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# Multi-criteria ranking of energy generation scenarios with Monte Carlo simulation

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## HIGHLIGHTS

- Two advanced optimization models were applied for EU energy policy scenarios development.
- Several advanced MCDA were applied for energy policy scenarios ranking: WASPAS, ARAS, TOPSIS.
- A Monte Carlo simulation was applied for sensitivity analysis of scenarios ranking.
- New policy insights in terms of energy scenarios forecasting were provided based on research conducted.

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## ABSTRACT

Integrated Assessment Models (IAMs) are omnipresent in energy policy analysis. Even though IAMs can successfully handle uncertainty pertinent to energy planning problems, they render multiple variables as outputs of the modelling. Therefore, policy makers are faced with multiple energy development scenarios and goals. Specifically, technical, environmental, and economic aspects are represented by multiple criteria, which, in turn, are related to conflicting objectives. Preferences of decision makers need to be taken into account in order to facilitate effective energy planning. Multi-criteria decision making (MCDM) tools are relevant in aggregating diverse information and thus comparing alternative energy planning options. The paper aims at ranking European Union (EU) energy development scenarios based on several IAMs with respect to multiple criteria. By doing so, we account for uncertainty surrounding policy priorities outside the IAM. In order to follow a sustainable approach, the ranking of policy options is based on EU energy policy priorities: energy efficiency improvements, increased use of renewables, reduction in and low mitigations costs of GHG emission. The ranking of scenarios is based on the estimates rendered by the two advanced IAMs relying on different approaches, namely TIAM and WITCH. The data are fed into the three MCDM techniques: the method of weighted aggregated sum/product assessment (WASPAS), the Additive Ratio Assessment (ARAS) method, and technique for order preference by similarity to ideal solution (TOPSIS). As MCDM techniques allow assigning different importance to objectives, a sensitivity analysis is carried out to check the impact of perturbations in weights upon the final ranking. The rankings provided for the scenarios by different MCDM techniques diverge, first of all, due to the underlying assumptions of IAMs. Results of the analysis provide valuable insights in integrated application of both IAMs and MCDM models for developing energy policy scenarios and decision making in energy sector.



## 1. Introduction

EU Energy and climate package was adopted in 2008 and aimed at gradually transforming Europe into a low-carbon economy. The package set legally binding targets to be achieved by 2020: to reduce GHG emissions by 20% compared to 1990; to reach a 20% share for renewable energy sources in final energy consumption along with the share of biofuels of 10% in transport fuels consumption; to achieve a 20% reduction in energy consumption by 2020 compared to 2005 (i.e., improvement in energy efficiency). Therefore, reduction in GHG emission, increase in the share of renewables in final energy consumption and improvement in energy efficiency have emerged as the key objectives for energy development in the EU. The costs of these policies are also to be

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taken into account. Therefore, assessment of energy scenarios in the EU requires to consider a number of trade-offs, especially as the increasing use of renewable requires a substantial investments. Novel energy-efficient technologies are also more expensive if compared to the conventional ones. Energy planning seeks to develop future energy scenarios and find a mix of energy sources along with conversion means so as to meet the energy demands in an optimal manner. Energy planning decisions should ensure balance among diverse ecological, social, technical, and economic aspects over space and time. However, IAMs do not allow for simultaneous consideration of the aforementioned issues, especially those involving qualitative assessments of future energy scenarios, e.g., supply security, impact on landscape etc. [1–3]. In general, energy planning faces certain requirements related to the very concept of sustainability. First, sustainable energy planning involves multiple (conflicting) criteria measured in different dimensions [4–7]. Second, uncertainty is often inherent to the decision information. Accordingly, assessment of energy policy scenarios for the EU (or any other region) requires broader application of sophisticated tools for comparative analysis.

Therefore, various optimization techniques have been employed in the area [8,9]. In principle, one can distinguish between the two large groups of these, viz. discrete and continuous optimization. In addition, energy planning might be based either on stand-alone models or IAMs, which, in turn, are related to partial or general equilibrium models, i.e., bottom-up (BU) and top-down (TD) models [10–14].

Focusing on the stand-alone models based on continuous optimization, one can refer to the study by Liu et al. [15], where dynamic interval-parameter optimization model was applied for energy system planning. Zhu et al. [16] utilised an in exact mixed-integer fractional programming model for the same purpose. Contrary to the continuous optimization, the discrete optimization is used to analyse a finite set of alternatives (e.g., energy planning scenarios).

A more aggregated approach usually rests upon application of IAMs. Zhang et al. [17] presented 19 IAMs (bottom-up, top-down, and integrated ones). Kriegler et al. [18] compared 11 IAMs and classified them into (i) Computable general equilibrium; (ii) Ramsey-type optimal growth models; and (iii) partial equilibrium energy system models. Currently, IAMs are often applied in order to model the use of renewables for energy production. Indeed, the areas of applications of IAMs are rather diverse in terms of both loci and the level of aggregation (i.e., country, region, or global analysis). Syri et al. [19] applied TIAM model to identify the mitigation scenarios for greenhouse gases under multiple scenarios. Føyn et al. [20] used ETSAP-TIAM to model the share of renewables in the energy system under different assumptions regarding $CO_2$ concentration limit and GHG emission price. Labriet et al. [21] applied TIAM along with stochastic programming to determine energy system development options across the world. Gracceva and Zeniewski [22] utilised TIAM to analyse shale gas development. Gracceva and Zeniewski [23] analysed the linkages between energy security and climate change mitigation by the means of TIAM. Anandarajah and Gambhir [24] employed TIAM-UCL model to estimate the impacts of renewables in terms of India's climate change mitigation targets. Bosetti et al. [25] applied WITCH along with GCAM and MARKAL-US to analyse the impact of energy technology price dynamics upon the development of energy production worldwide. Specifically, they looked into dependence of such variables as nuclear and wind power generated, carbon emission, carbon captured and stored, carbon price, and various metrics of sensitivity on different price levels of low-carbon technologies. Marcucci and Fragkos [26] analysed the trends in carbon emissions in China, India, Europe, and USA by combining multiple IAMs and Index Decomposition Analysis.

Optimization with respect to multiple objectives is referred to as Multi-criteria Decision Making (MCDM). The latter is further broken down in regards to continuous/discrete nature of the problems analysed: Multi-objective Decision Making deals with continuous problems, whereas Multi-Attribute Decision Making (MADM) deals with discrete ones. For surveys on applications of MCDM in energy planning, see, for instance, Huang et al. [27], Zhou et al. [28], and Løken [29]. Recently, Troldborg et al. [30] applied the PROMETHEE technique along with Monte Carlo simulation to assess the options for energy generation. Brand and Missaoui [31] used the TOPSIS method to rank electricity generation options in Tunisia. Şengül et al. [32] employed the fuzzy TOPSIS to prioritize renewable energy supply systems in Turkey. Franco et al. [33] utilised a fuzzy MCDM methodology for selection of energy plant location. Yazdani-Chamzini et al. [34] unified COPRAS and AHP techniques for renewable energy project planning.

MCDM techniques allow assigning different importance to different objectives and thus identify the most promising alternatives under different priorities. In order to check the robustness of results with respect to shifts in priorities, different approaches might be taken. For instance, predefined weighting schemes might be applied [35]. Second, fuzzy weights can be employed. However, the latter option would mask some information on the possible outcomes of final ranking. Another option would be to apply a Monte Carlo simulation. Indeed, Monte Carlo simulations have been applied in the area of MCDM and, in most cases, the decision variables were defined in terms of the underlying distributions [36–38].

Given the complexity surrounding the processes and decisions of energy production, uncertainty has been introduced into estimations underlying IAMs by means of different techniques (Fragkos et al. [39]). Scenarios are often defined in order to model changes in economy, technology, policy, and environment. However, less attention has been paid to the issue of the analysis of the results obtained. As IAMs yield multiple variables of interest for each scenario, it is important to ensure a comprehensible comparison thereof. This paper, therefore, links large-scale IAMs with small-scale operational research tools (viz., MCDM techniques) in order to facilitate multi-criteria comparison of the IAM-based energy development scenarios. What is more, a Monte Carlo analysis is involved in order to check the robustness of the results. By doing so, we are able to prioritize the energy development scenarios and check stability of the ranking.

This paper aims at ranking energy development scenarios for the EU by employing MCDM techniques. In order to follow a sustainable approach, the proposed ranking in the paper accounts for economic and environmental dimensions. The ranking is based on the estimates rendered by the two IAMs, namely TIAM and WITCH. The data are fed into the three MCDM techniques: the method of weighted aggregated sum/product assessment (WASPAS), proposed by Zavadskas et al. [40], the Additive Ratio Assessment (ARAS) method, proposed Turskis and Zavadskas [41], and technique for order preference by similarity to ideal solution (TOPSIS, proposed by Hwang and Yoon [42]. Even though the aforementioned techniques have already been known, the paper furthers their application in that the egalitarian weighting is supplemented by a Monte Carlo simulation, where weights are assumed to be based on the draws from the uniform distribution. Therefore, a sensitivity analysis is carried out to check the impact of perturbations in weights upon the final ranking. The paper, therefore, contributes to the literature regarding sustainable energy planning under uncertainty and provides valuable insights in application of mathematical models for developing energy scenarios, which, indeed, constitutes an important strand for decision making in energy sector. Results of the research are applicable for long-term energy modelling and decision making in energy sector. In

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