Sensitivity and uncertainty analyses of a composite index measuring sustainable energy transition in the European Union

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Energy has a key role in the process of advancing sustainable development. Sustainable energy transition is a long-term process that can be hindered by different social, economic and environmental effects (e.g. greenhouse gas emissions, energy poverty) and influenced by the challenges related to the recent energy crisis and contemporary energy trends (e.g. rising energy prices, the threat of European gas shortages, regional differences in the use of renewable energy sources and the aftereffects of Covid-19 pandemic). Monitoring energy transition progress and examining its temporal trends and spatial characteristics can provide a basic policy analysis framework for strategic energy policy development in the European Union (EU) at regional and national levels. An important approach for this endeavour is the indicator-based assessment of trends. Composite indicators are widely used to track and compare countries' progress in domains that are closely related to policymaking such as sustainable development and quality of life assessment. Constructing such indicators includes multiple steps and decisions, some of which cannot be justified with statistical principles or methodologies as addressing these factors requires uncertainty and sensitivity analyses. This study develops a composite index to measure the performance of the EU member states in terms of sustainable energy transition. As the construction methodology and most statistical analyses are already available, this study focuses on uncertainty and sensitivity analysis, assessing the sustainable energy transition index, which uses representative indicators that cover three pillars of sustainable energy transition that include economic and development, human and social and natural and environmental dimensions. The weights of the base indicators are based on expert panel opinion, which was determined referencing sustainability and policy considerations. Base indicators' aggregation summarises weighted standardised values. Regarding the sensitivity of the composite index, these two factors are found to be the most probable sources of uncertainty. These factors contribute to the final index value that calculates the extent of uncertainty using the Monte Carlo methodology. This study also uses variance-based sensitivity analysis to identify the most significant factors of uncertainty. The results provide a comprehensive overview of EU member states' progress in sustainable energy transition that is primarily unbiased as changing the chosen input factors only induces a maximum average rank change of three. Out of the two factors assessed, the aggregation method is found to be the greater source of uncertainty.

Keywords:
sustainable energy,
energy transition,
composite indicator,
energy policy,
sensitivity analysis

Introduction

While transitioning to a sustainable energy system is an enormous challenge, it is also a core aspect of overall sustainable development. Energy transition is a fundamental objective of decarbonisation policies that can be advanced by promoting energy efficiency and the use of renewable energy technologies (Neofytou et al. 2020). Sgouridis–Csala (2014: p. 2609) defined sustainable energy transition as 'a controlled process that leads an advanced, technical society to replace all major fossil fuel primary energy inputs with sustainably renewable resources while maintaining a sufficient final energy service level per capita'. This process requires coordinated transformations in societal, equity, economic and environmental dimensions. The Covid-19 pandemic and the changes incurred by lockdowns presented an opportunity for policymakers to move further on the path of sustainability from environmental and human perspectives (Kuzemko et al. 2020); however, remains unclear whether permanent changes in behaviour occurred regarding issues such as air quality, fossil fuel demand and climate change mitigation.

Composite indicators are widely used in policymaking domains such as sustainable development and quality of life assessment or measuring and comparing countries' environmental performance (Munda–Nardo 2009, Pinar 2022). Such measures are useful for understanding the direction of trends, facilitating comparisons across countries, identifying areas for action and creating a means of communication with the general public, experts, stakeholders and decision-makers. These measures establish a big picture to facilitate countries' performance comparison and ranking (Saisana–Tarantola 2002). A composite index is a simplified representation of reality, presenting an aggregation of relevant variables for considering an issue or system (OECD et al. 2008) to assess and summarise multiple aspects of sustainability. Csizovszky–Buzási (2023) created a composite indicator measuring community resilience in Hungary. The sustainable development goals index (SDGI) tracks annual countries' performance concerning the United Nations sustainable development goals (SDGs) on a global scale, based on 100 sub-indicators. Building from the SDGI methodology, the Europe sustainable development index assesses the progress of the 27 EU member states as well as European Free Trade Association countries, the UK and EU candidate countries (Lafortune et al. 2021). The SDGI and the Europe SDGI are calculated to track long-term trends in addition to assessing annual progress (Lafortune et al. 2020). The human development index (HDI) is a composite tool that is more focused on measuring countries' social and economic development and offers a general index for global assessment and critique based on minimal listing of capabilities that focus on basic quality of life indicators. HDI measurement has also included sustainability and environmental metrics since 2020 (UNDP 2020). Therefore, while the HDI is a welfare index with social and economic focus, it has a definite connection with sustainable energy consumption, particularly in the case of households. Until a certain level of human well-being is achieved, increased energy consumption and economic growth contributes to human development (LaBelle et al. 2022). The energy transition index (ETI) developed by the World Economic Forum (2021) is based on the energy triangle that includes environmental sustainability, energy security and access and economic development and growth. For some composite indices focusing on environmental performance or sustainability, methodological approaches can change from time to time, e.g. the base indicators included may be altered to highlight issues that are more prominent in a given year. Because of these changes, not all composite indices can be analysed as time series. The environmental performance index (Wolf et al. 2022) is one example of this phenomenon as it is not calculated annually because not all of the sub-indicator data are available as time series and issue categories have disparate beginning and end years.

An advantage of composite indices is that they can be used to summarise complex issues, providing a way to elicit summary figures or time series analysis that can attract public interest. However, expressing the conclusion of complex policy issues and a great amount of base indicator data in just one value can diminish the possibility of decomposition and complex evaluation. Defining the set of base indicators and individual weighting is a critical concern that is often affected by the availability of data and/or researcher (customer) preconceptions (Hétfa Kutatóintézet 2022) In addition, such composites may have weaknesses in construction, which involves multiple steps and methodological decisions. All stages of composite index calculation should be transparent and statistically sound (Saisana–Tarantola 2002). To compensate for this, often the final aggregate values of composite indicators are informative as well as the values of individual indicator clusters.

Another method for addressing the weaknesses in the construction and methodology of composite indices is sensitivity analysis, in which one or multiple a model's factors are altered to assess the effects on the outcome of calculations. This methodology has been traditionally used for to evaluate policymaking decisions (Razavi et al. 2021). In a detailed sensitivity analysis of the HDI, Aguña–Kovacevic (2010) assessed the uncertainty of minimum goalpost values for re-scaling and the weights of sub-indicators, confirming that uncertainty is unavoidable in composite indices. Kuc-Czarnecka et al. (2023) examined SDG implementation and the interactions between goals using a methodology based on sensitivity analysis. Güdemann–Münnich (2023) employed variance-based sensitivity and uncertainty analysis on their own composite index based on the SDGs. Sinisterra-Solís et al. (2024) analysed the sensitivity of their composite index assessing sustainable agriculture using a variance-based methodology, Sobol's sensitivity index and the Latin Hypercube Sampling Design. Zhang–Zhou (2024) used a variance-based approach similar to sensitivity analysis methods to determine the importance of each weight in their newly proposed energy security indicator framework. Pinar (2022) examined the sensitivity of the EPI using the stochastic dominance efficiency methodology. Data envelopment analysis (DEA) is also employed for assessing the sensitivity of composite scores (Cherchye et al. 2008). Endrődi-Kovács–Tankovsky (2023) examined the robustness and sensitivity of a proposed composite indicator that evaluates EU membership by changing parameters by +/−30% using Monte Carlo simulation. Alberti et al. (2023) tested winsorisation and weighting systems in an uncertainty analysis of the Cultural and Creative Cities Monitor.

The weights of composite indicators are often determined based on the perceived importance of base indicators, which might cause them to not perform according to the original intention, raising concerns that can be addressed using uncertainty and sensitivity analysis. (Burgass et al. 2017) Determining uncertainty in indicator weights is particularly significant if they are defined by a panel of stakeholders or experts with multiple opinions (Saisana–Tarantola 2002). Another cause of methodological concern and potential errors is the chosen aggregation method, which can fundamentally change a composite indicator's performance. The most widely used aggregation methods are linear and geometric aggregation (Burgass et al. 2017). According to Saisana et al. (2005), other sources of general composite indicator uncertainty may include the selection of base indicators, data selection, data editing, data normalisation and the composite indicator formula.

This study endeavours to construct a transparent and statistically sound methodology for examining the composite indicator. The research undertaken during the development of the sustainable energy transition index (SETI) focused on three basic dimensions of sustainable energy transition (Iddrisu–Bhattacharyya 2015), which are (1) the economic and development-related dimension, (2) the human and social dimension and (3) the natural resource-related and environmental dimension. The three pillars or sub-indicators of the SETI were chosen because these dimensions adequately represent the cross-sectoral and interdisciplinary nature of energy sustainability (IAEA 2015). To further ensure the SETI's transparency, this study references the variance-based method from Saltelli et al. (2002) for the uncertainty analysis, Monte Carlo methodology and the sensitivity analysis, which is detailed below.

Methodology

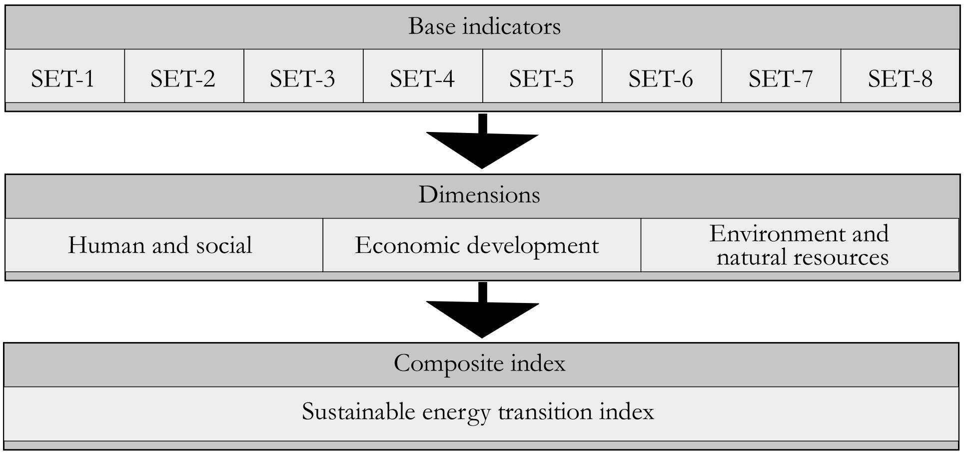
Sustainable energy transition index (SETI)

Sustainable energy transition is a key element of promoting social welfare and justice and the circular economy. This study constructs the SETI indicator set and composite index to measure the performance of the EU member states regarding this trend, developing representative indicators to cover the three dimensions of sustainable energy transition. SETI's construction followed steps suggested by the Organization for Economic Development and Co-operation (OECD et al. 2008) for the compilation of composite indicators. The eight selected base indicators (SET-1–SET-8) cover important aspects of sustainable energy management such as residential energy consumption, energy prices, population affected by energy poverty, encompassing energy intensity, energy import dependency and share of fossil fuels and unconditional renewables in energy consumption. After carefully selecting the indicators and the imputation of missing data, the dataset was analysed using statistical methods such as stationarity and normality tests. To make the variables comparable, the dataset was standardised using the z-score method. Weights were determined based on sustainability and policy considerations. Rather than assigning base indicators to a single pillar, each of the base indicators was assumed to affect all three of the dimensions of sustainable energy transition to varying degrees. The first step of weighting established an interaction matrix through expert panel evaluation to assess the driving factors of the selected indicators on the three dimensions of sustainable energy. The second step assigned the weighting factors, ensuring that the relative importance of the three dimensions within the overall SETI remained equal.

The values of the three sub-systems are the sum of weighted standardised values of the selected indicators. The final index value was calculated as the arithmetic mean of these three dimensions and normalised on a scale of 0–100 for better understanding. The structure of the SETI is illustrated on Figure 1. The detailed steps for constructing each composite indicator were presented in previous studies (Szép et al. 2021, 2022). Therefore, only the weighting and aggregation steps are presented in more detail below as these are the main subjects of this study's uncertainty and sensitivity analyses.

Figure 1

Sustainable energy transition index (SETI) structure



Uncertainty and sensitivity analyses

A number of methodological choices must be made when constructing a composite indicator, all of which introduce uncertainty into a composite indicator's values. Uncertainty analysis is used to assess the uncertainty of an index, which results from methodological choices that cannot be justified for theoretical reasons or data properties such as the weights assigned to sub-indicators and the aggregation method itself (Saisana–Tarantola 2002, Aguña–Kovacevic 2010). Following the uncertainty analysis, this study conducts a sensitivity analysis to examine how the uncertainty of each methodological choice contributes to the output variance of the composite index (Saisana et al. 2005).

Uncertainty and sensitivity analyses are conducted using R 4.3.1 (R Core Team 2023), RStudio (R Studio Team 2020) and the COINr package (Becker et al. 2022), which enables the construction and analysis of composite indicators. First, the methodology of constructing the SETI was implemented in R for weighting and aggregation steps, using the built-in tools to conduct the uncertainty and sensitivity analyses following the methodology described below.

This study focuses on the aggregation and weighting of the SETI as the most probable sources of uncertainty (Greco et al. 2019). Sensitivity analysis identifies the input factors that are more significant in affecting the final composite value. The study employs the Monte Carlo approach for the uncertainty analysis, re-calculating the composite index multiple times while randomly varying the selected input factors (Saisana et al. 2005). Output distributions are estimated by altering the input factors and re-running the calculations multiple times. Calculating the median value of the Monte Carlo results allows for comparison with the nominal index value of the composite indicator to assess the extent to which changing the input factors affects the output of the composite calculation. This study uses a flexible variance-based sensitivity approach for the sensitivity analysis, which was introduced by Saisana et al. (2005).

The first stage aggregation method (when the base indicators are aggregated into the sub-indicators of the three pillars) was originally a weighted summarisation wherein base indicators are multiplied by their respective weights and summed to obtain the scores for the environmental, economic and social pillars. The final index was calculated as the arithmetic mean of these three values.

The harmonic mean is chosen as an alternative aggregation method for the uncertainty analysis. While arithmetic and geometric means are the most widely used to aggregate composites (Aguña–Kovacevic 2010, Burgass et al. 2017), the negative weights in our methodology ruled out the use of the geometric mean as an alternative in our uncertainty analysis. In the original methodology, the weights for the other uncertain factor assessed were based solely on expert panel evaluation. This study conducts an overall perturbation of weights to assess uncertainty, generating 100 replications of all original weights, each with a random amount of added noise that vary between +/–50%.

In contrast, the sensitivity analysis uses 400 replications (N*(d+2)), referencing the experimental design proposed by Saltelli (2002), where N is the number of replications and d is the number of uncertain assumptions, which is 2 in this case. The number of bootstrap replications used for calculating the quartiles is set to 100. When sampling the weighting scheme and weights, the composite indicator calculations qualify as a non-linear model; therefore, a variance-based methodology is most appropriate for sensitivity analysis (Saltelli et al. 2000). The study applies sensitivity analysis to the SETI values as the output of the model.

The sensitivity of an individual input factor can be measured using the sensitivity index, which describes the contribution of a given factor to the model's output variance (Eq. 1).

$$S_i = V_i/V \tag{1}$$

where V is the total output variance and V_i is the fraction of the unconditional output variance that is accounted for by the uncertainty of the given factor. The decomposition formula for V that is used to calculate V_i was described by Saisana et al. (2005). Only the calculations above are required if no interaction effects exist between sets of input factors in the model that might introduce further uncertainty.

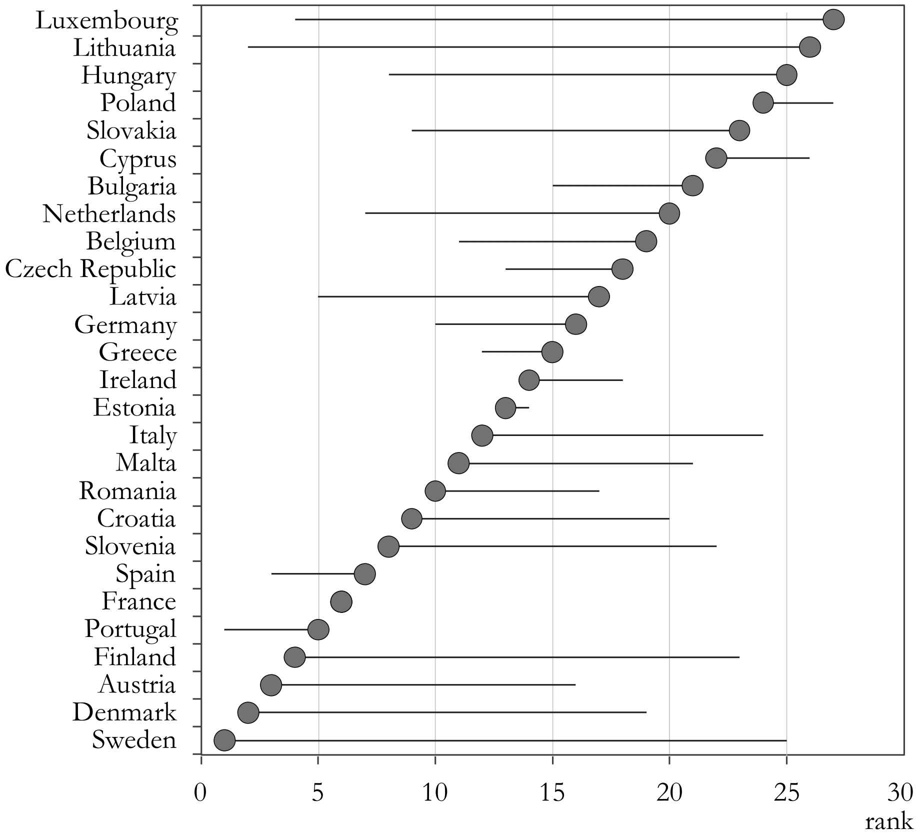
This study calculates total effect sensitivity indices (S_{Ti}) for all factors to account for their interactions, referencing Saisana et al. (2005), where the difference between S_i and S_{Ti} for a given input factor reveals the significance of interactions for that factor in the output of the model.

Results and discussion

The Monte Carlo SETI values for the 27 EU Member States are calculated for each of the 400 combinations of aggregation methods and set of weights, producing a ranking distribution. Figures 2–4 illustrate the median and corresponding 5th and 95th percentiles of the distribution of the recalculated SETI values per country for the three cases assessed.

Figure 2

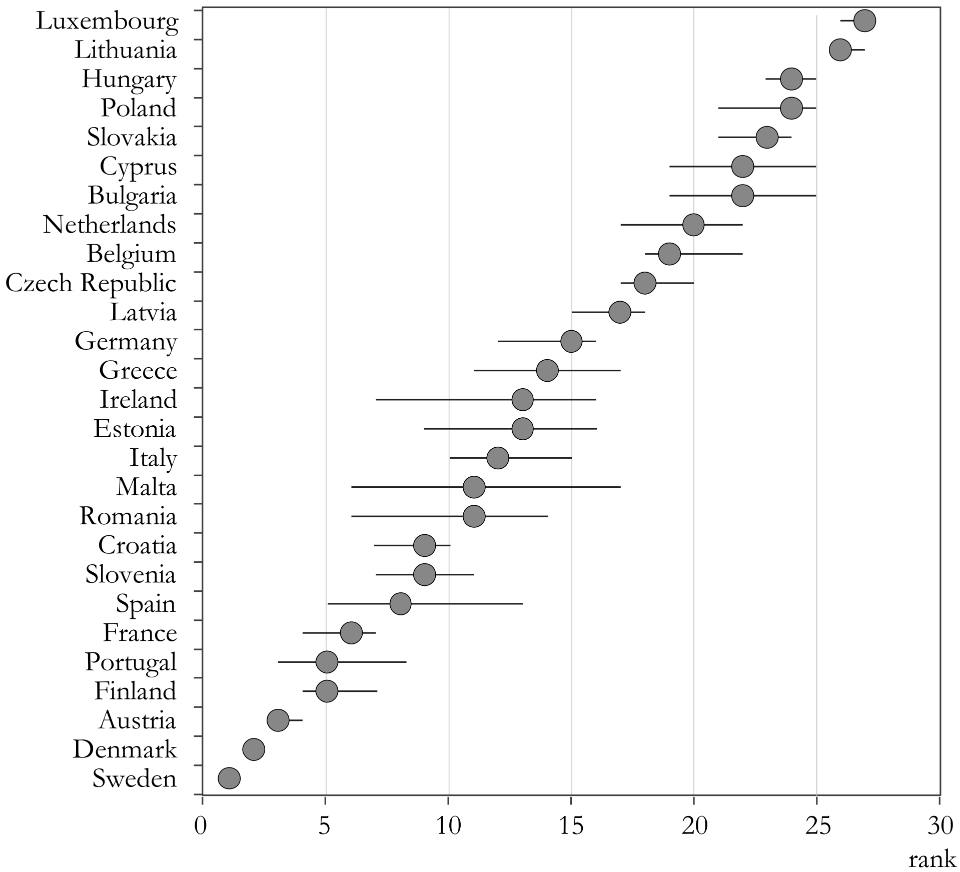
Uncertainty analysis (UA) results showing the median (in grey) and the corresponding 5th and 95th percentiles (bounds) of the distribution of the recalculated SETI for 27 countries



Notes: uncertain input factor: aggregation method; countries are ranked according to median values.

Figure 3

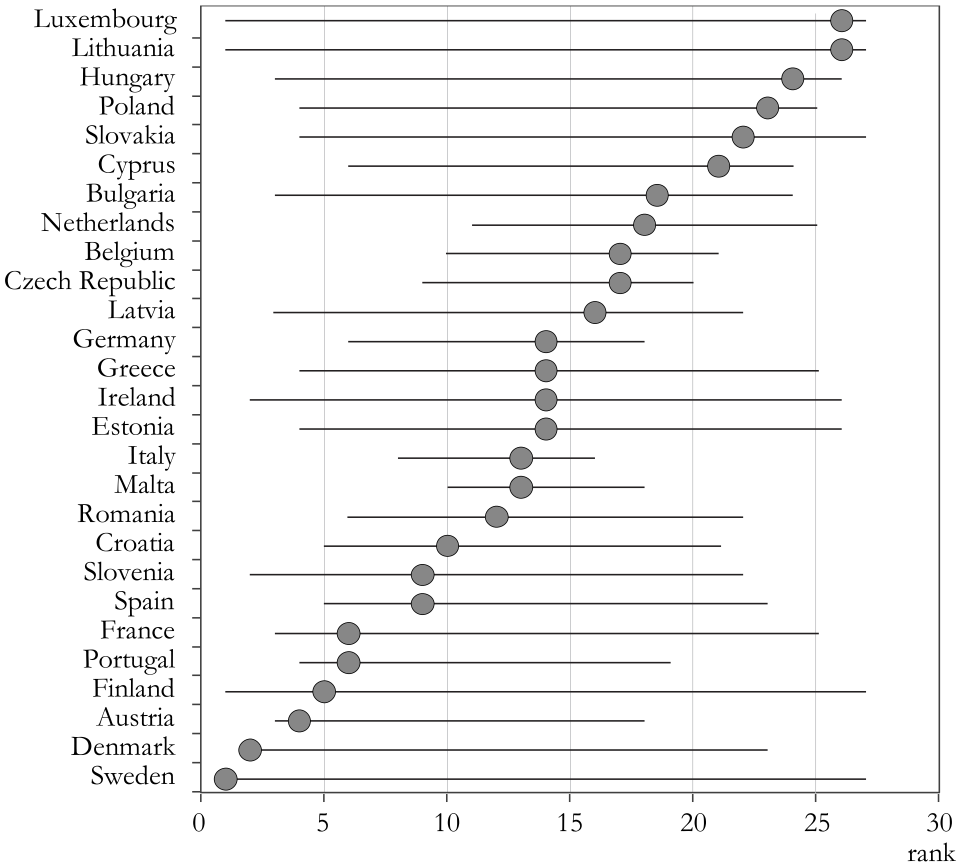
UA results showing the median (in grey) and the corresponding 5th and 95th percentiles (bounds) of the distribution of the recalculated SETI for 27 countries



Notes: uncertain input factor: weights of the base indicators; countries are ranked according to median values.

Figure 4

UA results showing the median (in grey) and the corresponding 5th and 95th percentiles (bounds) of the distribution of the recalculated SETI for 27 countries



Notes: uncertain input factors: aggregation method and weights of the base indicators; countries are ranked according to median values.

For almost all countries, the nominal SETI value is extremely close to the recalculated median value of the distribution that includes the two types of uncertainty assessed in this study. This holds true for the two cases in which only one uncertain factor is examined (only the weights or only the weighting scheme) as well as the third case including both uncertain factors. Based on the results for the first case, changing the aggregation method causes a maximum of 1 median rank change for most member states. In the second case, changing the weights results in more diverse rank changes for the assessed countries; however, the bounds of the distribution are narrower. The third case combining the results of cases 1 and 2 reveals that the median rank changes are more varying and the bounds are greater, indicating that interactions between uncertainty occur that are caused by changing both the weights and the aggregation method. Still, the maximum value of rank change is 3, and is only present in the cases of Bulgaria and Germany when both uncertain factors are present. Table 1 presents the rank changes for all member states in detail.

Table 1

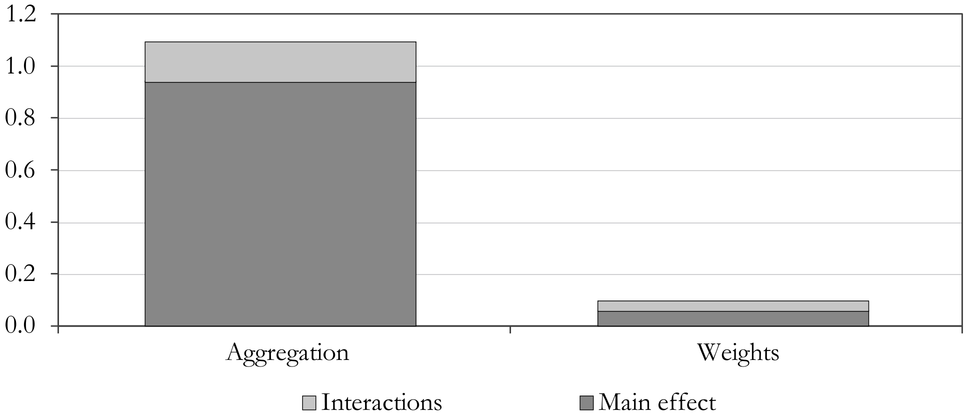
Nominal ranks of EU member states and median ranking values calculated with Monte Carlo analysis in three cases of uncertain input factors

Nominal rank	Country	Median		
		uncertain input factor: weights	uncertain input factor: weighting scheme	uncertain input factors: weights and weighting scheme
1	Sweden	1	1	1
2	Denmark	2	2	2
3	Austria	3	3	4
4	Finland	5	4	6
5	Portugal	5	5	5
6	France	6	6	6
7	Spain	8	7	9
8	Slovenia	9	8	9
9	Croatia	9	9	10
10	Romania	11	10	12
11	Malta	11	11	14
12	Italy	12	12	14
13	Estonia	13	13	14
14	Ireland	13	14	14
15	Greece	14	15	13
16	Germany	15	16	13
17	Latvia	17	17	16
18	Czech Republic	18	18	17
19	Belgium	19	19	17
20	Netherlands	20	20	18.5
21	Bulgaria	22	21	18
22	Cyprus	22	22	22
23	Slovakia	23	23	21
24	Poland	24	24	24
25	Hungary	24	25	23
26	Lithuania	26	26	26
27	Luxembourg	27	27	26

Figure 5 and Table 2 present the results of the sensitivity analysis. Each bar in Figure 5 represents the sensitivity of the results for each uncertain input factor, based on the average SETI ranking change compared with nominal values. In addition to the sensitivity of single uncertain factors, the sensitivity from their interactions is presented.

Figure 5

Sensitivity analysis results



Notes: uncertain input factors: aggregation method and weights of the base indicators.

Table 2

Sensitivity analysis results

Variable	S_i	S_{Ti}	S_{i_q5}	S_{i_q95}	S_{Ti_q5}	S_{Ti_q95}	S_{Ti}–S_i
Weights	0.057	0.099	−0.061	0.166	0.070	0.124	0.042
Aggregation	0.933	1.087	0.640	1.315	0.898	1.277	0.154

Notes: S_i is the main effect of each uncertain factor, S_{Ti} is the total sensitivity of each uncertain factor, S_{Ti}–S_i is the effect of interactions and S_{i_q5} and S_{i_q95} are the 5th and 95th quartiles for the main effect of each uncertain factor.

In cases that introduce both input factors, when an input factor explains more than 0.5 of the output variance, it is considered to be significant (Saisana et al. 2005). Based on the results in Table 2, S_i and S_{Ti} values for the aggregation factor are both greater than 0.5, indicating that the uncertain input factor that contributes most to the sensitivity is the aggregation method in the case of SETI.

Conclusion

This study constructs a new indicator set to measure the clean energy transition in EU member states. The methodology for building the index and the associated statistical calculations have been presented in detail in earlier publications (Szép et al. 2021, 2022). This study presents uncertainty and sensitivity analyses of the SETI, particularly concerning the weighting step that was based on expert panel opinion and the aggregation step, which have considerable influence on the end result of composite indicators. The uncertainty analysis, employing the Monte Carlo methodology, confirms that neither changing the weights, nor changing the aggregation method results in a median rank change greater than 1, whereas the influence of uncertainty is more significant when both factors are present simultaneously; however, the maximum difference between the median ranks and the nominal ranks is only 3. The variance-based sensitivity analysis reveals that the primary source of total uncertainty is the aggregation step. Based on the results, the original SETI provides a predominantly unbiased view of the EU members' progress in sustainable energy transition.

The results of this study further validate that the SETI is a robust indicator with a strong holistic approach that could be suitable to inform policymakers engaged in designing sustainable development of national energy and environmental policies. The base indicators and the steps during the development of the index were chosen to emphasise the goals of affordable and clean energy and combating climate change, adhering to SDGs 7 and 13 (UN 2015). The SETI was primarily developed for time series analysis as examining existing tendencies and determining the ways in which they connect to changing trends of the past is essential to the decision-making process. Assessing differences in sustainable energy performance may advance the process of integrating and mainstreaming sustainable development into national energy policies by highlighting the influential roles of success factors. Comparing countries' performance also offers insights about potential gaps and core areas in sustainable energy transition.

Tracking tendencies has become especially crucial since Covid-19 pandemic and the energy crisis resulting from the war in Ukraine have amplified the EU's existing challenges. Supply chain disruptions and the environmental effects of climate change are not only reflected in the trends of indicators, but directly affect the global population (Tóth et al. 2023, Kiss–Balla 2022). In addition, soaring energy prices are pressuring inflation rates in EU member states, deepening energy poverty and increasing inequality and the number of vulnerable households (Kashour 2023). To promote energy affordability, investments in renewable energy and energy efficiency improvement may be a solution and could lead to resilient and decarbonised energy systems. In the long term, implementing the European Green Deal and accelerating sustainable energy transition could increase the EU's resilience against future challenges.

Comparing the SETI with other, widely used composite indices related to sustainability; namely, the World Economic Forum's ETI (World Economic Forum 2021), the HDI (UNDP 2020) and the SDGI (Lafortune et al. 2021), the rankings of EU member states in 2021 reveal that Sweden, Denmark, Finland and Austria are in the top ranks for all indices. These countries exhibit the highest sustainability performance, with characteristics such as low energy intensity, a high share of renewables and a low proportion of the population affected by energy poverty. Strong and effective policies have set these countries on a track as the leaders in advancing sustainability in the EU. Concerning the other member states, four additional groups have been identified based on SETI score; however, these are highly heterogeneous and not connected to specific regions (Szép et al. 2022). The rankings for each of the compared indices differ, which is attributable to the differing purposes of each composite indicator. While the SETI and ETI focus on energy transition with some similar base indicators (e.g. household electricity prices, import dependency), these indices have different social and environmental indicators related to energy. The SDGI addresses a wider set of themes that encompass the great variety of SDGs, and the HDI has a strictly social and economic focus that sets it apart from the other three sustainability indices. Comparing the SETI, HDI and SDGI as time series in the 2017–2021 time period, the trends primarily show improvement and are similar for most EU member states, despite differences in the rankings. Based on these tendencies, the EU is taking definitive steps towards sustainability, in fields of energy, economics and social policy.

While the primary causes of uncertainty in indicator systems usually concern weighting and aggregation, examining only these two steps is a limitation of this study. A more extensive sensitivity analysis could also include normalisation, the second level of aggregation or missing data imputation steps. The other limitation is that the uncertainty and sensitivity of SETI is analysed using the data for a single year, despite the intended use of our composite index being time series assessment. Handling time series data requires the use of more complex types of programming functions in R and may be the subject of further research.

This study uses the SETI to assess and compare the sustainable energy performance of the 27 EU member states. Future research can extend the methodology to countries and regions outside of the EU, e.g. to assess Middle East and North Africa (MENA) countries. Another research direction could be to extend the methodology to NUTS 3 regions or to assess specific cities. The latter option would require slight adjustments to the list of indicators to adapt to the differences that arise when examining cities instead of countries (e.g. import dependency is not applicable for cities).

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REFERENCES

AGUÑA, C. G.–KOVACEVIC, M. (2010): *Uncertainty and sensitivity analysis of the human development index* UNDP, New York.

ALBERTI, V.–CAPERNA, G.–MAURI, C.–PANELLA, F.–TACAO MOURA, C. J.–BANYS, K.–SYMEONIDIS, K.–DOMINGUEZ TORREIRO, M.–SAISANA, M. (2023): *Cultural and creative cities monitor* Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/975348

BECKER, W.–CAPERNA, G.–DEL SORBO, M.–NORLEN, H.–PAPADIMITRIOU, E.–SAISANA, M. (2022): COINr: An R package for developing composite indicators *Journal of Open Source Software* 7 (78): 4567. https://doi.org/10.21105/joss.04567

BURGASS, M. J.–HALPERN, B. S.–NICHOLSON, E.–MILNER-GULLAND, E. J. (2017): Navigating uncertainty in environmental composite indicators *Ecological Indicators* 75: 268–278. https://doi.org/10.1016/j.ecolind.2016.12.034

CHERCHYE, L.–MOESEN, W.–ROGGE, N.–VAN PUYENBROECK, T.–SAISANA, M.–SALTELLI, A.–LISKA, R.–TARANTOLA, S. (2008): Creating composite indicators with DEA and robustness analysis: the case of the Technology Achievment Index *Journal of the Operational Research Society* 59: 239–251. https://doi.org/10.1057/palgrave.jors.2602445

CSIZOVSZKY, A.–BUZÁSI, A. (2023): Analysis of community resilience in Hungary – an adaptation of the basic resilience indicators for communities (BRIC), 2020 *Regional Statistics* 13 (4): 752–778. https://doi.org/10.15196/RS130408

ENDRŐDI-KOVÁCS, V.–TANKOVSKY, O. (2023): A composite indicator to evaluate EU membership: the case of Central and Eastern European member states, 2004–2021 *Regional Statistics* 13 (5): 899–924. https://doi.org/10.15196/RS130505

GRECO, S.–ISHIZAKA, A.–TASIOU, M.–TORRISI, G. (2019): On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness *Social Indicators Research* 141: 61–94. https://doi.org/10.1007/s11205-017-1832-9

GÜDEMANN, L.–MÜNNICH, R. (2023): Quality and sensitivity of composite indicators for sustainable development *Austrian Journal of Statistics* 52 (5): 82–100. https://doi.org/10.17713/ajs.v52i5.1539

HÉTFA KUTATÓINTÉZET (2022): *Integrált előzetes fenntarthatósági vizsgálati módszertan és fenntarthatósági teljesítmény indikátorrendszer* Budapest.

IDDRISU, I.–BHATTACHARYYA, S. C. (2015): Sustainable energy development index: a multi-dimensional indicator for measuring sustainable energy development *Renewable and Sustainable Energy Reviews* 50 (C): 513–530. https://doi.org/10.1016/j.rser.2015.05.032

KASHOUR, M. (2023): Interlinkages between human development, residential energy consumption, and energy efficiency for the EU-27 Member States, 2010–2018 *Regional Statistics* 13 (1): 36–54. https://doi.org/10.15196/RS130102

KISS, E.–BALLA, D. (2022): Analysing national climate change-related documents: spatial and temporal dimensions worldwide *Regional Statistics* 12 (3): 131–158. https://doi.org/10.15196/RS120306

KUC-CZARNECKA, M.–MARKOWICZ, I.–SOMPOLSKA-RZECHUŁA, A. (2023) SDGs implementation, their synergies, and trade-offs in EU countries – sensitivity analysis-based approach *Ecological Indicators* 146: 109888. https://doi.org/10.1016/j.ecolind.2023.109888

KUZEMKO, C.–BRADSHAW, M.–BRIDGE, G.–GOLDTHAU, A.–JEWELL, J.–OVERLAND, I.–SCHOLTEN, D.–VAN DE GRAAF, T.–WESTPHAL, K. (2020): Covid-19 and the politics of sustainable energy transitions *Energy Research & Social Science* 68: 101685. https://doi.org/10.1016/j.erss.2020.101685

LaBelle, M. C.–Tóth, G.–Szép, T. (2022): Not fit for 55: prioritizing human well-being in residential energy consumption in the European Union *Energies* 15: 6687. https://doi.org/10.3390/en15186687

Lafortune, G.–Fuller, G.–Schmidt-Traub, G.–Kroll, C. (2020): How is progress towards the sustainable development goals measured? Comparing four approaches for the EU *Sustainability* 12 (18): 7675. https://doi.org/10.3390/su12187675

Lafortune G.–Cortés Puch, M.–Mosnier, A.–Fuller, G.–Diaz, M.–Riccaboni, A.–Kloke-Lesch, A.–Zachariadis, T.–Carli, E.–Oger, A. (2021): *Europe sustainable development report 2021: transforming the European Union to achieve the sustainable development goals. SDSN* SDSN Europe and IEEP, Paris.

Munda, G.–Nardo, M. (2009): Noncompensatory/nonlinear composite indicators for ranking countries: a defensible setting *Applied Economics* 41 (12): 1513–1523. https://doi.org/10.1080/00036840601019364

Neofytou, H.–Nikas, A.–Doukas, H. (2020): Sustainable energy transition readiness: a multicriteria assessment index *Renewable and Sustainable Energy Reviews* 131: 109988. https://doi.org/10.1016/j.rser.2020.109988

OECD–European Union–Joint Research Centre–European Commission (2008): *Handbook on constructing composite indicators: methodology and user guide.* https://doi.org/10.1787/9789264043466-en

Pinar, M. (2022): Sensitivity of environmental performance index based on stochastic dominance *Journal of Environmental Management* 310: 114767. https://doi.org/10.1016/j.jenvman.2022.114767

Razavi, S.–Jakeman, A.–Saltelli, A.–Prieur, C.–Ioos, B.–Borgonovo, E.–Plischke, E.–Lo Piano, S.–Iwanaga, T.–Becker, W.–Tarantola, S.–Guillaume, J. H. A.–Jakeman, J.–Gupta, H.–Melillo, N.–Rabitti, G.–Chabridon, V.–Duan, Q.–Sun, X.–Smith, S.–Sheikholeslami, R.–Hosseini, N.–Asadzadeh, M.–Puy, A.–Kucherenko, S.–Maier, H. R. (2021): The future of sensitivity analyis: an essential discipline for systems modelling and policy support *Environmental Modelling and Software* 137: 104954. https://doi.org/10.1016/j.envsoft.2020.104954

R Core Team (2023). _*R: a language and environment for statistical computing*_. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

RStudio Team (2020): *RStudio: Integrated development for R.* RStudio, PBC, Boston, MA.

Saisana, M.–Saltelli, A.–Tarantola, S. (2005): Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators *Journal of Royal Statistic Society* 168 (2): 307–323. https://doi.org/10.1111/j.1467-985X.2005.00350.x

Saisana, M.–Tarantola, S. (2002): *State-of-the-art report on current methodologies and practices for composite indicator development* Report EUR 20408 EN. European Commission–Joint Research Centre, Ispra.

Saltelli, A.–Tarantola, S.–Campolongo, F. (2000): Sensitivity analysis as an ingredient of modeling *Statistical Science* 12 (4): 377–395.

Saltelli, A. (2002): Making best use of model valuations to compute sensitivity indices *Computer Physics Communications* 145 (2): 280–297. https://doi.org/10.1016/S0010-4655(02)00280-1

SGOURIDIS, S.–CSALA, D. (2014): A framework for defining sustainable energy transitions: principles, dynamics, and implications *Sustainability* 6 (5): 2601–2622. https://doi.org/10.3390/su6052601

SINISTERRA-SOLÍS, N. K.–SANJUÁN, N.–RIBAL, J.–ESTRUCH, V.–CLEMENTE, G.–ROZAKIS, S. (2024): Developing a composite indicator to assess agricultural sustainability: influence of some critical choices *Ecological Indicators* 161: 111934. https://doi.org/10.1016/j.ecolind.2024.111934

SZÉP, T.–PÁLVÖLGYI, T.–KÁRMÁN-TAMUS, É. (2021): A comprehensive indicator set for measuring the sustainable energy performance in the European Union. In: BARTHA, Z. (ed.): *Entrepreneurship in the raw materials sector* pp. 9–19., Proceedings of the International Conference of the University of Miskolc Faculty of Economics, Miskolc (LIMBRA)., Taylor & Francis Group, 2021. https://doi.org/10.1201/9781003259954-2

SZÉP, T.–PÁLVÖLGYI, T.–KÁRMÁN-TAMUS, É. (2022): Indicator-based assessment of sustainable energy performance in the European Union *International Journal of Sustainable Energy Planning and Management* 34: 107–124. http://doi.org/10.54337/ijsepm.7055

TÓTH, A.–KÁLMÁN, B. G.–POÓR, J.–CSEH PAPP, I. (2023): Impact of the Covid-19 pandemic on unemployment in selected countries and country groups *Regional Statistics* 13 (3): 451–486. https://doi.org/10.15196/RS130304

WOLF, M. J.–EMERSON, J. W.–ESTY, D. C.–DE SHERBININ, A.–WENDLING, Z. A. (2022): *2022 environmental performance index* Yale Center for Environmental Law & Policy, New Haven, CT.

ZHANG, L. P.–ZHOU, P. (2024): Reassessing energy security risk incorporating external shock: a variance-based composite indicator approach *Applied Energy* 358: 122665. https://doi.org/10.1016/j.apenergy.2024.122665

INTERNET SOURCES

INTERNATIONAL ATOMIC ENERGY AGENCY [IAEA] (2005): *Energy indicators for sustainable development: guidelines and methodologies.* https://www.iaea.org/publications/7201/energy-indicators-for-sustainable-development-guidelines-and-methodologies (downloaded: March 2024)

UNITED NATIONS [UN] (2015): *Transforming our world: the 2030 agenda for sustainable development.* https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981 (downloaded: March 2024)

UNITED NATIONS DEVELOPMENT PROGRAMME [UNDP] (2020): *Human development report 2020: the next frontier: human development and the Anthropocene* New York. https://hdr.undp.org/content/human-development-report-2020 (downloaded: March 2024)

WORLD ECONOMIC FORUM (2021): *Fostering effective energy transition – 2021 edition insight report. April 2021.* https://www.weforum.org/publications/fostering-effective-energy-transition-2021/ (downloaded: March 2024)