or scorecard to measure national performance on energy security?

Most recently, Azzuni and Breyer (2017, 2020) stated that the key research gap thus far is the lack of a comprehensive definition of energy security that takes into account all energy security dimensions. It was noted that energy security assessments need to be simultaneously holistic and detailed. Using a structural approach, 15 energy security dimensions were therefore determined to permit precise evaluation: availability, cost, culture, cyber security, diversity, efficiency, employment, environment, health, literacy, location, military, politics, resilience, technology and efficiency, and time frame. The authors claim this provides the foundation for the most detailed and complete approaches to assessing energy security.

Gasser (2020) contributed by presenting results of a detailed analysis of 63 key quantitative indicators measuring the energy security of multiple countries. The author of the review concluded that in energy security assessments thus far there exists a lack of transparency. This shortfall was noted specifically in the selection of indicators, methodologies, indicators weighting and aggregation of functions. Poor data processing and multivariate analysis' techniques were also pointed out, with few papers performing uncertainty, sensitivity or robustness analysis. Such analysis' provide additional validity to results and thus are strongly recommended going forward. Further, the main bulk of papers construct indices based on past data with few providing forecasting to support future energy policies (Gasser, 2020).

Since 2012, the Global Energy Institute (GEI) has been providing detailed global energy security analysis on a quadrennial basis, with the most recent being in 2020. Each publication generates an International Energy Security Risk Index (IESRI), which has been contributing to a better understanding of global energy markets. The report emphasizes that in order to build an International Index, the data for analysis must be considered reliable. To be so, the key data characteristics were identified: Sensibility, credibility, accessibility, transparency, completeness and updateable. The papers display dynamic weighting schemes for the chosen indicators for each version, with the metrics being categorized into the following: Global Fuels, Fuel Imports, Energy Expenditure, Price & Market Volatility, Energy Use Intensity, Electric Power Sector, Transportation Sector and Environmental. However, Augutis et al. (2017) noted in their literature review that there exists a challenge associated with objectively determining the weight of each criteria, since priorities have a political and subjective nature. GEI further noted issues of data availability, with non-OECD countries containing more transparent and clear data than of OECD nations[12].

The influence of energy supply diversity was addressed by numerous papers. Gupta (2008) harnessed the Herfindahl-Hirshmann Index to assess oil supplier diversity taking into account the average geopolitical risks for different countries. Geng and Ji (2014) created an Energy Market Concentration index, using an H-H index, to

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[12] https://www.globalenergyinstitute.org

assess external energy diversity as part of the formulation of one complex indicator. Park and Bae (2021) explored Korea's energy import dependence using data from 10 primary energy sources. They noted that the H-H index, along with the Shannon Index, required more specific data that are not easily accessible to the public. Further noted was the lack of studies addressing the correlation between energy dependence and diversity. Chuang and Ma (2013) used both the Shannon Index and H-H index to evaluate the diversity of primary energy supply in Taiwan to help mitigate domestic energy supply shortages and cost fluctuation risks. Flouri et al. (2015) used a Monte Carlo simulation to assess European natural gas supply security in light of Europe's increasing import dependence, projected to be over 85% by 2030. The simulation focused on the adaptability of EU nations when subjected to disruption of three Algerian natural gas pipelines. Biresselioglu et al. (2015) investigated the natural gas supply of 23 importing nations globally between 2001 and 2013 using an index built using the Principle Components Analysis index. They observed that a significant portion of the existing literature focused on single year assessments, limiting the ability to track changes in countries rankings over time.

Few papers address the uncertainty drivers of energy security in a low carbon world. Guivarch et al. (2015) explored the influence of climate policies on energy security indicators. It was concluded from their study that climate policies had a limited positive effect on specific aspects of energy security. Guivarch and Monjon (2017) in further work noted European targets to simultaneously decrease Carbon Dioxide emissions and improve energy security would be difficult to accomplish. For example, the deployment of renewable energies induces a greater dependency on natural gas for peak load and back-up, especially Russian gas. The Crimea conflict revealed Europe's vulnerability in this instance. Further it was recommended that primary fuel indicators are prioritized when assessing energy security in the short term, whilst electricity indicators become crucial in the longer term. Huang et al. (2021) highlighted that satisfying the 3E (economic growth, energy consumption and environmental protection) trilemma poses as a major challenge when trying to achieve high levels of energy security. The literature review in this paper examines the prevalence of various dimensions and indicators used to assess energy security. Energy intensity and CO2 intensity emerged as the most commonly applied indicators for energy security assessments. Following, an energy security performance framework was developed to provide an all-encompassing index to better quantify and compare global energy security using an MCDA method. The WorldRiskIndex was formulated in 2022 comprising of 100 indicators which aims to quantify to what extent nations are susceptible, able to cope and able to adapt to extreme natural events. With the increase in frequency and intensity of such events as a result of climate change, such an index serves as guidance for decision makers to mitigate disaster risks[13]. Table 2 depicts some key applications of MCDA methodologies in assessing energy security.

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[13] https://weltrisikobericht.de/weltrisikobericht-2022-e

Author	**MCDA Methodology**	**Research Objective**	**Region**	**Time horizon**	**No. of indicators**	**Data Sources**
Ren and Dong (2018**)**	Fuzzy Analytic Hierachy Process	To evaluate energy electricity supply and security	Brazil, Russia, China, India, South Africa	1990-2010	9	IEA and World Bank
Phillis et al. (2020**)**	PROMETHEE	To provide a framework for defining and measuring the sustainability of national energy systems	Europe	2000-2017	12	World Bank Eurostat Govdata360 Sources for Emissions Database Emission Database for Global Atmospheric Research Institute for Health Metrics and Evaulation
Cabeça et al. (2021)	ELECTRE TRI-nC	To classify members of the European Union in terms of their energy efficeincy governence effectiveness	European Union	2013 and 2016	14	Energy Efficiency Policies and Measures Database ODYSSEE-MURE database World Energy Council
Huang et al. (2021)	SWA (Simple Weighted Average) TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	To establish an efficient and integrated methodology for assessing China's energy security	China	2008-2017	11	Chinese Energy Statistical Yearbook

	GRA (Grey Relational Analysis)					
Kozlowska et al. (2022)	Analytic Heirachy Process	To develop an algorithm which simulates how policy makers think when assessing energy security	European Union	2012-2020	9	Eurostat
P. Ziemba (2022)	Fuzzy Saw and NEAT F (Net Effect and Absolute Total Flow) PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations)	To examine past, present and future energy security globally	Global	2020-2030	*29*	IESRI (International Energy Security Risk Index)
Wulf et al. (2023**)**	PROMETHEE	To rank the sustainability of innovative energy technologies	Germany	2018	18	Ecoinvent Database

Table 2 - Applications of MCDA in studies on Energy Security

In summary, there exist a number of key downfalls in the existing literature surrounding energy security assessments. The lack of literature analyzing several years was noted, therefore this study attempts to build on assessments which see how energy security evolves through time. The rising military and political tensions arisen due to the annexation of Crimea have obliged European nations to boost their energy security mechanisms to seek out alternative natural gas supplies to Russia[14]. No current studies incorporate the Shannon index to measure the diversity of oil and gas suppliers in Europe. The addition of such indicators therefore provides a unique perspective to understanding energy security across Europe by accounting for the evolving political stabilities of supplier nations. A similar index to account for the suppliers of coal to Europe was desired, however due to the lack of easily accessible specific data, as iterated by Park and Bae (2021), it was not possible. By selecting a temporal frame which accounts for a period prior and during the Crimea conflict, efforts to diversify suppliers can be accounted for in the assessment. As Table 1 highlighted, emission reduction targets are being actively addressed throughout Europe to address climate change. The incorporation of indicators to acknowledge international efforts to comply with such targets is essential when assessing energy security. Further, there exist few studies which incorporate sensitivity and robustness analysis'. The execution of these within this study provide a deeper insight into the nature of the data and the validity of the results. The lack of statistical tests to identify more specific trends in the results of studies is also apparent. This study therefore provides such an analysis, in the form of the Kruksal-Wallis test, to ascertain whether there exist regional trends in energy security within Europe.

3. ELECTRE TRI-nC Methodology

The ELECTRE TRI-nC method has been selected for this assessment given that its capabilities strongly align with the objectives of this study. This method holds several advantages, including the ability to handle ordinal and incomplete data. The criteria weighting function permits appropriate prioritization of different criteria. Furthermore, ELECTRE TRI-nC generates clear and intuitive outputs which can be assessed for their validity through stability and scenario analysis'. This work will follow the ELECTRE TRI-nC formulation, adapted from Doumpos and Figueira (2019).
$A = \{a_1,...,a_i,..., a_n\}$ denote the set of *potential actions*, also known as alternatives, which in this case are the European nations;
$G = \{g_1...,g_j,...,g_n\}$ designate the set or *coherent family of criteria*;
$g_j(a_i)$ the *performance* of action a_i on criterion g_j;
$C = \{C_1,...,C_h,...,C_q\}$ is the set of ordered categories with $q \geq 2$;
$B = \{B_1...,B_h...,B_q\}$ the set of characteristic profiles on reference actions that define categories in C; and
$B_h = \{b_{h1}...,b_{hl}...,b_{h|Bh}\}$ the set of reference actions categorising category C_h, $for\ h = 1, \ldots , q$.

Let g_j denote a *pseudo criterion* which is associated with two thresholds: an indifference threshold, q_j, and a preference threshold, p_j, such that $p_j \geq q_j \geq 0$. The indifference thresholds account for the imperfect nature of

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[14] https://www.europarl.europa.eu

the data used to compute the performances of g_j *for all* $a_i \in A$, as well as the subjectivity involved in defining the analysis criteria. The indifference threshold (q_j) represents the performance level below which actions are considered equally adequate, whilst the preference threshold (p_j) represents the performance level above which actions are considered suitable.

With the aforementioned definition of pseudo-criteria and the associated thresholds, three binary relations are established for each criterion $g_j \in G$.

Per-criterion indifference relations play an essential role in evaluating actions based on individual criteria. This relation states, put simply, that actions a and b are indifferent according to criterion g_j, denoted by aI_jb. This occurs when *whenever* $|g_i\ (a) - g_j\ (b)| \leq q_j$. Let $C(aIb)$ denote the set of criteria such that aI_jb holds.

Another important definition is the per-criterion strict preference relation. Denoted as aP_jb , this relation signifies that action *a* is strictly preferred over action *b* with respect to action g_j. Specifically, aP_jb holds true when the performance difference between actions *a* and *b*, represented by $g_j(a) – g_j(b) > p_j$, ie., when there is a significant advantage of *a* over *b*, for the criterion under consideration. Let $C(aPb)$ denote the set of criteria such that aP_jb holds true.
This definition states that action *a* is weakly preferred to *b* with respect to criterion g_j. Specifically, aQj holds true when $q_j < g_j(a) – g_i(b) \leq p_j$, *i.e.*, when the difference between *a* and *b* falls within the range defined by the indifference threshold q_j and the preference threshold p_j. Building upon these definitions, it is now possible define the per-criterion outranking relation.

The outranking relation determines the relative superiority of actions. Denoted as aS_jb , it signifies that action *a* outranks action *b* according to criterion g_j. In *stricto sensu*, aS_jb holds true when either aI_jb, aP_jb *or* aQ_jb holds. In *latu sensu*, aS_jb holds true when aI_jb, aP_jb *or* aQ_jb, *or* bQ_jb hold. Electre methods are, fundamentally, outranking based methods which begin with the construction of comprehensive outranking relations considering all criteria. The ELECTRE TRI-nC method more specifically constructs a singular outranking relation.

3.1. The construction of an Outranking Relation

In Electre methods, outranking relations are constructed on the premise of two fundamental concepts: concordance and non-discordance, which determine whether action *a* outranks action *b*. These concepts are represented by the comprehensive concordance index and per-criterion discordance indices. The concordance index deduces the degree of agreement among different criteria for action comparisons. The discordance index measures the extent to which criteria deviate from concordance. By integrating these indices, a degree of credibility is established for the assertion '*a outranks b*', providing a measure of confidence in the relationship. Finally, a categorical credibility index must be defined to gage to validity of '*a outranks the set* B_h'.

The concept of concordance with the assertion of ‘*a outranks b*’ revolves around the presence of a robust concordant coalition of criteria, favouring action *a* over action *b*. Each criterion, represented by g_j, has a certain degree of influence determined by its relative importance coefficient of weight, w_j. These coefficients serve as preference parameters and sum up to 1. Therefore, the strength of the concordant coalition comprises of the criteria which support the assertion ‘*a outranks b*’ and a portion of the power from criteria where ‘*action b is weakly preferred to a*’. To capture this concept, the concordance index is created and is formulated as follows:

$$c(a,b) = \sum_{j\in C(a\{I,Q,P\}b)} w_j + \sum_{j\in C(\{bQa\}} \varphi_j \qquad (1)$$

$$\varphi = \frac{g_j(a)-g_j(b)+p_j}{p_j-q_j} = \in [0,1]. \qquad (2)$$

The concept of non-discordance with the assertion ‘*a outranks b*’ relates to the lack of significant opposition coalition of criteria that opposes the claim that ‘*a outranks b*’. Non-discordance implies that there is no powerful minority group that opposes the claim. The opposing power of each criterion, g_j, is measured using a preference parameter known as the veto threshold, denoted as v_j. The veto threshold signifies the level which a criterion can challenge the superiority of action ‘a’ over action ‘b’. To quantify this opposing power, a per-criterion discordance index is employed, taking the following form:

$$d_j(a,b) = \begin{array}{ccc} 1 & if & g_j(a)-g_j(b) < -v_j, \\ \frac{g_j(a)-g_j(b)+p_j}{p_j-v_j} & if & -v_j \leq g_j(a)-g_j(b) < p_j, \\ 0 & if & g_j(a)-g_j(b) \geq -p_j. \end{array} \qquad (3)$$

The credibility of the assertion of ‘*a outranks b*’ is the extent to which ‘*a outranks b*’. A way of modelling it is through the deployment of the following expression:

$$\sigma(a,b) = c(a,b)\prod_{j=1}^{n} T_j(a,b), \qquad (4)$$

where

$$T_j(a,b) = \begin{cases} \frac{1-d_j(a,b)}{1-c(a,b)} & if\ d_j(a,b) > c(a,b), \\ 1 & otherwise \end{cases} \qquad (5)$$

This degree of credibility enables the establishment of a meaningful relationship between ordered pair of actions, creating a form of fuzzy relation.

The maximum operator is used to define the categorical credibility indices and is defined as follows:

$$\sigma(a, B_h) = max_{l=1,\dots,|B_h|}\{\sigma(a, b_{hl})\} \quad (6)$$

$$\sigma(B_h, a) = max_{l=1,\dots,|B_h|}\{\sigma(b_{hl}, a)\{b_{h1}\}\} \quad (7)$$

The formulas above use the max operator to deduce the maximum value among the set of individual credibility indices. This choice is not arbitrary but based on certain logical principles: $b_{h1.}$

In the first case B_h contains a single reference action, i.e, $I = 1$ and thus $B_h = \{b_{h1}\}$, then $\sigma(a, B_h) = \sigma(a, b_{h1})$. In the second case there is more than one reference action, thus it happens that $b_{hr} \in B_h$ such that $\sigma(a, b_{hr}) \leq \sigma(a, B_h)$, then, for all values of a, $\sigma(a, B_h \backslash b_{hr}) = \sigma(a, B_h)$. The justification for the definition of $\sigma = (B_h, a)$ follows a similar rationale, refer to Almeida-Dias et al. (2012) for further details.

To transform the valued relation into a concise one, it is essential to establish a cut-off level, represented by λ. This cut-off level serves as a preference parameter and defines the minimum level of credibility required by the decision-maker to confirm the assertion '*a outranks* B_h'. λ typically falls within the range of [0.5,1]. With this in mind, the comprehensive binary relations can be defined and are as follows:

λ-*indifference*: $aI^{\lambda}B_h \Leftrightarrow \sigma(a, B_h) \geq \lambda \text{ and } \sigma(B_h, a) \geq \lambda$
λ-*preference* (in a broader sense): $a \succ^{\lambda} B_h \Leftrightarrow \sigma(a, B_h) \geq \lambda \text{ and } \sigma(B_h, a) < \lambda$
λ-*outranking*: $aS^{\lambda}B_h \Leftrightarrow \sigma(a, B_h) \geq \lambda$
λ-*incomparability*: $aR^{\lambda}B_h \Leftrightarrow \sigma(a, B_h) < \lambda \text{ and } \sigma(B_h, a) < \lambda$

The comprehensive binary relations listed above will be employed in the exploitation procedure to allocate actions to respective categories. To maintain simplicity, the superscript λ with be omitted from the notation of these comprehensive binary relations.

3.2. The Exploitation of the Outranking Relation: The Assignment Procedures

Let us consider two dummy categories, C_{q+1}, where B_{q+1} consists of an (ideal) action that dominates all other action; and C_0, where B_0 consists of an (anti-ideal) action that is dominated by all other actions. The comprehensive relations discussed previously make it possible to define the potential relationships between an action a and the sets B_h, where h ranges from 0 to $q+1$. There are only three possible cases:

A sequence where action a is λ-preferred to the first sets of B_h, followed by the reverse sequence of the remaining sets of B_h. To simplify the notation, the mention of action a that sets B_h, and the parameter λ, can be omitted. We represent this case as follows:

$$\succ . . . \succ \succ^{-1} . . . \succ^{-1}.$$

An indifference sequence is introduced between the previous relations, *i.e.*:

$$\succ \ . . . I . . . I \succ^{-1} . . . \succ^{-1}.$$

Instead of an indifference sequence, it is an incomparability sequence, *i.e.*:

$$\succ \ . . . R . . . R \succ^{-1} . . . \succ^{-1}.$$

Before delving into the definitions of the two procedures that make up ELECTRE TRI-nC, it is necessary to introduce the following *selecting function*:

$$\rho(a, B_h) = min\{\sigma(a, B_h), \sigma(B_h, a)\}. \quad (8)$$

To begin, choose a credibility or cut-off level, λ, which falls in the range [0.5,1]. Starting with h = *(q + 1)*, decrement the value of *h* until reaching the first value, denoted as *t*, where $\sigma(a, B_t)$ exceeds λ. At this point, C_t is referred to as the *descending pre-selected category*. The subsequent steps are as follows:

For t = q, select 'C_q' as a possible category to assign to action 'a'
For 0 < t < q, if $\rho(a, B_t) > \rho(a, B_{t+1})$, then select '$C_t$' as a possible category to assign 'a'; otherwise, select 'C_{t+1}'
For t = 0, select 'C_1' as a possible category to assign to 'a'

For this assignment procedure, again select a credibility or cut-off level, λ, which falls in the range [0.5,1]. Increase *h* from *0* until the first value, *k*, such that $\sigma(a, B_t)$ exceeds λ (C_k is referred to as the *ascending pre-selected category*). The subsequent steps for this procedure are then as follows:

For k = 1, select 'C_1' as a possible category to assign to action 'a'
For 0 < k < q+1, if $\rho(a, B_k) > \rho(a, B_{k-1})$, then select '$C_k$' as a possible category to assign 'a'; otherwise, select 'C_{k-1}'
For k = q+1, select 'C_q' as a possible category to assign to 'a'

Both of these procedures should be applied in conjunction with each other. Together, they establish an interval range for assigning each action, as opposed to providing a single category. The ELECTRE TRI-nC method therefore identifies both a lower and upper category boundary. Thus, the method determines the lowest and highest possible categories to which an action can be assigned. Consequently, for a given action, the ELECTRE TRI-nC method results in one of the three possible outcomes: a single category if the two selected categories are the same, two categories if the categories are consecutive, or an interval comprising of more than two consecutive categories (bounded by the two selected categories).

3.3. ELECTRE methods: strengths and weaknesses

Figueira and Roy (2009) and Figueira et al. (2012) assessed the strengths and weaknesses of ELECTRE methods. The valuable features include:

- The use of qualitative indicators is possible;
- Criteria with different measurement units and scales can be integrated;
- Each criterion is treated separately, with no performance compensation;
- They consider imperfect knowledge of data and acknowledge subjectivity when constructing criteria

On the contrary, the weaknesses were depicted as follows:

- Generally, ELECTRE methods do not provide a score for individual actions
- When all criteria are quantitative, alternative methods may yield more suitable results
- ELECTRE methods may have intransitive behaviour, which is only an issue if transitive preferences are a priori

By transparently highlighting the characteristics, users of the ELECTRE methodologies can derive more meaningful insights from their analysis.

4. Data Processing and Analysis Methodology

Figure 1 depicts the general process to formulate, execute and analyze the model implemented into MCDA U-Laval.

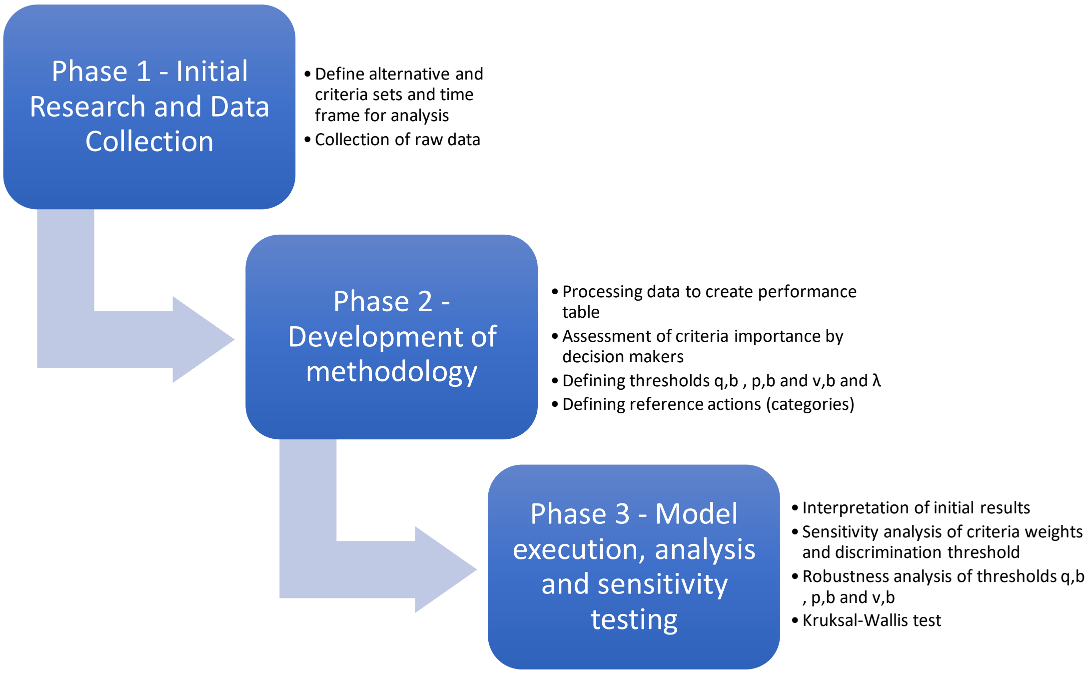

Figure 1 - General process for model implementation in MCDA U-Laval

The study conducted analyses for the evolution of the energy security in 26 EU members (Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden) together with the United Kingdom. This group was chosen due to their complex, dynamic and interconnected energy dependencies and geopolitical relationships in light of Crimea and Climate Change.

This study will assess energy security changes in the years 2013 and 2018. Between these years, the European region has experienced a notable shift in energy strategies and policies in response to the Crimea conflict, in an attempt to enhance energy security. The evolving energy landscape during this period, amidst increasing climate change concerns, will also be evaluated.

Table 3 comprehensively presents the dimensions of energy security with their underlying values and components. The chosen framework follows that of Sovakool and Mukherjee (2011), dividing the dimensions of energy security into 5 categories: Availability (d1), Affordability (d2), Technological development and efficiency (d3), Environmental and social sustainability (d4) and Regulation and governance (d5).

Dimension	Explanation	Underlying Values	Components
d1	Maintaining adequate energy supplies. Achieving energy self-sufficiency. Promoting diversification of energy technologies. Harnessing domestic energy supplies. Maintaining appropriate reserve-production ratios	Self-sufficiency, resource availability, supply security, independence, imports, diversity, equilibrium, disparity	Security of Supply and Production Dependency Diversification
d2	Achieving cost-effective energy generation, ensuring energy prices are stable and accessibility to energy services that are fair and inclusive.	Cost, stability, predictability, equity, justice, alleviating energy poverty	Price Stability Access and Equity Decentralization Affordability
d3	The ability to be flexible and responsive when faced with energy adversity. Pursuing research and development of innovative energy technologies with appropriate investments into infrastructure and maintenance. Providing high quality energy services.	Investment, employment, technology development and diffusion, energy efficiency, stockholding, safety and quality	Innovation and Research Safety and Reliability Resilience Efficiency and Energy Intensity Investment and Employment
d4	Minimising environmental degradation, mitigating GHG emissions and adapting to climate change.	Stewardship, aesthetics, conservation of natural habitats, water quality and availability, public health, mitigation of climate change, adaptation to climate change	Land Use Water Climate Change Pollution
d5	Having diplomatic and transparent policy making methods. Possessing competitive and inclusive energy markets which promote trade of energy technology and fuels. Providing education on energy issues and security	Transparency, accountability, legitimacy, integrity, stability, resource management, geopolitics, trade freedom, competition, profitability, interconnections	Governance Trade and Regional Interconnectivity Competition and markets Knowledge and Access to Information

Table 3 - Energy security dimensions, explanations, components and deployed indicators for this study. Adapted from Sovacool and Mukherkjee (2011)

To ensure a comprehensive assessment of energy security in Europe, 8 indicators were chosen which collectively cover all previously described dimensions. The indicators used in this study and corresponding dimensions are given in Tables 4 and 5.

g1	Energy intensity
g2	Nuclear electricity generation
g3	GHG emissions per capita
g4	Renewable energy generation
g5	GDP per capita (PPP)
g6	Shannon index for oil
g7	Shannon index for natural gas
g8	Energy consumption per capita

Table 4 - The chosen indicators for this study

	g1	*g2*	*g3*	*g4*	*g5*	*g6*	*g7*	*g8*
d1		x				x	x	x
d2					x			
d3	x							
d4		x	x	x				x
d5						x	x	

Table 5 - Indicators and corresponding dimensions

To compliment the assessment, sensitivity and robustness analysis' will be performed to affirm the validity of the results. In addition to this, a Kruksal-Wallis test is executed to ascertain whether there are any significant localized energy security trends within Europe.

4.1. Indicator Descriptions

To formulate each indicator for implementation in MCDA U-Laval, different approaches were applied to process each dataset, such that it was suitable for analysis. Descriptions of each indicator, their relevance to energy security and their application to this study, are outlined in the following subsections.

Prior to performing the current analysis, the model was executed with 10 indicators for all successive years from 2013 through to 2019. It was found that for successive years there existed little to no significant changes in categorical placements. The two additional indicators deployed were energy efficiency and oil stock compliance. Energy efficiency was deemed inappropriate for the analysis, given that energy intensity already acts to capture a similar aspect of energy security. Oil stock compliance was deemed redundant due to its inaccuracy in assessing energy security. The formulation for this indicator was such that it accounted for only the oil reserves present in each nation. In some cases, oil stocks are held abroad under bilateral agreements between governments, guaranteeing that in the event of a crisis they will be available. A proportion of oil stocks held abroad can also be owned by agencies or companies with the stockholding obligation, which can be purchased based on short term contracts and leases[15]. Therefore, the statistics regarding oil supplies can be an underrepresentation of national oil capacity, as a result of the indiscrete nature of the data, given that not all datasets account for these international

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[15] https://www.iea.org/data-and-statistics/data-tools/oil-stocks-of-iea-countries

stockholding arrangements. Such alterations highlight energy security as an abstract concept, and thus any attempts to define and measure it will be immediately constrained by the limitations of the indicators used. This is an issue of operationalizing an indiscrete variable. Subsequently, any study of energy security is defined by the indicators used to represent the concept, highlighting the importance of careful consideration for the indicators used. Following the data analysis of 10 criterion, this issue became apparent. As a result, by omitting two of the variables that obscured the explanatory power of the indicators overall, the results increased in ecological validity.

4.1.1. Energy intensity

The first indicator is tied to dimension 3: technological development and efficiency. Energy intensity measures the energy required to produce a unit of output. In this context of the data used, it is the kilograms of oil equivalent (KGOE) per thousand euro (PPP). Lower scores imply less energy is required to produce a certain economic output, which in turn reduces the strain on energy resources. Further low scores indicate mature and developed energy technologies. The dataset was taken from Eurostat and normalized for better interpretation of the distribution of scores amongst the nations.

4.1.2. Nuclear Electricity Generation

The second criterion falls into dimensions *d1* and *d4*: availability and environmental and social sustainability respectively.

Domestic nuclear power generation has several positive implications on energy security. Such energy sources further boost the diversity of a nations' energy mix, aiding the mitigation of risks associated with supply disruptions, price volatility and geopolitical tensions associated with other energy sources. Furthermore, the low carbon nature of nuclear poses ever increasing levels of vitality in light of efforts to decarbonize energy markets. The reliability of nuclear power also contributes to the general stability of a nation's energy system, ensuring the needs of all critical infrastructure are met.

Despite nuclear power's clear benefits, concerns regarding safety in its use as an energy source have been highlighted through past events. More specifically, the negative impacts of nuclear power plant malfunctions were highlighted in the events following the Chernobyl (1986) and Fukushima Daiichi (2011) disasters. One of the main causes of such incidents is the result of human error, as opposed to risks associated to the material itself[16]. Subsequently, there has been a shift of focus to reducing the potential for human error as a result of organizational weakness.

Although the incident rate of utilizing nuclear power are relatively low, with a reduction by a factor of 1600 of severe nuclear power plant accidents, since the use of early Generation 1 reactors, there is still a need for a

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[16] https://world-nuclear.org

response to be implemented. From these incidents, energy security regulations have made strong efforts to mitigate against any future incidents, through the use of high quality materials, thoughtful planning, robust back-up protocol and systems and thorough design. In this, the nuclear industry has been able to learn from past accidents. Another factor for consideration is the safety of workers handing such nuclear materials and working in these environments. This issue has been addressed through the insurance that workers have appropriate PPE, continuous monitoring of all equipment's and remote handling where appropriate[17]. Furthermore, the mortality rate of nuclear energy is significantly lower to that of coal energy sources, which are considerably more widespread in this industry.

Despite the risks, nuclear energy has the potential to greatly change the landscape of energy security, to aid the shift to more renewable sources of energy. All of these effects have been collated and included in new safety efforts that ensures standardized regulations and design across all European nations, in respect to the national regulators, the role of operators and the international collaborators involved[17].

Kosai and Unesaki (2020) evaluated the nuclear energy supply of the United States using six nuclear related indicators, namely: nuclear share, nuclear intensity, nuclear use per capita, nuclear diversification, independence and public opinion. The work aims to aid policy makers decisions related to nuclear energy utilization, therefore contributing to enhanced overall energy security. The 2020 IESRI report incorporated nuclear energy into their power generation metric. The report recognised the negative impact the Fukushima Daiichi incident had on energy security. Further noted was the anticipation of increased energy security risks for Germany amid their nuclear plant closures in 2022.

To formulate the data such that it was suitable as an input for analysis, the nuclear electricity generation of each nation was divided by its respective total electricity generation. Both datasets were extracted from Our World in Data[17]. This dataset made it apparent that such an energy source was only deployed by 12 of the 27 nations. Therefore, the other 15 nations' input values for this metric were 0.

4.1.3. GHG Emissions per Capita

The third indicator falls into dimension 4: environmental and social sustainability. It reflects the relative progress each nation has made towards global efforts to combat climate change, with lower values for this metric implying strong levels of international compliance with regulations and emission targets. Furthermore, lower emission scores demonstrate a nations ability to prioritise less emission intensive energy sources, which correspond to providing long-term energy security. The datasets for this metric were taken from Our World in Data. For each year and nation, the tonnes of emissions were divided by the population.

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[17] https://ourworldindata.org

4.1.4. Renewable energy generation

The fourth indicator, similarly to *g3*, is associated with the dimension 4: environmental and social sustainability. The indicator is considered as a Sustainable Development Goal indicator, as was developed to assess the progress towards targets set within the EU Sustainable Development Strategy[18]. Higher shares of renewable energy sources promote energy independence. In light of rising geopolitical tensions, such a factor proves vital to maintaining energy security. Further, higher scores reflect climate change mitigation efforts and can track to what extent nations are progressing towards a cleaner energy mix. The data for this metric was taken from Eurostat, whereby the percentage of electricity from renewable energy sources was obtained. The share of energy from renewable sources is calculated for four elements: transport, heating and cooling, electricity and overall renewable energy sources share. By incorporating all elements into the metric, a more accurate reflection of each nations overall transition to renewable energy is attained. The data was normalized in excel for a more clear-cut relative comparison between the European countries.

4.1.5. GDP per Capita (Corrected by PPP)

The fifth indicator belongs to dimension 2, Affordability. GDP per capita, corrected by PPP, provides a firm insight into the purchasing power citizens of nation have. A higher value for this metric implies citizens have a higher level of economic freedom, permitting higher resilience to energy price shocks. Furthermore, better scores imply the nation is capable of investing in infrastructure and technologies to enhance energy security. The data was sourced from the World Bank, and was normalised in Excel to aid visual interpretation.

4.1.6. Shannon Index for diversity of suppliers of oil

The sixth indicator belongs to dimensions 1 and 5: Availability and Regulation and governance respectively. The Shannon index calculates the degree of diversity within a dataset, with higher values indicating higher levels of diversity.

In this context, the equation has the following elements:

$$H = -\sum_{i=1}^{s} (p_i)(\ln p_i) * x_i \quad (9)$$

where:
H is the Shannon diversity score,
s is the number of importer countries,
p is the proportion of oil imported from country i,
x is the index score for political stability and absence of terrorism for country i.

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[18] https://ec.europa.eu/eurostat/cache/metadata/en/nrg_ind_share_esmsip2.htm

In the context of oil, higher diversity scores imply that nations possess sufficient levels of oil import diversity from nations that have high levels of political stability. Therefore, these scores provide a robust indication of the risk and resilience of nations to supply disruptions.

The data for oil exporting nations was sourced from Eurostat, whilst the political stability and absence of terrorism data was sources from World Bank.

4.1.7. Shannon index for diversity of suppliers or natural gas

Indicator 7 is identical in its methodology to that of indicator 7, with only the energy source being natural gas instead of oil. It is noteworthy to mention that when calculating the indices, nations who have one politically stable importer can be penalised. For example, Sweden for some analysed years was solely reliant on Denmark for their natural gas. Therefore, due to the nature of the index calculation, Sweden received a score of 0 in despite the fact that Denmark is a very reliable and stable energy exporter.

4.1.8. Energy Consumption per Capita

Indicator 8 corresponds to categories 1 and 4: availability and environmental and social sustainability respectively. Lower values for this metric imply better resource efficiency and an overall reduced energy demand relative to the population size. By having a lower energy demand, the ability to provide energy primarily from domestic resources becomes more facile. Further, less intense energy consumption is tied to few emissions which contributes to long term energy security by minimizing the risks and costs connected with climate change.

Indicator	Data Source	Unit	Direction	Reference
Energy Intensity	Eurostat	Kilograms of oil equivalent (KGOE) per thousand euro in purchasing power standards (PPS)	Minimise	Sovacool and Mukherjee (2011) Guivarch and Monjon (2017)
Nuclear Electricity Generation	Our World in Data	%	Maximise	Sovacool and Mukherjee (2011) Kosai and Unesaki (2020)
GHG emissions/ capita	Our World in Data	Tonnes Carbon Dioxide (CO2)	Minimise	Chung et al. (2017) Sovacool and Mukherjee (2011)

		Equivalents / Capita		Lin and Raza (2020)
Renewable energy generation	Eurostat[19]	%	Maximise	Chung et al. (2017) Augutis et Al. (2017) Sovacool and Mukherjee (2011)
GDP per Capita (PPP)	World Bank[20]	US Dollar ($)	Maximise	Sovacool and Mukherjee (2011) Geng and Ji (2014)
Shannon Index Oil	Political Stability Index and Absence of Terrorism - World Bank Oil Imports - Eurostat	Dimensionless	Maximise	Chung et al. (2017) Park and Bae (2021) Sovacool and Mukherjee (2011)
Shannon Index Natural Gas	Political Stability Index and Absence of Terrorism - World Bank Natural Gas Imports - Eurostat	Dimensionless	Maximise	Chung et al. (2017) Park and Bae (2021) Sovacool and Mukherjee (2011)
Energy Consumption per Capita	Our World in Data	kWh/Capita	Minimise	Sovacool and Mukherjee (2011) IESRI (2018)

Table 6 - Description of Indicators Used

The aforementioned indicators were chosen based on those used in studies of energy security, which are outlined in the references column of table 6. Together with the framework followed and outlined in table 3, the key dimensions of energy security are accounted for in the assessment. Table 6 summarizes the chosen criteria for this assessment with their corresponding data source, unit, direction and references.

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[19] https://ec.europa.eu/eurostat

[20] https://www.worldbank.org

4.2. Criteria Weighting

4.2.1. The Deck of Cards method for criteria weighting

Criteria weighting is essential when using the ELECTRE TRI-nC method to assign the relative importance to each criterion. The chosen weighting method for this analysis is the Deck of Cards Method, also referred to as the Simos-RoyFigueira method (Figueira and Roy, 2002). This method can be executed using a software, available online, called DecSpace[21]. The procedure uses a deck of cards, with each card representing a criterion to be ranked. Additionally, blank cards are utilised to indicate the difference in importance between successive criteria. The parameter ratio *Z*, representing the weight ratio between the most and least important criterion(s), needs to be defined.

To implement the method, the following steps are performed in an interactive exercise between the analyst and the DM to gather the required information.

Each criterion is represented by a physical card. The DM is provided with a set of cards equal to the number of criteria. Then, the DM is asked to order these cards from least to most important, with cards of equal importance being next to each other. By doing this, a complete pre-order of all the criteria is established.

Next, the DM considers the relative closeness of importance between successive ranks or subsets of criteria with equal importance. The blank cards are introduced to represent the difference in importance between criteria. The DM is asked to place blank cards between criteria with a larger relevance gap, while subsets with smaller relevance differences have no blank cards. Each blank card represents one unit of weight difference between consecutive cards or subsets.

The analyst then asks the DM to estimate the weight ratio between the most and least important criterions. Precise values can prove to be difficult, thus alternative approaches such as assigning votes or considering an interval of possible values, can be used. The ratio *Z* in DecSpace is known as the parameter ratio. It is defined as the ratio between the most and least important subsets of criteria.

By incorporating the information attained through the aforementioned steps, the weights of the criteria can be normalised and applied to the ELECTRE TRI-nC method.

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[21] http://app.decspacedev.sysresearch.org

4.2.2. Weighting of Criteria

The DM was asked to prioritize the criteria in a questionnaire. The questionnaire made use of a linear 1-5 scale, with increments of 0.5, whereby '1' denoted 'irrelevant criteria' and '5' denoted 'very relevant criteria'. The DM is a Green Hydrogen Engineer for Shell in the Netherlands. The scores for each criterion were then used as inputs for the DecSpace software. The blank spaces between the criteria were deduced by the DM and displayed a systematic approach as seen in Figure 2.

Figure 2 - Input of blank cards in DECSPACE as per the DM's priorities

Finally, parameter *Z* was defined. Z is defined as the ratio in importance level between the most and least important criterion. Since the most and least important criterion subsets had values of 5 and 2 respectively, *Z* assigned a value of 2.5. With all input data complete in DecSpace, a set of normalized weights as input for the analysis were obtained. The results from the questionnaire, along with the final weights, denoted as *k*, from DecSpace can be seen below in Table 7.

Criteria	DM	*k*
Energy intensity	3.5	10.5
Nuclear electricity generation	5	15.8
GHG emissions per capita	4	12.6
Renewable energy generation	4	12.6
GDP per capita (PPP)	3.5	10.6
Shannon index for oil	5	15.8
Shannon index for natural gas	5	15.8
Energy consumption per capita	2	6.3

Table 7 - DM questionnaire score and corresponding weights determined through DecSpace

The DM assigned a reasonable priority energy intensity and a maximum importance to nuclear power. A focus on promoting zero carbon energy solutions aligns with their score for GHG emissions and renewable energy generation. The importance of GDP per Capita (PPP) was assigned a reasonable value. The DM recognized the upmost importance of having stable and diverse energy suppliers, as seen through the scores assigned to both Shannon Indices. Low scores for energy consumption per capita indicate the DM places more importance on the production and supply of energy with regards to energy security.

4.3 Performance Tables

The performance tables for 2013 and 2018 can be seen in tables 8 and 9. Note the data points highlighted in orange were those which required filling, which will be explained in the data remarks section 4.6.

The performance tables of reference alternatives for 2013 and 2018 can be seen in tables 10 and 11, respectively. The reference alternatives serve as benchmarks for categorizing countries based on their indicator performance. They were created by establishing percentile bounds at 0%, 20%, 40%, 60%, and 80% for each indicator over the years studied.

For 2013 Ireland scored best for energy intensity, whilst Estonia has the scored the worst. France possessed the highest nuclear electricity output, whilst 15 of the European nations studied possessed no nuclear electricity deployment. Latvia possessed the lowest GHG emission per capita score whilst Luxembourg had the highest. Luxembourg had the lowest renewable energy output, whilst Norway had the highest. Luxembourg and Bulgaria were the most and least wealthy nations, respectively. Luxembourg and Finland performed the weakest for the Shannon index for diversity of suppliers of oil, whilst the United Kingdom proved the strongest. Finland, Ireland and Sweden all attained the lowest score for the Shannon index for diversity of suppliers of natural gas, each with a sole supplier. France was given the strongest score. Romania had the lowest energy consumption per capita score, whilst Norway had the highest score.

In 2018 Ireland, similarly to 2013, scored best for energy intensity. Finland became the worst scoring nation in 2018, closely followed by Estonia. France retained the highest percentage of nuclear electricity in their energy mix in Europe. Luxembourg retained the highest GHG emissions per capita score, whilst the lowest score was given to again to Latvia, along with Romania. The Netherlands had the smallest share of renewables for electricity generation, whilst Norway remained furthest ahead with decarbonisation efforts. Luxembourg and Bulgaria remained the most and least wealthy nations respectively over the period studied. Luxembourg remained with 1 sole supplier for oil, along with Czechia, denoting them the worst performing nations. Portugal had the strongest diversity score for oil. Sweden diversified their natural gas suppliers, whilst Finland and Ireland remained with the poorest scores for the Shannon index for diversity of suppliers for natural gas. Germany proved to have the best score for Shannon index for diversity of suppliers for natural gas. The most and least energy demanding nations per capita remained the same as that of 2013.

Alternatives	Energy Intensity	Nuclear Electricity	GHG emissions per capita	Renewable energy generation	GDP PPP	Shannon index for oil	Shannon index for natural gas	Energy consumption per capita
Austria	0.48	0.00	8.00	32.67	0.47	0.61	0.30	48505.23
Belgium	0.74	0.51	9.20	7.67	0.43	0.75	0.93	64125.37
Bulgaria	0.82	0.32	5.70	18.90	0.16	0.21	0.41	26555.25
Croatia	0.52	0.00	4.30	28.04	0.22	0.30	0.62	22296.15
Czechiaa	0.77	0.35	10.10	13.93	0.31	0.34	0.45	46644.07
Denmark	0.41	0.00	7.40	27.17	0.46	0.57	0.46	37861.13
Estonia	1.00	0.00	14.90	23.36	0.27	0.48	0.22	58702.07
Finland	0.86	0.33	9.50	36.63	0.41	0.00	0.00	62910.23
France	0.59	0.73	5.70	13.88	0.39	0.97	1.00	46007.51
Germany	0.53	0.15	10.20	13.76	0.45	0.86	0.66	47361.55
Greece	0.53	0.00	7.50	15.33	0.26	0.41	0.41	29699.36
Hungary	0.57	0.00	4.40	16.20	0.24	0.03	0.34	24061.92
Ireland	0.35	0.00	8.10	7.52	0.47	0.33	0.00	35893.66
Italy	0.42	0.00	6.10	16.74	0.36	0.71	0.73	30816.12
Latvia	0.59	0.00	3.60	37.04	0.22	0.48	0.09	21788.31
Lithuania	0.52	0.00	4.40	22.69	0.26	0.01	0.20	20920.37
Luxembourg	0.46	0.00	19.00	3.49	1.00	0.00	0.43	84137.46
Netherlands	0.64	0.00	9.80	4.69	0.49	0.92	0.52	60911.81
Norway	0.54	0.33	8.80	66.48	0.66	0.48	0.41	103703.21
Poland	0.61	0.03	8.40	11.45	0.24	0.17	0.19	29578.53
Portugal	0.45	0.00	4.60	25.70	0.28	0.69	0.39	27884.04
Romania	0.47	0.00	3.90	23.89	0.19	0.25	0.38	18270.23
Slovakia	0.64	0.20	6.60	10.13	0.28	0.48	0.15	35842.93
Slovenia	0.64	0.00	7.30	23.16	0.30	0.48	0.09	39029.04
Spain	0.49	0.20	5.40	15.08	0.32	0.80	0.76	34008.01
Sweden	0.67	0.55	4.70	50.15	0.46	0.61	0.00	63351.69
United Kingdom	0.45	0.43	7.40	21.84	0.40	1.00	0.84	36969.36

Table 8 - Performance table inputs for 2013, where orange values were filled in as per section 4.6

Alternative	Energy Intensity	Nuclear Electricity	GHG emissions per capita	Renewable energy generation	GDP PPP	Shannon index for oil	Shannon index for natural gas	Energy consumption per capita
Austria	0.52	0.00	7.50	33.78	0.49	0.38	0.25	46131.66
Belgium	0.83	0.38	8.70	9.47	0.45	0.79	0.80	63410.91
Bulgaria	0.92	0.34	6.10	20.58	0.20	0.23	0.44	30576.26
Croatia	0.57	0.00	4.30	28.05	0.25	0.55	0.42	23593.49
Czechiaa	0.77	0.34	10.10	15.14	0.35	0.22	0.09	45937.52
Denmark	0.43	0.00	6.00	35.16	0.49	0.68	0.39	34583.81
Estonia	0.99	0.00	13.60	29.97	0.31	0.56	0.22	58728.53
Finland	1.00	0.35	8.30	41.19	0.42	0.44	0.00	60603.01
France	0.64	0.71	5.00	16.38	0.40	0.85	0.79	43422.83
Germany	0.54	0.12	9.10	16.66	0.47	0.89	1.00	45753.93
Greece	0.64	0.00	6.80	18.00	0.25	0.40	0.44	29981.85
Hungary	0.66	0.00	5.10	12.55	0.27	0.10	0.25	27758.57
Ireland	0.28	0.00	8.10	10.94	0.72	0.81	0.00	38595.13
Italy	0.48	0.00	5.80	17.80	0.37	0.75	0.71	30957.24
Latvia	0.63	0.00	4.10	40.02	0.26	0.56	0.19	22505.13
Lithuania	0.61	0.00	4.80	24.70	0.31	0.31	0.57	24498.47
Luxembourg	0.49	0.00	15.70	8.94	1.00	0.00	0.38	76382.31
Netherlands	0.69	0.00	9.20	7.39	0.49	0.88	0.65	57062.31
Norway	0.65	0.33	8.40	71.57	0.60	0.56	0.44	103555.87
Poland	0.70	0.03	8.70	14.94	0.27	0.41	0.57	31661.17
Portugal	0.54	0.00	5.00	30.20	0.30	1.00	0.48	29902.40
Romania	0.45	0.00	4.10	23.88	0.25	0.42	0.25	20218.59
Slovakia	0.77	0.18	6.60	11.90	0.27	0.56	0.24	35080.09
Slovenia	0.68	0.00	6.90	21.38	0.33	0.56	0.02	39165.72
Spain	0.56	0.20	5.80	17.02	0.35	0.79	0.86	34986.29
Sweden	0.75	0.55	4.10	59.92	0.46	0.61	0.69	61463.21
United Kingdom	0.47	0.41	5.70	24.29	0.41	0.96	0.64	33682.48

Table 9 - Performance table inputs for 2018, where orange values were filled in as per section 4.6

[Alternative]	Energy Intensity	Nuclear Electricity	GHG emissions per capita	Renewable energy generation	GDP PPP	Shannon index for oil	Shannon index for natural gas	Energy consumption per capita
Extent	0.31	0.33	5.82	24.38	0.30	0.79	0.69	42199.63
b1	0.66	0.00	9.45	3.49	0.16	0.00	0.00	60469.86
b2	0.59	0.00	7.79	11.91	0.25	0.21	0.16	43216.12
b3	0.52	0.00	6.30	15.68	0.28	0.34	0.31	34741.98
b4	0.46	0.10	4.62	23.60	0.40	0.59	0.44	26821.00
b5	0.35	0.33	3.63	27.87	0.46	0.79	0.69	18270.23

Table 10 - Performance table of reference alternatives for 2013

[Alternative]	Energy Intensity	Nuclear Electricity	GHG emissions per capita	Renewable energy generation	GDP PPP	Shannon index for oil	Shannon index for natural gas	Energy consumption per capita
Extent	0.49	0.34	4.68	25.68	0.28	0.81	0.68	38176.69
b1	0.77	0.00	8.74	7.39	0.20	0.00	0.00	58395.28
b2	0.66	0.00	7.28	12.03	0.27	0.39	0.22	41719.99
b3	0.59	0.00	5.91	16.81	0.32	0.47	0.30	34043.01
b4	0.50	0.08	5.00	22.88	0.40	0.65	0.53	29918.29
b5	0.28	0.34	4.06	33.07	0.48	0.81	0.68	20218.59

Table 11 - Performance table of reference alternatives for 2018

4.4. Inputs for Criterion Parameters

Table 12 depicts all the input criterion parameters used for the analysis in MCDA U-Laval. The weights of criteria, *k*, were deduced as per section 4.2. All other parameters were deduced with aid of an MCDA U-Laval expert.

[Parameter]	**Energy Intensity**	**Nuclear electricity generation**	**GHG emissions per capita**	**Renewable energy generation**	**GDP per capita (PPP)**	**Shannon index for oil**	**Shannon index for natural gas**	**Energy consumption per capita**
k	10.5	15.8	12.6	12.6	10.6	15.8	15.8	6.3
q^α	∅	∅	∅	∅	∅	∅	∅	∅
q^β	0.01	0.1	5	2	0.1	∅	∅	1000
p^α	∅	∅	∅	∅	∅	∅	∅	∅
p^β	0.02	0.2	10	5	0.2	∅	∅	3000
v^α	∅	∅	∅	∅	∅	∅	∅	∅
v^β	0.6	0.5	∅	30	0.6	∅	∅	40000
Direction	Min	Max	Min	Max	Max	Max	Max	Min
Threshold	Const.	Const.	Const.	Const.	Const.	Const.	Const.	Const.

Table 12 - All input parameters used in MCDA U-Laval

4.5. Descriptive Statistics

Tables 13 and 14 display the descriptive statistics of all processed input data used for 2013 and 2018.

From 2013 to 2018 the average energy intensity score increased by 10%, implying a general digressing trend regarding the efficiency of converting GDP to energy within Europe. The standard deviation remained relatively constant, implying the range of data performance scores around the mean did not significantly change. For nuclear electricity generation, the average score and standard deviation remained constant. The maximum score slightly increased, with some nations increasing their nuclear output whilst others marginally decreased theirs. The average greenhouse gas emissions per capita in Europe decreased by 6%, with the standard deviation also decreasing. Such remarks imply a converging compliance towards environmental policies. The average renewable energy generation increased slightly over the period, whilst the standard deviation increased. Therefore, despite efforts in Europe being generally positive, some nations are making disproportionate efforts to increase their renewable energy outputs. The average GDP per capita (PPP) increased slightly, indicating that despite challenges such as the Crimea conflict, the European economy has continued to resiliently grow. The Shannon indices for diversity of suppliers for both oil and natural gas both displayed positive trends, indicating active efforts to diversify energy suppliers to thus reduce dependence on suppliers from politically unstable regions. Further, the standard deviation for both indicators decreased. These remarks carry significance in light of the Crimea conflict, displaying regional cooperation and successful diversification strategies. Finally, the data reveals a slight decrease in average energy consumption per capita. This observation is noteworthy, given the persistent rise of energy-intensive lifestyles that naturally contribute to a higher final energy consumption. However, this decreasing trend can be attributed to technological advancements that enhance energy efficiency throughout supply chains, which offsets the energy consumption surge driven by modern lifestyles.

	Average	**Standard Deviation**	**Minimum**	**Maximum**
Energy intensity	0.58	0.15	0.35	1.00
Nuclear electricity generation	0.15	0.21	0.00	0.73
GHG emissions per capita	7.60	3.42	3.63	19.01
Renewable energy generation	21.92	14.00	3.49	66.48
GDP per capita (PPP)	0.37	0.17	0.16	1.00
Shannon index for oil	0.47	0.31	0.00	1.00
Shannon index for natural gas	0.41	0.29	0.00	1.00
Energy consumption per capita	42882.76	20451.23	18270.23	103703.21

Table 13 - Descriptive Statistics for 2013

	Average	**Standard Deviation**	**Minimum**	**Maximum**
Energy intensity	0.64	0.17	0.28	1.00
Nuclear electricity generation	0.15	0.21	0.00	0.71
GHG emissions per capita	7.17	2.80	4.06	15.74
Renewable energy generation	23.66	15.02	7.39	71.57
GDP per capita (PPP)	0.40	0.17	0.20	1.00
Shannon index for oil	0.56	0.28	0.00	1.00
Shannon index for natural gas	0.44	0.28	0.00	1.00
Energy consumption per capita	42599.95	18906.33	20218.59	103555.87

Table 14 - Descriptive statistics for 2018

4.6. Data Remarks

The nature of the MCDA U-Laval software requires for all datasets to be complete. Upon data collection, there existed some gaps which required intuition to minimize the effect they would have on the validity of the results.

When conducting the Shannon-Wiener diversity index for Oil, some of the exporter entities were labelled as groups of nations namely:

- Other African Countries;
- Other European Countries;
- Other FSU (Former Soviet Union) countries;
- Other Latin American Countries;
- Other Asian Countries;
- Other Middle East Countries.

Since there existed no political stabilities explicitly for these groups, averages were taken of all the nations within each respective group and this political stability value was applied to the index formulation.

Upon compiling the final input data for all criteria amongst all nations, there existed few, yet notable, gaps namely:

- Renewable energy generation values for the United Kingdom
- Shannon-Wiener Diversity Index of Oil values for Estonia, Latvia, Luxembourg, Norway, Slovakia and Slovenia
- Shannon-Wiener Diversity Index of Natural Gas for Bulgaria, Greece and Norway

For the aforementioned data gaps, the average of all other nations scored within each respective indicator was deduced and used to complete the datasets. This approach assumes that the average score from the other nations is a reasonable approximation for the absent values. Since different datasets provide inconsistent data for each nation, it was chosen to proceed with an average for the United Kingdom’s renewable energy generation.

5. Results

The MCDA U-LAVAL software was utilized to implement the ELECTRE TRI-nC algorithm[22]. The model was run taking the weights generated with the prioritizations of the DM and use of DecSpace. The appropriate performance tables of reference alternatives were utilized to permit the model to assign worst and best categories

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[22] https://mcda.fsa.ulaval.ca/

to each country for each year. For simplified notation, Category 1 represents "bad", Category 2 represents "weak", Category 3 represents "moderate", Category 4 represents "good" and Category 5 represents "excellent". The results can be seen in table 15 below.

Prior to presenting the results, a sensitivity analysis was conducted to determine an appropriate discrimination threshold, λ. The analysis, outlined in the following section, revealed that $\lambda = 0.55$ was the most suitable.

12 of the 27 nations analyzed were assigned the same energy security categories for both 2013 and 2018, implying their level of energy security remained the most stable. These nations were: Belgium, Bulgaria, Denmark, Estonia, France, Germany, Greece, Italy, Luxembourg, Portugal, Slovenia and the United Kingdom. Austria experienced a digression in their categorical placement from 2013 to 2018, moving down from category 4 to category 3. Belgium and Bulgaria remained assigned to categories 4 and 3 respectively for both years studied. Croatia's lower bound improved from category 3 to category 4. Czechia experienced both bounds drop down from category 3 to category 2. Denmark remained in category 4 throughout the analysis, whilst Estonia remained in category 2. Finland saw their energy security improve from category 2 to category 3. France remained one of the strongest performing nations for both 2013 and 2018, being assigned to category 5 throughout. Germany also proved to be impressive, with consistent category 4 placements. Greece also remained consistent, assigned to category 3 for both years. Hungary saw their categorical assignment shift marginally from between category 2 and 3 to category 2. Ireland saw improvement, with their placement rising from between categories 2 and 3 to between categories 3 and 4. Italy sustained good levels of energy security, assigned to category 4. Latvia saw a positive shift from category 3 to category 4 over the years studied. Lithuania, though less commendable, saw its categorical placement rise from category 3 to between categories 3 and 4. Luxembourg sustained an ambiguous placement between categories 2 and 4. The Netherlands saw some slight improvement through time, with their placement evolving from between categories 2 and 3 to between categories 2 and 4. Norway poses as the biggest outlier in this study, with a consistent placement between the lowest and highest categories: 1 and 5. Poland partially shifted up from category 2 to between categories 2 and 4. Portugal remained impressive throughout, assigned to category 4 for both years. Romania encountered partial digression whereby its placement slipped from category 4 to between categories 3 and 4. Slovakia saw their placement shift upwards lightly from between categories 2 and 3 to category 3. Slovenia remained assigned to between categories 2 and 3 for both years analyzed. Spain remained impressive throughout, with a slight adjustment of the upper bound from category 5 to category 4, with the lower bound remaining at category 4. Sweden performed strongly throughout, with category 4 placements in 2013 rising to between categories 4 and 5 in 2018. The United Kingdom, along with France, sustained the highest categorical placement.

	2013		2018	
Alternatives	-	+	-	+
Austria	4	4	3	3
Belgium	4	4	4	4
Bulgaria	3	3	3	3
Croatia	3	4	4	4
Czechia	3	3	2	2
Denmark	4	4	4	4
Estonia	2	2	2	2
Finland	2	2	3	3
France	5	5	5	5
Germany	4	4	4	4
Greece	3	3	3	3
Hungary	2	3	2	2
Ireland	2	3	3	4
Italy	4	4	4	4
Latvia	3	3	4	4
Lithuania	3	3	3	4
Luxembourg	2	4	2	4
Netherlands	2	3	2	4
Norway	1	5	1	5
Poland	2	2	2	4
Portugal	4	4	4	4
Romania	4	4	3	4
Slovakia	2	3	3	3
Slovenia	2	3	2	3
Spain	4	5	4	4
Sweden	4	4	4	5
United Kingdom	5	5	5	5

Table 15 - Results of MCDA U-Laval Analysis

To evaluate the reliability, robustness and significance of the findings, a sensitivity analysis and robustness analysis were performed. Sensitivity analysis permits the assessment of the impact of varying key parameters, namely the discrimination threshold and criteria weights, to ascertain the variability of the results in diverse contexts. Robustness analysis is credible in the context of this assessment, given that it provides insights as to what extent the results remain similar when subjective to changes in preference parameters, namely threshold q,β , p,β and v,β thresholds.

5.1. Sensitivity Analysis

5.1.1 Discrimination Threshold Sensitivity

The discrimination threshold, denoted by λ, also known as the indifference threshold, refers to a critical value which distinguishes the significance of different criteria or alternatives in a decision-making process. By changing the discrimination threshold, more flexible and realistic decision rules can be implemented to understand their influence on the results (Thokala and Duenas, 2012). By raising λ, decision makers require a larger difference in performance scores between alternatives to consider them categorically different. Conversely, decreasing λ implies smaller performance score differences are required for alternatives to be significantly different from each other (Rogers and Bruen, 1998).

To determine the most suitable discrimination threshold value, a sensitivity analysis was performed. Discrimination values of 0.55, 0.6, 0.65 and 0.7 were applied to the datasets for all years whereby the inclusive bounds could be determined by means of the stability analysis function in MCDA U-Laval. For each discrimination threshold value, the range of the inclusive bounds was determined, and an average of all years was calculated. The threshold value of 0.55 was found to have the lowest average range of inclusive bounds and therefore can provide the greatest confidence in the reliability and consistency of the results. The distribution of categories for each distribution threshold can be seen in tables 16 and 17 below.

	λ=0.55	λ=0.6	λ=0.65	λ=0.7
<Bad , Excellent>	1	1	1	1
<Weak , Weak>	3	4	5	3
<Weak ,Moderate>	5	2	1	2
<Weak , Good>	1	1	1	2
<Moderate , Moderate>	5	7	7	6
<Moderate , Good>	1	1	2	4
<Good , Good>	8	8	8	6
<Good , Excellent>	1	1	0	1
<Excellent , Excellent>	2	2	2	2

Table 16 - Discrimination sensitivity results for 2013

	λ=0.55	λ=0.6	λ=0.65	λ=0.7
<Bad , Excellent>	1	1	1	1
<Weak , Weak>	3	3	3	3
<Weak ,Moderate>	1	1	1	1
<Weak , Good>	3	1	1	1
<Moderate , Moderate>	5	6	7	7
<Moderate , Good>	3	4	1	2
<Good , Good>	8	8	10	8
<Good , Excellent>	1	1	1	2
<Excellent , Excellent>	2	2	2	2

Table 17 - Discrimination sensitivity results for 2018

The discrimination threshold, in general, induces minimal change in the distribution of categories. The performance categories are therefore well distinguished, providing robust results whilst reducing arbitrariness in the decision-making process.

5.1.2 Criteria Weights Sensitivity

A sensitivity analysis regarding the weights of the energy security criteria was performed. By examining how the rankings change when weights are modified, a deeper understanding of the relative importance of each criterion to the overall categorical assignments is established.

Maliene et. al (2018) performed a one-at-a-time sensitivity analysis of criteria weights on 5 different MCDA methods namely: WSM, WPM, rAHP, TOPSIS and COPRAS. By systematically and individually increasing or decreasing the weight of criterions, the influence that each may have on the categorical allocations can be better understood. Respective percentage increases and decreases of 5% and 50% were applied to each criterion, whilst retaining proportional contributions of all other criteria in each case. The sensitivity coefficients were calculated by counting up the number of times categorical rankings changed for both worst and best categorical placements for all countries.

The arbitrary changes in criteria weights results a maximum of 2 categorical ranking shifts throughout for either the worst or best categorical assignments. Tables 18 and 19 display the coefficients for each year for respective increase or decreases in the weights of criteria, with the final column showing the cumulative changes for each criterion over all the years analysed.

From Tables 18 and 19, 2013 appeared to be more sensitive than 2018 in all cases with the most significant changes in category assignments originating from a 50% decrease in indicator weights. Nuclear electricity generation, along with both Shannon index metrics, proved to be the most critical to determining categorical assignments for both 2013 and 2018. Such an observation aligns with the fact that these indicators possess the highest criteria weights. In 2013, energy consumption per capita was the least influential metric in influencing category assignments, with all other indicators proving to have relatively similar levels of influence on the results. Energy intensity, GHG emissions per capita, renewable energy generation, GDP per capita and energy consumption per capita all displayed similarly trivial influence on the results in 2018.

	-50%	-5%	5%	50%
Energy intensity	6	3	0	4
Nuclear electricity generation	5	1	2	9
GHG emissions per capita	3	1	2	6
Renewable energy generation	6	2	1	5
GDP per capita (PPP)	1	1	2	6
Shannon index for oil	11	0	3	5
Shannon index for natural gas	11	1	1	4
Energy consumption per capita	4	1	0	1

Table 18 - 2013 relative sensitivity coefficients calculated as the number of changes in the alternative rankings due to a change in criteria weights

	-50%	-5%	5%	50%
Energy intensity	2	1	0	4
Nuclear electricity generation	8	0	1	7
GHG emissions per capita	3	0	1	2
Renewable energy generation	4	1	0	4
GDP per capita (PPP)	1	0	1	5
Shannon index for oil	7	0	1	7
Shannon index for natural gas	9	1	0	4
Energy consumption per capita	3	0	0	1

Table 19 - 2018 relative sensitivity coefficients calculated as the number of changes in the alternative rankings due to a change in criteria weights

5.1.3 q,β , p,β and v,β sensitivity

To assess the robustness of the results a scenario analysis was performed in MCDA U-Laval. For this part of the analysis, a systematic approach was applied to assess the robustness of the pre-defined threshold values of q,β , p,β and v,β. Each threshold value was both increased and decreased by 5%, 10% and 15% for each criterion, with the number of changes in category ranking assignments visible in tables 20 through 21 below. The scenario analysis uncovered that the results remained almost entirely stable throughout the analysis when subject to changes in threshold q,β, with only 4 cases whereby categorical changes observed. For energy consumption per capita in 2013, all negative adjustments in q,β induced 1 category change. For GHG emissions per capita, there exists 1 category change for a 15% increase in q,β. For thresholds p,β and v,β, there existed more changes which can be seen in tables 20, 21, 22 and 23.

From tables 20 and 21, there exist only singular changes in a worst or best categorical placement for one country for each scenario of p,β. In 2013, only renewable energy generation and energy consumption per capita influenced the results, with the latter inducing a category shift with the smallest change in p,β. For 2018, all indicators except energy intensity and renewable energy generation there existed a degree of change for at least one of the percentage increments or decrements.

From tables 22 and 23, it can be seen that variations in the veto threshold has some influence on the results. No best or worst category assignment changed by more than place, with the most drastic change to a single alternative being a shift of both the worst and best categorical assignments by one rank. The altering of threshold values for renewable energy generation appeared to have the biggest influence on changing the results, suggesting it possesses a higher influence on decision outcomes. Another noteworthy observation was the variation in change of categorical assignments over the years studied. 2018 experienced the biggest impact from the scenario analysis, whilst 2013 changed the least. Overall, the results experienced little change due to changes due to variations in the veto threshold, implying robust data inputs.

	-15%	-10%	-5%	5%	10%	15%
Energy intensity	0	0	0	0	0	0
Nuclear electricity generation	0	0	0	0	0	0
GHG per capita	0	0	0	0	0	0
Renewable energy generation	1	0	0	0	0	0
GDP per capita (PPP)	0	0	0	0	0	0
Energy consumption per capita	1	1	1	0	0	0

Table 20 – 2013 Robustness coefficients calculated as the number of changes in alternative rankings due to changes in the veto threshold for different criteria for p,β

	-15%	-10%	-5%	5%	10%	15%
Energy intensity	0	0	0	0	0	0
Nuclear electricity generation	0	0	0	0	0	1
GHG per capita	0	0	0	1	1	1
Renewable energy generation	0	0	0	0	0	0
GDP per capita (PPP)	1	1	0	0	0	0
Energy consumption per capita	1	0	0	0	0	0

Table 21 – 2018 Robustness coefficients calculated as the number of changes in alternative rankings due to changes in the veto threshold for different criteria for p,β

	-15%	-10%	-5%	5%	10%	15%
Energy intensity	0	0	0	0	0	0
Nuclear electricity generation	0	0	0	0	0	0
Renewable energy generation	3	3	1	0	0	1
GDP per capita (PPP)	1	1	0	1	1	1
Energy consumption per capita	2	2	0	0	1	3

Table 22 – 2013 Robustness coefficients calculated as the number of changes in alternative rankings due to changes in the veto threshold for different criteria for v,β

	-15%	-10%	-5%	5%	10%	15%
Energy intensity	0	0	0	1	1	1
Nuclear electricity generation	0	0	0	1	1	1
Renewable energy generation	0	0	0	2	2	2
GDP per capita(PPP)	1	1	0	1	1	1
Energy consumption per capita	1	1	1	0	0	0

Table 23 – 2018 Robustness coefficients calculated as the number of changes in alternative rankings due to changes in the veto threshold for different criteria for v,β.

5.2. Kruksal-Wallis Test

The Kruksal-Wallis Test is a rank-based nonparametric test used to determine whether there are any statistically significant differences between two or more groups. It is an omnibus test statistic, in that it cannot provide insights into which groups are statistically different from each-other. The statistical test was therefore deployed to deduce whether there was any significant differences in the levels of energy security between different regions of Europe. In order to perform this test, IBM SPSS Statistics were used. It was first required to group the countries into specific categories based on their geographical origins within Europe. The United Nations Geoscheme was deemed appropriate for assigning nations to a region, namely Northern, Eastern, Southern or Western[23].

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[23] https://unstats.un.org/unsd/methodology/m49

To facilitate the analysis in SPSS, the qualitative rankings from MCDA U-Laval ranging from 'bad' to 'excellent' were converted into numerical rankings. The conversion was such that 'bad' was assigned to 1, 'weak' was assigned to 2, 'moderate' was assigned to 3, 'good' was assigned to 4 and 'excellent' was assigned to 5. Since MCDA U-Laval also provides a range within which each alternative falls, these lower (worst) and upper (best) bounds were analysed separately.

To perform the analysis, the input values for the significance and confidence levels were at 0.05 and 95% respectively. The null hypothesis, to be challenged, was "the distribution of scores is the same across all groups". For each year, the worst and best scores were analysed independently which therefore required 2 individual statistical tests. For each test a Significance score, *Sig.*^{a,b}, was obtained along with the decision to either retain or reject the null hypothesis. In both 2013 and 2018, the decision was to accept the null hypothesis, implying no significant differences in the energy security rankings amongst the different regions in Europe. The outcome of the statistical test is inconclusive, which may be attributed to a number of different factors. Firstly, the use of 8 indicators is insufficient to be representative of the true state of energy security in every country, since alone, they cannot capture the full complexity of the concept. As a result, certain strengths and weaknesses of each nations energy security landscapes may have been missed, which could disproportionately skew the inputs for the analysis. In addition to this, the use of a 1 to 5 scale to categorise nations' energy security may limit the ability to detect subtle differences between countries' levels of energy security. Furthermore, there is the temporal limitation. Since energy security levels are ever-changing, the Kruksal-Wallis test in this context only provides 2 cross-sectional snapshots, rather than potentially meaningful short-term trends.

6. Discussion

6.1. Discussion of results

To explain the changes in the energy security performance scores from 2013 to 2018 the percentile performances of each indicator for each nation across both years were calculated. With such processed data, it is possible to ascertain which criteria contributed to digressions or progressions in their performance scores for each nation. Tables 24 and 25 display the percentile performance scores for 2013 and 2018 respectively. The scale ranges from 0 to 1, whereby 0 and 1 denote the 0th and 100th percentiles respectively. The indicators with data to be minimised were inverted such that the tables can be interpreted homogenously with respect to those to be maximised. Table 26 displays the changes in relative percentile performance from 2013 to 2018. Negative values denote digressions in relative performance from 2013 to 2018, whilst positive values denote relative progression. This approach to the analysis of the results enables relative comparisons between nations' performance within and between both years studied. One limitation of such an approach is that although nations can in some cases progress, for example by reducing GHG emissions, digressions in their relative percentile performances can be seen. Another important consideration for the analysis is the quality of the national statistics systems which can vary from country to country, which can create disparities in the accuracy of data.

	Energy Intensity	**Nuclear Electricity**	**GHG emissions per capita**	**Renewable energy generation**	**GDP (PPP)**	**Shannon index for oil**	**Shannon index for natural gas**	**Energy consumption per capita**
Austria	0.73	0.00	0.39	0.85	0.88	0.65	0.35	0.27
Belgium	0.15	0.92	0.23	0.12	0.69	0.81	0.96	0.08
Bulgaria	0.08	0.73	0.65	0.50	0.00	0.19	0.50	0.81
Croatia	0.62	0.00	0.92	0.81	0.08	0.27	0.77	0.89
Czechia	0.12	0.85	0.12	0.31	0.46	0.35	0.65	0.35
Denmark	0.96	0.00	0.50	0.77	0.81	0.62	0.69	0.46
Estonia	0.00	0.00	0.04	0.69	0.31	0.42	0.31	0.23
Finland	0.04	0.77	0.19	0.88	0.65	0.00	0.00	0.15
France	0.42	1.00	0.69	0.27	0.58	0.96	1.00	0.39
Germany	0.58	0.62	0.08	0.23	0.73	0.88	0.81	0.31
Greece	0.54	0.00	0.42	0.38	0.23	0.38	0.50	0.69
Hungary	0.46	0.00	0.89	0.42	0.19	0.12	0.38	0.85
Ireland	1.00	0.00	0.35	0.08	0.85	0.31	0.00	0.54
Italy	0.92	0.00	0.62	0.46	0.54	0.77	0.85	0.65
Latvia	0.39	0.00	1.00	0.92	0.12	0.42	0.15	0.92
Lithuania	0.65	0.00	0.85	0.58	0.27	0.08	0.27	0.96
Luxembourg	0.81	0.00	0.00	0.00	1.00	0.38	0.62	0.04
Netherlands	0.23	0.00	0.15	0.04	0.92	0.92	0.73	0.19
Norway	0.50	0.81	0.27	1.00	0.96	0.42	0.50	0.00
Poland	0.35	0.58	0.31	0.19	0.15	0.15	0.23	0.73
Portugal	0.85	0.00	0.81	0.73	0.38	0.73	0.46	0.77
Romania	0.77	0.00	0.96	0.65	0.04	0.23	0.42	1.00
Slovakia	0.308	0.653	0.577	0.153	0.346	0.423	0.192	0.577
Slovenia	0.27	0	0.539	0.615	0.423	0.423	0.115	0.424
Spain	0.693	0.692	0.731	0.346	0.5	0.846	0.884	0.616
Sweden	0.193	0.961	0.77	0.961	0.769	0.692	0	0.116
United Kingdom	0.885	0.884	0.462	0.538	0.615	1	0.923	0.5

Table 24 - Percentile performance of all indicators for all nations in 2013

	Energy Intensity	**Nuclear Electricity**	**GHG emissions per capita**	**Renewable energy generation**	**GDP (PPP)**	**Shannon index for oil**	**Shannon index for natural gas**	**Energy consumption per capita**
Austria	0.77	0.00	0.39	0.81	0.81	0.19	0.27	0.27
Belgium	0.12	0.88	0.23	0.08	0.69	0.73	0.92	0.08
Bulgaria	0.08	0.81	0.54	0.50	0.00	0.12	0.50	0.73
Croatia	0.62	0.00	0.89	0.69	0.04	0.38	0.46	0.92
Czechia	0.15	0.77	0.08	0.27	0.50	0.08	0.12	0.31
Denmark	0.96	0.00	0.58	0.85	0.85	0.65	0.42	0.58
Estonia	0.04	0.00	0.04	0.73	0.35	0.42	0.19	0.19
Finland	0.00	0.85	0.31	0.92	0.65	0.35	0.00	0.15
France	0.46	1.00	0.77	0.31	0.58	0.85	0.88	0.39
Germany	0.69	0.62	0.15	0.35	0.77	0.92	1.00	0.35
Greece	0.50	0.00	0.46	0.46	0.12	0.23	0.50	0.77
Hungary	0.39	0.00	0.73	0.19	0.23	0.08	0.35	0.85
Ireland	1.00	0.00	0.35	0.12	0.96	0.81	0.00	0.46
Italy	0.85	0.00	0.62	0.42	0.54	0.69	0.85	0.69
Latvia	0.54	0.00	1.00	0.88	0.15	0.42	0.15	0.96
Lithuania	0.58	0.00	0.85	0.65	0.38	0.15	0.65	0.89
Luxembourg	0.81	0.00	0.00	0.04	1.00	0.38	0.38	0.04
Netherlands	0.31	0.00	0.12	0.00	0.88	0.88	0.77	0.23
Norway	0.42	0.73	0.27	1.00	0.92	0.42	0.50	0.00
Poland	0.27	0.58	0.19	0.23	0.27	0.27	0.69	0.65
Portugal	0.73	0.00	0.81	0.77	0.31	1.00	0.62	0.81
Romania	0.92	0.00	0.96	0.58	0.08	0.31	0.31	1.00
Slovakia	0.19	0.65	0.50	0.15	0.19	0.42	0.23	0.50
Slovenia	0.35	0.00	0.42	0.54	0.42	0.42	0.08	0.42
Spain	0.65	0.69	0.65	0.38	0.46	0.77	0.96	0.54
Sweden	0.23	0.96	0.92	0.96	0.73	0.62	0.81	0.12
United Kingdom	0.89	0.92	0.69	0.62	0.62	0.96	0.73	0.62

Table 25 - Percentile performance of all indicators for all nations in 2018

	Energy Intensity	Nuclear Electricity	GHG emissions per capita	Renewable energy generation	GDP (PPP)	Shannon index for oil	Shannon index for natural gas	Energy consumption per capita
Austria	0.04	0.00	0.00	-0.04	-0.08	-0.46	-0.08	0.00
Belgium	-0.04	-0.04	0.00	-0.04	0.00	-0.08	-0.04	0.00
Bulgaria	0.00	0.08	-0.12	0.00	0.00	-0.08	0.00	-0.08
Croatia	0.00	0.00	-0.04	-0.12	-0.04	0.12	-0.31	0.04
Czechia	0.04	-0.08	-0.04	-0.04	0.04	-0.27	-0.54	-0.04
Denmark	0.00	0.00	0.08	0.08	0.04	0.04	-0.27	0.12
Estonia	0.04	0.00	0.00	0.04	0.04	0.00	-0.12	-0.04
Finland	-0.04	0.08	0.12	0.04	0.00	0.35	0.00	0.00
France	0.04	0.00	0.08	0.04	0.00	-0.12	-0.12	0.00
Germany	0.12	0.00	0.08	0.12	0.04	0.04	0.19	0.04
Greece	-0.04	0.00	0.04	0.08	-0.12	-0.15	0.00	0.08
Hungary	-0.08	0.00	-0.15	-0.23	0.04	-0.04	-0.04	0.00
Ireland	0.00	0.00	0.00	0.04	0.12	0.50	0.00	-0.08
Italy	-0.08	0.00	0.00	-0.04	0.00	-0.08	0.00	0.04
Latvia	0.15	0.00	0.00	-0.04	0.04	0.00	0.00	0.04
Lithuania	-0.08	0.00	0.00	0.08	0.12	0.08	0.38	-0.08
Luxembourg	0.00	0.00	0.00	0.04	0.00	0.00	-0.23	0.00
Netherlands	0.08	0.00	-0.04	-0.04	-0.04	-0.04	0.04	0.04
Norway	-0.08	-0.08	0.00	0.00	-0.04	0.00	0.00	0.00
Poland	-0.08	0.00	-0.12	0.04	0.12	0.12	0.46	-0.08
Portugal	-0.12	0.00	0.00	0.04	-0.08	0.27	0.15	0.04
Romania	0.15	0.00	0.00	-0.08	0.04	0.08	-0.12	0.00
Slovakia	-0.12	0.00	-0.08	0.00	-0.15	0.00	0.04	-0.08
Slovenia	0.08	0.00	-0.12	-0.08	0.00	0.00	-0.04	0.00
Spain	-0.04	0.00	-0.08	0.04	-0.04	-0.08	0.08	-0.08
Sweden	0.04	0.00	0.15	0.00	-0.04	-0.08	0.81	0.00
United Kingdom	0.00	0.04	0.23	0.08	0.00	-0.04	-0.19	0.12

Table 26 - Relative changes in percentile performance of all indicators for all nations from 2013 to 2018

In the case of Austria, all indicators remained relatively constant with exception of the Shannon index for oil which dropped from the 65th percentile to the 19th percentile. Such a drop is indicative of a drop in the diversity of suppliers in conjunction with the political stability of supplier nations, which can best explain the digressive performance scores from 2013 to 2018.

All of Belgium's indicators remain in similar percentile regions for both years, with high percentile performance scores in the 3 highest weighted criteria: Nuclear electricity capacity and the Shannon indices for oil and natural gas. Despite Belgium's overall good performance score, notably lower scores were obtained for renewable energy generation, energy consumption per capita and energy intensity. Such indicators highlight areas for improvement.

Bulgaria sustained a moderate score for both years studied. No single indicator's performance changed significantly, with a net marginal digression in relative performance scores which was not significant enough to induce a change in category. Bulgaria's GDP per capita score for both years was the lowest of the nations studied. Such a metric is implicit to the prosperity of other indicators, such as energy intensity, which induce long term improvements in energy security. The use of the average score for Shannon index for natural gas, due to data unavailability, correlated with the moderate nature of Bulgaria's other relative metric scores. Therefore, the influence on the results would be minimal.

The analysis of Croatia's results outlines the limitation of percentile comparisons, with Croatia's category evolution marginally improving whilst the relative individual performance of all but one indicator digressing slightly. Relatively strong performances for GHG emissions per capita, renewable energy generation and energy consumption per capita were sustained. The Shannon index for oil progressed slightly, a trend which, if sustained, will result in very high levels of oil security in the future. Conversely, the score for Croatia's Shannon index for natural gas decreased significantly, highlighting no active efforts to diversify natural gas suppliers in light of ongoing political unrest.

Czechia experienced digression in their relative performance from 2013 to 2018. Despite a consistently strong score for nuclear electricity capacity and a moderate yet sustained scores for most indicators, the Shannon indices for oil and natural gas both drastically changed. For oil, Czechia's relative score reduced from the 35th to the 8th percentile. The percentile score for natural gas dropped from the 65th to the 12th percentile. The diminishing performance of both Shannon indices highlights Czechia's need to address their choice and diversity of suppliers. More specifically, Czechia's high dependence on Russian oil, being over 50% of total supply in both years. Despite Czechia's close proximity to Russia, the raw datasets used for this analysis indicate no imports of natural gas from Russia.

Denmark sustained a good category placement across both years studied. Marginal progressions for GHG emissions per capita, renewable energy generation, GDP per capita, Shannon index for oil and energy consumption per capita are seen. The singe indicator preventing potential categorical progression was the Shannon index for natural gas, which digressed from the 69th percentile to the 42nd. Denmark therefore should make efforts to improve this score to optimise their energy security situation.

Estonia failed to progress from their weak category placement from 2013 to 2018. The explanation for such is maintained moderate to poor scores for all indicators with the exception of renewable energy generation. The most notable area for improvement is Estonia's GHG emissions per capita, with all other poor indicator performance scores requiring attention. The use of the average performance score for Estonia's Shannon index for oil, considering their general performance, had little influence on the final results for both years.

Finland's performance improved marginally, however only reached the moderate category level in 2018. Despite sustaining high relative scores in nuclear electricity capacity, renewable energy generation and GDP per capita, Finland's other indicators received poor scores. More specifically, the Shannon indices for oil and natural gas, energy consumption per capita and energy intensity. In 2013 Finland received all oil imports from Norway which, despite Norway's political stability, caused a score of 0 due to the nature of the index formulation. In 2018 the performance score for oil increased, though still relatively moderate, in light of active diversification of suppliers. In both 2013 and 2018 Finland imported natural gas solely from Russia, which again induced a score of 0. It is worth noting that, through the initial analysis including 2019, Finland actively diversified their natural gas imports though still remaining predominantly reliant on Russia.

France sustained the highest categorical placement for both 2013 and 2018, which can be attributed to very high scores for half of the metrics used which include: nuclear electricity generation, GHG emissions per capita and the Shannon indices for both oil and natural gas. Areas highlighted by the analysis which France can focus on to further optimise their energy security include renewable energy generation, energy consumption per capita and energy intensity.

Germany maintained a good categorical assignment, with no digressions in relative performance of any indicator from 2013 to 2018. The performance scores for the Shannon indices of both oil and natural gas in 2013, though already impressive, improved further. Renewable energy generation improved, yet still remained a relatively moderate score. The most notable area that requires ongoing improvement for Germany is their renewable energy generation which, despite improving, remained relatively poor.

Greece sustained a moderate score throughout the analysis, owing to generally mediocre performance scores. Greece performed best for the energy consumption per capita metric, which was seen to improve with time. Due to worsening debt crisis' during the time of the study, Greece attained poor relative scores for GDP per capita. Despite this, noticeable efforts to increase renewable energy generation can be seen. The Shannon index for oil dropped notably from the 50th percentile to the 35th percentile, highlighting an area for attention. The use of the average score for the Shannon index for oil would have had little effect on their overall results, due to the generally mediocre scores in all other indicators relative to the rest of Europe.

Hungary's categorical placement digressed marginally from 2013 to 2018, being assigned predominantly to the weak energy security category. The GHG emissions and energy consumption per capita metrics proved the strongest for Hungary, though in 2018 relative emissions levels digressed slightly. This digression can be explained in part by the reduced relative performance of renewable energy generation from 2013 to 2018. An area of relative weakness for Hungary is their diversity of suppliers for oil, which remained very poor in 2018.

Ireland experienced improvements in categorical placement from 2013 to 2018, though remained predominantly in the moderate performance range. Excellent performance scores were sustained for GDP per capita and energy intensity. GHG emissions per capita and energy consumption per capita sustained moderate relative scores. Ireland significantly improved their relative performance score for the Shannon index of oil. In 2013 Ireland received over 70% of their oil from Norway which, though politically stable, is a high level of dependency on one nation which gives a poor score. In 2018 active diversification to the United States and Canada, together supplying half of Irelands oil, improved their relative score. Irelands sole dependency on the United Kingdom for natural gas resulted in its respective index scores to be 0 for both years. The lack of nuclear electricity generation and relatively low renewable energy generation scores can also be seen.

Italy was seen to have good energy security performance scores for both years, with the majority of the metrics obtaining strong relative scores except for the lack nuclear deployment. The indicator for Italy that was the ‘poorest’, though still moderate, is renewable energy generation.

Latvia saw improvement in energy performance from 2013 to 2018, displaying excellent relative performance scores for 3 of the low carbon indicators; GHG emissions per capita, renewable energy generation and energy consumption per capita. The relative state of Latvia’s economy was outlined, though it marginally improved in the period of study. The Shannon index score for natural gas remained within the 15th percentile for both years. This can be attributed to the proportions of natural gas coming from Russia in 2013 and 2018 being 96% and 87% respectively, with all remaining supplies coming from Lithuania. However, from the prior analysis of 2019 it was evident that Latvia had made efforts to diversify their suppliers and improve their energy security score in this domain. Use of the average Shannon index score for oil was not seen to hinder the categorical performance progression from 2013 to 2018.

Lithuania improved marginally in its categorical placement from 2013 to 2018. Similar to Latvia, impressive relative scores for GHG emissions per capita and energy consumption per capita indicate that Lithuania is at the forefront of Europe’s low carbon energy transition. The relative score for renewable energy generation has evidently progressed, reiterating efforts to phase out fossil fuels in their energy mix. Economic development is apparent, however relative to Europe scores remain below average. The Shannon index for oil failed to improve from its poor score from 2013 to 2018, owing to a lack of diverse suppliers. In 2013, over 99% of Lithuania’s oil supply came from Russia, which reduced to just over a 79%. The nature of Russia’s political instability, in light of the ongoing annexation of Crimea, induces more threat to Lithuania’s oil supply relative to a heavy dependence on another, more politically stable, nation. Conversely efforts to diversify Lithuania’s natural gas supplies are evident, with a 38-percentile improvement from 2013 to 2018. Such an improvement can be attributed to substituting Russia with Norway as a natural gas supplier, providing around a third of Lithuania’s supply.

Luxembourg maintained a mediocre performance placement for both years studied, allocated between a weak and good energy security level. The broad placement range can be attributed to some indicators performing in the bottom 10th percentile whilst others proved to be very strong. Luxembourg's economic superiority within Europe is apparent across both years, coupled with a strong performance score for energy intensity. Luxembourg's lack of effort to decarbonise their energy environment can be seen through bad scores for GHG emissions per capita, renewable energy generation and energy consumption per capita. The relative percentile score for the Shannon index for natural gas notably digressed, despite the fact that the index value changed only slightly. The general trend of improvement in the natural gas index across all nations can explain why the relative percentile score was changed so significantly. The use of the average Shannon index score for oil would have had little effect on the overall categorical placement for Luxembourg, due to the polarised performance of all other indicators for both years.

The Netherlands obtained an ambiguous categorical placement for 2013 and 2018, owing to its polarised performance scores across the metrics used in this study. Strong scores for GDP per capita and both Shannon indices imply strong levels of economic stability and geopolitical interconnectivity. However, consistently poor scores for all environmentally related indicators highlight areas for attention. Most notably are the poor scores for renewable energy generation, denoting the Netherlands as one of the lowest capacities in Europe for both years studied, something, which in more recent years, has been addressed. More specifically, an IEA data and statistics report shows from 2018 to 2020 the renewable energy generation has increased by over 50%[24]

Norway was the most ambiguous result within this study, with its categorical placement ranging between the worst and best categories for both years. Excellent scores for both renewable energy capacity and GDP per capita are evident. With the exception of GHG emissions per capita and energy consumption per capita, all other indicators received mediocre scores. Despite the strong renewable sector in Norway, it is evident that fossil fuels still play a pivotal role in satisfying their energy needs. Despite 2 poor indicator scores, it remains unclear as to why Norway receives such a broad categorical placement since other nations with more polarised results obtained less broad placements. The lack of available data for oil and natural gas imports resulted in default mediocre scores, inhibiting a true reflection of their security. Further, since Norway is a significant exporter of both oil and natural gas, the Shannon index formulation, if data was available, would have compromised their score which inaccurately reflects their energy security. Due to the lack of available data, both Shannon index score inputs for Norway were averages of all other European nations in the assessment. Regardless of the lack of data, Norway's exporting nature with regards to oil and natural gas will have hindered their index scores. Norway produces more oil than it consumes by a magnitude of approximately 1. Therefore, although Norway imports some oil, the true Shannon index score would not reflect their degree of energy security.

Furthermore, Norway imports no natural gas, which would have resulted in a score of 0 for the Shannon index[25]. The exporting nature of Norway, together with the nature of the Shannon index formulation, will have hindered Norway's performance in this assessment.

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[24] https://www.iea.org/data-and-statistics/charts/evolution-of-renewable-electricity-generation-in-the-netherlands-2000-2020

[25] https://www.worldometers.info/gas/norway-natural-gas/

The assessment of Poland's energy security highlighted generally poor levels of energy security in Europe, reflected by the indicator performance scores. Scores for GHG emissions per capita, renewable energy capacity, GDP per capita, Shannon index for oil and energy intensity indicate Poland's lacking energy security progress relative to the rest of Europe. Despite this, some strengths and progress are evident in the data for the year studied. Consistent use of domestic nuclear energy is clear, providing stability when subjected to shortfalls in other energy sources. Energy consumption per capita, though digressed slightly from 2013, remained strong in 2018 relative to Europe. The most significant finding is that of the progress of Poland's natural gas security, with improved from the 23rd to the 65th percentile relative to other nations. Despite having a diverse set of suppliers in 2013, Belarus constituted over 87% of the total supply which, due to the nature of the index scoring system, resulted in a poor score. In 2018 this dependency reduced to 71%, causing the score to improve.

Portugal sustained good levels of energy security for both 2013 and 2018, with only the lack of Nuclear electricity generation being an area for consideration. Portugal's relatively poor economic strength relative to Europe can be seen to further revert over the time period. The priority of sustainable energy practices is clear from the data, with GHG emissions per capita, renewable energy capacity and energy consumption per capita all consistently scoring well. Both Shannon indices were optimised from already impressive scores making evident efforts to ensure oil and gas supplies are secure.

Romania obtained generally good scores for both 2013 and 2018, reflected by relative scores for GHG emissions per capita, renewable energy capacity, energy consumption per capita and energy intensity. The poor economic status and development of Romania is clear, scoring amongst the worst In Europe for both 2013 and 2018. The diversity scores for oil and gas highlight areas for improvement. For oil in 2013, Romania's sole suppliers were Russia and Kazakhstan. In 2018 Romania diversified their suppliers and improved their index score, though the percentile score disproportionally reflective due to the net improvements across of European nations over the period studied. The index score for natural gas diminished marginally, from an already mediocre relative score, due to the increased dependence on a sole supplier.

Slovakia saw marginal improvements in energy security from 2013 to 2018, though remaining moderately secure relative to the rest of Europe. No relatively strong scores were obtained, with a mix of weak to moderate scores for all metrics with the exception of nuclear energy generation. The most notable digressions in relative metric scores were seen for GDP per capita and energy intensity. Despite a moderate score for GHG emissions per capita, Slovakia's renewable energy generation has remained poor relative to the rest of Europe. Although Slovakia's dependency on Russian gas was alleviated, sustained and increased reliance on Ukraine as their primary supplier resulted in a poor score being sustained. Such suppliers highlight energy security risks for Slovakia's natural gas supply. The use of the Europe's average score for the Shannon index for oil will have had little effect on the results, due to Slovakia's weak to mediocre scores for all other metrics used in the assessment.

Slovenia's energy security sustained weak to moderate assignments for both years studied. The best performing metric for both years, relative to the rest of Europe, was the share of renewable energy. Despite this, marginal digression in its performance can be seen over the period studied. The metrics highlighting areas for improvement are the Shannon index for natural gas and energy intensity. Data shows Slovenia's heavy dependence on Austria, who supplied over 99% of their domestic demand. Despite Austria's net importing status regarding natural gas, upon inspection it appears Slovenia's supply may not be totally fulfilled by domestic Austrian gas. However, after further investigation, due to Slovenia's proportionally lower consumption than Austria, this does in fact align[23]. Despite a lack of indication of the data used in this report, further resources suggest a reliance on Russian for Austria's natural gas imports. [OECD Statistics] So it follows, in light of the annexation of Crimea, complications regarding security of energy supply, due to the dynamic supply chain relationships including transit nations, could be faced in the future. Therefore, efforts to diversify natural gas suppliers could aid future energy security of both the transit and importing nations. For similar reasons used to Slovakia, the use of the average score for the Shannon index for oil will have low levels of influence on the overall results.

Spain's performance remained strong throughout the assessment, owing to generally impressive scores for all indicators compared to the rest of Europe. The metrics that reinforce the high categorical placement for both years are nuclear electricity generation, GHG emissions per capita, both Shannon indices for oil and natural gas, and energy intensity. The indicator highlighting underperformance relative to the rest of Europe for both years is renewable energy generation.

Sweden's performance remained strong for both 2013 and 2018, with marginal categorical progression relative to the rest of Europe. All metrics, with the exception of the Shannon index for natural gas, energy consumption per capita and energy intensity, performed well. In 2013, Denmark was the sole supplier of natural gas. Despite Denmark's strong political stability score, the nature of the index formulation penalises dependency on a single supplier. In 2018, efforts to eliminate this sole dependency can be seen, with a total of 6 supplier nations and an impressive index score relative to the rest of Europe. Sweden's energy consumption per capita score relative to Europe was poor, indicating high levels of energy demand relative to the population. However, with the deployment of low carbon technologies and stable supplies of fossil fuels, it is not considered to be a big concern. The consistently poor score for energy intensity reinforces Sweden's poor resource efficiency, however Sweden's strong economy suggests it is not a detrimental factor.

The United Kingdom, along with France, remained one of the best performing nations for both 2013 and 2018, with no metrics performing poorly. GHG emissions was the worst performing metric in 2013, which was seen to be improve significantly in 2018 with a rise in percentile performance of 23% relative to Europe. Digression in the relative Shannon index score for natural gas can be seen, though it still remains strong. Progression in the UK's relative energy consumption per capita score from 2013 to 2018 is also seen. The use of the average performance of renewable energy generation was not seen to compromise the UK's strong overall performance.

6.2. Comparison with IESRI index

Since this work is the first to assign categories to nations' energy security levels, comparisons were made against the IESRI index which provides each nation with a risk index score. The index scored the top 75 energy consuming countries, therefore the following nations studied within this paper were not available for score comparisons: Estonia, Latvia, Lithuania, Luxembourg and Slovenia. The data for the remaining countries was processed in excel to obtain relative percentile performances for ease of comparison, to deduce whether both models converge or differentiate for different nations. The 2018 IESRI index provides the most holistic comparison compared to prior IESRI reports, which only cover 10 of the 27 countries assessed in this paper. Therefore, the results for 2018 were benchmarked against those of the 2018 IESRI index, whereby 22 of the 27 nations in this study have available data for comparison[26]. 29 indicators were used, namely: global oil reserves, global oil production, global gas reserves, global gas production, global coal reserved, oil import exposure, gas import exposure, coal import exposure, total energy import exposure, fossil fuel import expenditure, energy expenditure intensity, energy expenditures per capita, retail electricity prices, crude oil prices, crude oil price volatility, energy expenditure volatility, world oil refinery usage, GDP per capita, energy consumption per capita, energy intensity, energy intensity, petroleum intensity, electricity capacity diversity, non-carbon generation, transport energy per capita, transport energy intensity, CO_2 emissions trend, CO_2 per capita and CO_2 GDP intensity. Of these 29 indicators, the values for 9 of the indicators remained constant for all countries analyzed.

From the aforementioned list, there exists total or partial overlap with all indicators used in this assessment. It can therefore be expected that there is some convergence between each approach to quantify energy security. The risk index scores from the IESRI report were converted into approximate categorical placement scores to aid comparison. To do this, each nations' score was converted into a percentile relative to all other scores. From there, the percentile values were allocated to a category ranking similar to that of this paper, with the following bounds shown in table 28:

Percentile range	Approximate categorical conversion
$0 < x \leq 20$	1
$21 < x \leq 40$	2
$41 < x \leq 60$	3
$61 < x \leq 80$	4
$81 < x$	5

Table 27 - Conversion bounds for categorical placements

With this conversion in mind, tabulated in table 29 are the values for both indices for 2018. The conversion is a simplification of the IESRI report results; however, it permits approximate comparisons to the categorical system implemented in the ELECTRE TRI-nC. With this approach, it is clearly visible which nations possess significant differentiation in their results.

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[26] https://www.globalenergyinstitute.org/international-energy-security-risk-index

	Results of this study		
	Worst	Best	Results of IESRI Report
Austria	3	3	2
Belgium	4	4	1
Bulgaria	3	3	3
Croatia	4	4	1
Czechia	2	2	4
Denmark	4	4	5
Finland	3	3	2
France	5	5	3
Germany	4	4	3
Greece	3	3	4
Hungary	2	2	3
Ireland	3	4	4
Italy	4	4	1
Netherlands	2	4	2
Norway	1	5	5
Poland	2	4	5
Portugal	4	4	1
Romania	3	4	5
Slovakia	3	3	2
Spain	4	4	1
Sweden	4	5	4
United Kingdom	5	5	5

Table 28 - Comparative categorical placements between IESRI report and this study

The countries within which the results best aligned were Austria, Bulgaria, Denmark, Finland, Germany, Greece, Hungary, Ireland, Slovakia, Sweden and Spain. Countries with moderate differences in performance levels between the two indices include: Czechia, France, the Netherlands and Romania. The nations with notable discrepancies in the results include: Belgium, Croatia, Italy, Norway, Poland, Portugal and Spain. The datasets, for which each index was formulated for such nations were investigated further, to identify the areas which can best explain the contrasting results.

Belgium was amongst one of the worst performers in the IESRI results. In the performance tables within this paper, there exist no indicators whereby it significantly underperforms relative to the other nations, with its worst performing indicator being GHG emissions per capita. The indicator performance breakdown of Belgium in the IESRI results show that all import exposure indicators perform poorly, contributing to Belgium's poor score. The formulation of these indicators takes into account the domestic resource base, the energy intensity of the economy and the diversity and reliability of the global fuel supplies, among others. On the contrary, Belgium scores highly in both Shannon Indices within this paper which best quantify import exposure risks. The Shannon index accounts for the political stability of the exporting nations, as well as the relative importance of each supplier. The disparity in the formulation of the indicators can best explain the difference in Belgium's scores within each assessment.

Croatia performed well in this assessment, contrary to its poor performance in the IESRI results. Again, the disparity can be primarily attributed to poor scores for the import exposure metrics. In particular, Croatia's coal import exposure was very high, which is an indicator that was not considered in this assessment. The indicators that performed well in both assessments, which reinforce Croatia's good scores within this paper, were energy intensity, energy consumption per capita, non-carbon energy sources and emissions per capita.

Italy performed well in this assessment, in contrast to the high energy risk index score in the IESRI report. All import exposure indicators, particularly coal, in the IESRI report implied high levels of energy insecurity. In contrast, Italy obtained strong scores within this paper for the Shannon Indices, which attempt to quantify a similar area of energy security. The lack of consideration for coal related indicators in this paper can again account for a large portion of the performance difference between each assessment. Other indicators in the IESRI report that contributed to Italy's high energy security risk index score, are retail electricity prices and non-carbon generation. Retail electricity prices were not accounted for in this paper, and the non-carbon generation metrics within this paper do similarly perform in the poor to mediocre range.

Norway possessed the most polarized results in this analysis, with the categorical placement being assigned between bad and excellent. The IESRI results depicted Norway an excellent energy security score. This is the only case in the analysis where such a large disparity exists. For all indicators, except energy consumption per capita, Norway performs around or significantly better than average. In the IESRI report, Norway's energy consumption per capita metric is accounted for and is, similar to this study, the worst performing nation for this metric. With the exception of coal import exposure, Norway scores from moderate to well in all other metrics. The nature of the category assigning system in MCDA U-Laval can therefore explain the bad category assignment, since if the aggregated system from the IESRI report was applied to this studies dataset, Norway would possess a better, singular, performance score.

Poland has a very low energy security risk score in the IESRI report, in contrast to this assessment, whereby the worst performing category is 3 increments lower. The excellent performance in the IESRI report can be attributed to Poland's extremely low scores for all import exposure metrics, whereby it was given a score of 0 for both Coal and Gas import exposure risks. One contrasting metric between the two assessments was energy consumption per capita, whereby IESRI report and this paper gave poor and good scores, respectively. The IESRI report uses the unit British thermal units (Btu), whereas this paper assesses the indicator in KWh. The unit Btu is typically used to quantity the energy content of fuels, whereas KWh is concerned with the electricity consumption. Therefore, the data collection and methodologies for the calculation of this metric for each index would differ. All other indicators display similarly mediocre performance scores for the indicator data inputs for both indices.

Furthermore, Portugal possessed contrasting performance scores between the two indices. The IESRI methodology yielded a score implying high energy security risk, whereas the approach in this paper posited a good result. All import exposure risk scores in the IESRI report were very poor. The Shannon Index score within this paper concerning oil was similarly given a poor score, however that of the natural gas performed slightly above average. The lack of consideration of coal within this assessment is further instated, whereby a very poor score was accounted for in the IESRI report. The CO2 emissions trend for Portugal in the IESRI report displayed a very poor score. This metric is concerned with the emissions produced relative to the previous year, which is something that was not considered in this paper. Instead, the focus was on emission levels and renewable energy capacity relative to the other nations within each year, whereby Portugal scored well in this assessment. All other related indicator data between each assessment complied.

Spain experienced a significant contrast between scores, similarly to Portugal, with this paper and the IESRI report approximating categories 4 and 1 respectively. Despite being assigned to the same approximate category as Portugal, as per the conversion approach in table 28, Spain did score considerably better than Portugal, thus highlighting the limitation of such an approach when attempting to draw comparisons. Nonetheless, Spain's poor performance in the IESRI index can be attributed primarily to their import exposure scores, particularly those for gas and coal. In stark contrast to the IESRI report scores, Spain's Shannon Indices for the diversity of suppliers in this paper both scored well above average. The disparity in the formulation of similar metrics can therefore predominantly explain the contrasting results. In all other metrics for the IESRI report, with the exception of CO2 emissions trend, Spain scored around or better than average.

7. Conclusions

The primary objective of this study was to demonstrate the implementation of the ELECTRE TRI-nC method in MCDA U-Laval, in order to assess energy security within Europe. The initial research conducted concerned assessing the evolution of energy security performance, on an annual temporal frame from 2013 through to 2018, using 10 indicators. The results displayed generally marginal performance changes year to year, with 2 indicators, namely energy efficiency and oil stock compliance. Thus, it was deemed appropriate to remove these indicators for the remainder of this assessment. The analysis was therefore focused solely on the remaining 8 indicators, to provide a more clear-cut set of performance results, which create greater contrast. To capture the multidimensional nature of energy security, indicators were selected to fulfill all the energy security dimensions included in the framework from Sovacool and Mukherkjee (2011).

Section 1 provides an introduction to the topic of energy security. This is achieved through outlining the dynamism of its definition, and the importance of being able to quantify different nations' performance, to mitigate the risks associated with energy crisis'.

The literature review of section 2 conducted an evaluation of existing energy security assessments which employ MCDA methods. This highlighted areas that require further development on the topic. The lack of literature assessing multiple years was noted. and as such, this study contributes to multi-year assessments. By choosing a temporal frame before and during the Crimea conflict, the evolving energy security performance levels of European nations was explored. The implementation of an array of climate concerned directives highlighted in the literature emphasise the importance of using sustainable energy indicators, to assess energy security. As such, this study incorporates several indicators related to the deployment and development of renewable and low-carbon technologies. Deployment of the Shannon Index of diversity to quantify Europe's supply security of oil and natural gas was not explored in the literature. Therefore, in light of current and ongoing risks regarding energy supply disruptions, this work incorporates such data to consider Europe's capacity to manage under such circumstances. The lack of sensitivity and robustness analysis' to validate findings in literature was noted, and as such, this study provides a deeper insight into the nature of the data.

In Section 3, a comprehensive overview of the precise methodology employed by ELECTRE TRI-nC is included. This provides context as to how the decision-making processes within the MCDA U-Laval software were undertaken.

Section 4 contains the methodological processes undertaken to formulate, execute and analyze the results of the model. The process is clearly outlined for clarity and poses guidance for further research. DecSpace software was utilized in conjunction with the DM from the green hydrogen energy field, to guide the criteria weighting process. Data was obtained from numerous up-to-date sources, to provide the most reliable and transparent assessment of energy security. The sources for the data were the following: Eurostat, World Bank and Our World in Data. All input data for the analysis, along with the techniques deployed to fill in data gaps, were displayed and outlined for transparency, and to assist future work dealing with incomplete datasets.

Section 5 contains the results and analysis, whereby the outputs of the MCDA U-Laval software were tabulated and described. With regards to the first research question, numerous analysis techniques to validate the robustness of the results were undertaken. A thorough sensitivity analysis of the MCDA U-Laval threshold values and criteria weights was performed to establish the robustness and validity of the results. The discrimination threshold sensitivity analysis induces marginal change on the results, highlighting the robust nature of the results. The sensitivity analysis of all other threshold values had little influence on the overall results, implying the datasets used in the analysis were robust, therein proving comparable results for future assessments on energy security in Europe. With regards to the second research question, a sensitivity of the influence of the criteria weight uncovered the most and least influential metrics to assess energy security in this study. Nuclear electricity generation, along with the Shannon indices for oil and natural gas proved to be the most influential in effecting the outcome of the results in both 2013 and 2018. Such results align with their higher priority assigned by the DM. Energy consumption per capita proved to be the least influential criteria, inducing the smallest change in the results. This can be attributed in part to its smallest initial criteria weight, k. The Kruksal-Wallis statistical test, using the SPSS Statistics software, was executed to determine whether there existed any energy security performance trends between different regions of Europe, as per the UN Geoscheme. The test found insignificant differences in performance trends, which can be attributed to the performance scales inability to discern more distinct differences in energy security. In reference to the third research question, an energy security performance hierarchy amongst European nations was found. The consistently best performing nations within this assessment were France and the United Kingdom, both of which were assigned the highest category placement for both 2013 and 2018. Other nations who displayed consistently high levels of energy security were Belgium, Denmark, Germany, Italy, Portugal, Sweden and Spain. The nations highlighting concern though poor, maintained, category placements were Estonia and Slovenia. The nations whose performance digressed to concerning energy security levels through the time period studied were Czechia and Hungary. The nations who displayed active progression, from initially poor scores, within the time period studied were Finland, Ireland and Poland. The ambiguous placement of Norway between the worst and best categories was justified, owing predominantly to missing data and drawbacks of the Shannon index formulation when assessing net exporting nations.

Section 6 holds a discussion of the results, which was divided into 2 sections. The first subsection explores the final results, whereby the strengths and weaknesses of each nation were addressed. It was deemed essential to determine where exactly nations progress or digress, given that the priorities of different nations, regarding energy security, are different. By producing a percentile-based performance scale of all indicators', data for each nation for both 2013 and 2018, implicit progressions and digressions in performance of each indicator were found. With regards to the fourth and final research question, active efforts to mitigate energy security risks in light of geopolitical and climatic concerns were seen. Improvements in the average Shannon index scores for oil and natural gas indicate active efforts increase energy supply security in response to the effects of the Crimea conflict, with those nations having digressing trends being addressed in the discussion. The net increase in the deployment of renewable energy sources of European nations show efforts are being made to improve domestic energy independence and comply with ongoing energy security directives to address climate and geopolitical instability concerns. The decrease in GHG emission levels per capita within Europe further reinstates clear efforts to comply with climate policies, such as the Paris agreement, as to achieve a sustainable, secure European energy landscape. The effect of missing data was addressed, noting that in all cases, with the exception of Norway, the results were not strongly influenced by inputting average values from all available nations' data. Limitations of the Shannon Index were uncovered, with Norway's predominantly exporting nature hindering its performance, due to the nature of the indices' formulation. The limitations regarding the use of a percentile performance system to analyze Europeans nations' progress were acknowledged. Individual nations' progression in particular metrics in some cases could not be visibly merited due to disproportionate improvements of the whole sample group. To this end, nuanced interpretation of the results is required to identify nations’ marginal progressions, which may not otherwise be visible due to temporal relativity. Disparities in data collected for the formulation of the Shannon Index was also considered. The importance of considering the transit nations' political stabilities and domestic demands was emphasized, given that both factors can contribute to the security of supply.

The second subsection of the discussion compares the final results of this study with those of the 2018 IESRI report energy security assessment, a comprehensive energy security assessment. The IESRI report was formulated such that each nation received a cumulative score, built up of scores from all 29 indicators used in the study. To aid comparison, these scores were converted into percentile performance scores, which then permitted approximate categorical placements. The relative scores were considered between only the European nations relevant to this study and, as such, external performance influence was eliminated. Strong levels of performance correlation were identified. Nations' results which differed were analyzed and the discrepancies between the results of this study and those of the IESRI report were soundly justified. It was found that coal-related indicators had a significant influence on the IESRI report performance scores, which were not included in this study. One limitation of this study was the small number of indicators assessed, comparison to the IESRI report. While all dimensions of energy security were incorporated into the data, this number may not fully represent the complexity of the topic. Furthermore, it was found that different formulations of indicators addressing the same dimension of energy security contributed, in part, to the contrast in final performance levels between the two papers. Therefore, in order to permit better comparisons between assessments in the future, transparency and standardization in the formulation of indicators is recommended.

Overall, this study has attempted to empirically quantify the extent to which each of the 27 nations assessed have either maintained, gained or lost significant energy security, between the years of 2013 and 2018. This was achieved through an analysis using MCDA U-Laval, and validated through a comparison to the ISERI report. All findings through the development of analysis have been outlined in the discussion, and draw attention to particular nations that may be suitable for further study in Europe's attempts to make the shift to a more sustainable and security energy landscape.

8. Suggestions for future work

Since assessing energy security is of a complex and evolving nature, it is essential to learn and adapt from existing work to ensure the results of any assessment are valid and up to date. In light of the rapidly evolving energy security priorities, it is recommended in further work to create independent criteria weights for each year, homing in on those criteria which are most relevant in light of specific geopolitical and environmental adversities. Work that incorporates several stakeholders' opinions is another option to enhance the assessment. By having criteria weights set by opinions originating from specific areas of the energy industry, converging and diverging trends in the results can be assessed. In the context of this energy security assessment for Europe, it is important to acknowledge that the availability of data was a limitation. The effects of the annexation of Crimea were studied, however a more up to date analysis is recommended to ascertain the effects of the 2022 invasion on energy security in Europe. In future assessments, it is recommended to carefully select indicators such that each distinctly belongs to a single dimension of energy security. In addition, the indicators should be picked to achieve an even distribution across each dimension. This approach will facilitate the evaluation of which dimensions have the greatest influence on the results, permitting a more equitable analysis. A final suggestion to enhance energy security assessment would be to perform concurrent MCDA methods. By doing so, the assessment can benefit from the complementary strengths of each method whilst mitigating their respective drawbacks. Deployment of the Kruksal-Wallis test in future assessments is recommended to ascertain trends regarding energy security in Europe. For example, by grouping nations who are and aren't within a close proximity to Russia could uncover significant energy security differences.

References

Almeida-Dias, J., Figueira, J. R., & Roy, B. (2010). Electre Tri-C: A multiple criteria sorting method based on characteristic reference actions. European Journal of Operational Research, 204(3), 565–580. https://doi.org/10.1016/j.ejor.2009.10.018

Almeida-Dias, J., Figueira, J. R., & Roy, B. (2012). A multiple criteria sorting method where each category is characterized by several reference actions: The ELECTRE TRI-nC Method. European Journal of Operational Research, 217(3), 567–579. https://doi.org/10.1016/j.ejor.2011.09.047

Asia Pacific Energy Research Centre (APERC). (2007). A quest for energy security in the 21st century. Institute of Energy Economics .

Augutis, J., Krikštolaitis, R., Martišauskas, L., Pečiulytė, S., & Žutautaitė, I. (2017a). Integrated Energy Security Assessment. Energy, 138, 890–901. https://doi.org/10.1016/j.energy.2017.07.113

Augutis, J., Krikštolaitis, R., Martišauskas, L., Pečiulytė, S., & Žutautaitė, I. (2017b). Integrated Energy Security Assessment. Energy, 138, 890–901. https://doi.org/10.1016/j.energy.2017.07.113

Azzuni, A., & Breyer, C. (2017). Definitions and dimensions of energy security: A literature review. Wiley Interdisciplinary Reviews: Energy and Environment, 7(1). https://doi.org/10.1002/wene.268

Azzuni, A., & Breyer, C. (2020). Global Energy Security index and its application on national level. Energies, 13(10), 2502. https://doi.org/10.3390/en13102502

Baumann, F. (2008). Energy Security as Multidimensional Concept.

Biresselioglu, M. E., Yelkenci, T., & Oz, I. O. (2015). Investigating the Natural Gas Supply Security: A new perspective. Energy, 80, 168–176. https://doi.org/10.1016/j.energy.2014.11.060

Cabeça, A. S., Henriques, C. O., Figueira, J. R., & Silva, C. S. (2021). A multicriteria classification approach for assessing the current governance capacities on energy efficiency in the European Union. Energy Policy, 148, 111946. https://doi.org/10.1016/j.enpol.2020.111946

Chuang, M. C., & Ma, H. W. (2013). Energy security and improvements in the function of diversity indices—Taiwan Energy Supply Structure Case Study. Renewable and Sustainable Energy Reviews, 24, 9–20. https://doi.org/10.1016/j.rser.2013.03.021

Doumpos, M., & Figueira, J. R. (2019). A multicriteria outranking approach for Modeling Corporate Credit Ratings: An application of the ELECTRE TRI-nC Method. Omega, 82, 166–180. https://doi.org/10.1016/j.omega.2018.01.003

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. https://doi.org/10.1016/j.ejor.2008.11.025

Figueira, J. R., Greco, S., Roy, B., & Słowiński, R. (2012). An overview of Electre methods and their recent extensions. Journal of Multi-Criteria Decision Analysis, 20(1–2), 61–85. https://doi.org/10.1002/mcda.1482

Figueira, J. R., Mousseau, V., & Roy, B. (2016). ELECTRE Methods. In Multiple criteria decision analysis (pp. 155–185). essay, Springer.

Figueira, J., & Roy, B. (2002). Determining the weights of criteria in the Electre type methods with a revised Simos' procedure. European Journal of Operational Research, 139(2), 317–326. https://doi.org/10.1016/s0377-2217(01)00370-8

Flouri, M., Karakosta, C., Kladouchou, C., & Psarras, J. (2015). How does a natural gas supply interruption affect the EU gas security? A Monte Carlo Simulation. Renewable and Sustainable Energy Reviews, 44, 785–796. https://doi.org/10.1016/j.rser.2014.12.029

Gasser, P. (2020). A review on energy security indices to compare country performances. Energy Policy, 139, 111339. https://doi.org/10.1016/j.enpol.2020.111339

Geng, J.-B., & Ji, Q. (2014a). Multi-perspective analysis of China's Energy Supply Security. Energy, 64, 541–550. https://doi.org/10.1016/j.energy.2013.11.036

Geng, J.-B., & Ji, Q. (2014b). Multi-perspective analysis of China's Energy Supply Security. Energy, 64, 541–550. https://doi.org/10.1016/j.energy.2013.11.036

Guivarch, C., & Monjon, S. (2017). Identifying the main uncertainty drivers of energy security in a low-carbon world: The case of europe. Energy Economics, 64, 530–541. https://doi.org/10.1016/j.eneco.2016.04.007

Guivarch, C., Monjon, S., Rozenberg, J., & Vogt-Schilb, A. (2015). Would climate policy improve the European Energy Security? Climate Change Economics, 06(02), 1550008. https://doi.org/10.1142/s2010007815500086

Gupta, E. (2008). Oil vulnerability index of oil-importing countries. Energy Policy, 36(3), 1195–1211. https://doi.org/10.1016/j.enpol.2007.11.011

Huang, B., Zhang, L., Ma, L., Bai, W., & Ren, J. (2021). Multi-criteria decision analysis of China’s energy security from 2008 to 2017 based on fuzzy BWM-dea-AR model and Malmquist Productivity index. Energy, 228, 120481. https://doi.org/10.1016/j.energy.2021.120481

Huang, S.-W., Chung, Y.-F., & Wu, T.-H. (2021). Analyzing the relationship between Energy Security Performance and decoupling of Economic Growth from CO2 emissions for OECD Countries. Renewable and Sustainable Energy Reviews, 152, 111633. https://doi.org/10.1016/j.rser.2021.111633

Hughes, L. (2009). The four ‘R’s of energy security. Energy Policy, 37(6), 2459–2461. https://doi.org/10.1016/j.enpol.2009.02.038

International Energy Security Risk Index. Global Energy Institute. (n.d.). https://www.globalenergyinstitute.org/international-energy-security-risk-index

Kleber, D. (2009). The US Department of Defense: Valuing Energy Security. Journal of Energy Security.

Kosai, S., & Unesaki, H. (2020). Quantitative evaluation of security of nuclear energy supply: United States as a case study. Energy Strategy Reviews, 29, 100491. https://doi.org/10.1016/j.esr.2020.100491

Kozłowska, J., Benvenga, M. A., & Nääs, I. de. (2022). Investment risk and energy security assessment of european union countries using multicriteria analysis. Energies, 16(1), 330. https://doi.org/10.3390/en16010330

Kruskal-Wallis H test using SPSS statistics. Kruskal-Wallis H Test in SPSS Statistics | Procedure, output and interpretation of the output using a relevant example. (n.d.). https://statistics.laerd.com/spss-tutorials/kruskal-wallis-h-test-using-spss-statistics

Lin, B., & Raza, M. Y. (2020). Analysis of Energy Security Indicators and CO2 emissions. A case from a developing economy. Energy, 200, 117575. https://doi.org/10.1016/j.energy.2020.117575

Maliene, V., Dixon-Gough, R., & Malys, N. (2018). Dispersion of relative importance values contributes to the ranking uncertainty: Sensitivity Analysis of multiple criteria decision-making methods. Applied Soft Computing, 67, 286–298. https://doi.org/10.1016/j.asoc.2018.03.003

Multicriteria decision aiding software MCDA-Ulaval: Université laval. ULaval. (2022, August 28). https://mcda.fsa.ulaval.ca/

Paravantis, J. A. (2019). Dimensions, Components and Metrics of Energy Security: Review and Synthesis.

Park, H., & Bae, S. (2021). Quantitative assessment of energy supply security: Korea case study. Sustainability, 13(4), 1854. https://doi.org/10.3390/su13041854

Phillis, A., Grigoroudis, E., & Kouikoglou, V. S. (2020). Assessing National Energy Sustainability using multiple criteria decision analysis. International Journal of Sustainable Development & World Ecology, 28(1), 18–35. https://doi.org/10.1080/13504509.2020.1780646

Ren, J., & Dong, L. (2018). Evaluation of Electricity Supply Sustainability and security: Multi-criteria Decision Analysis Approach. Journal of Cleaner Production, 172, 438–453. https://doi.org/10.1016/j.jclepro.2017.10.167

Repowereu: Affordable, secure and Sustainable Energy for Europe. European Commission. (n.d.). https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

Rogers, M., & Bruen, M. (1998). Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within Electre. European Journal of Operational Research, 107(3), 542–551. https://doi.org/10.1016/s0377-2217(97)00175-6

Schumacher, E. F. (1982). Schumacher on Energy : Speeches and Writings of E.F. Schumacher.

Sovacool, B. K., & Mukherjee, I. (2011). Conceptualizing and measuring energy security: A synthesized approach. Energy, 36(8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Thokala, P., & Duenas, A. (2012). Multiple criteria decision analysis for health technology assessment. Value in Health, 15(8), 1172–1181. https://doi.org/10.1016/j.jval.2012.06.015

UNSD — methodology. (n.d.). https://unstats.un.org/unsd/methodology/m49/

What is the Paris Agreement?. Unfccc.int. (n.d.). https://unfccc.int/process-and-meetings/the-paris-agreement

World Risk Index. (2022). Bündnis Entwicklung Hilft.

Wulf, C., Haase, M., Baumann, M., & Zapp, P. (2023). Weighting factor elicitation for Sustainability Assessment of Energy Technologies. Sustainable Energy & Fuels, 7(3), 832–847. https://doi.org/10.1039/d2se01170k

Ziemba, P. (2022). Energy Security Assessment based on a new dynamic multi-criteria decision-making framework. Energies, 15(24), 9356. https://doi.org/10.3390/en15249356