Title:

Towards a Decarbonized and Sustainable Energy System: Multi-Criteria Decision-Making Applications for Evaluation of Energy Efficiency Projects and Hydrogen Production Technologies

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Introduction:

The transition towards a decarbonized and sustainable energy system (SES) is now widely viewed as essential in the global effort to combat climate change and ensure a resilient energy future. As climate change becomes evident and the globe witnesses related world natural disasters, efforts are focusing on the energy sector, given its massive contribution to global warming (Sofuoğlu & Kirikkaleli, 2023). The energy sector's emission contribution is around 49.4 billion tons of CO_2equivalent, which is 73.2% of total greenhouse gas (GHG) emissions (Das & Sharma, 2023). Hence, sustaining economic growth with consideration for sustainable development goals (SDGs) requires affordable and clean energy to power the economy with minimal harmful impact on Earth; a number of the United Nations SDGs are related to energy sector concerns (Santika et al., 2019). With the transition towards a sustainable energy sector and the reduction of GHG emissions, net zero emission plans have become a dominant objective.

Developing decarbonization and net-zero emission policies requires consideration of a number of sustainability dimensions to ensure long-term success and viability (Charani Shandiz et al., 2021). First, the environmental dimension, involving the reduction of GHG emissions and mitigation of the environmental impacts, is an essential consideration. Equally important is the economic dimension: the promotion of economic resilience, growth, and cost-effective transitions. Also essential is the social dimension concerned with equitable outcomes, consideration of communities and social justice. Finally, the technological dimension features the importance of adopting and developing clean and efficient technologies, and energy infrastructure. Considering and balancing these sustainability dimensions is essential for the design of decarbonization and net-zero emission plans that mitigate climate change and contribute to a more resilient, cost-effective SES.

Despite the progress towards decarbonization and net-zero emission plans, there are obstacles that slow the transition process of energy systems. Many studies have focused on only one aspect, such as environmental impacts, or economic performance, neglecting a comprehensive analysis that considers the balance of SDG objectives (Chen et al., 2019). The transition towards a decarbonized SES is not only a technical challenge, but should also be guided by sustainability, with consideration of a combination of economic, socio-political, and environmental aspects. Moreover, dealing with climate change is not just a problem to be solved; it is an urgent, ongoing effort to protect people and communities, especially who have already been or will be harmed severely by the impact of climate change. Additionally, identifying optimal decarbonization scenarios requires rational decision-making, given the long-term impacts of energy projects on the economy, the environment, and people's lives. Consequently, future energy scenarios require a decision-making technique that addresses the long-term sustainability of energy systems, based on multiple criteria that ensure effective and optimally viable options.

This study examines the role of multicriteria decision-making (MCDM) techniques in facilitating the decision-making process in two case studies: (1) energy efficiency projects evaluation towards sustainable industrial energy management: a case study of an Egyptian petrochemical complex; and (2) evaluation of sustainable hydrogen production technologies (HPT) for hydrogen economy development in Egypt. EE and HPT are two important components of the transition towards a SES. EEP enables the reduction of energy consumption and the mitigation of GHG emissions, while HPT offer promising solutions for clean and versatile energy carriers that produce no harmful emissions.

Methodology:

In many real-world situations, decision-makers need to evaluate and compare different options based on a number of factors. MCDM is a decision-making approach used to prioritize or make a choose among several alternatives when there are multiple conflicting criteria or objectives to consider (Aruldoss et al., 2013). MCDM provides a structured methodology to for making informed and rational decisions in complex and uncertain scenarios (Hobbs & Meier, 2000).

MCDM starts with the determination of the decision to be made or the problem to be solved, followed by identification and clarification of the decision criteria that represent the factors or attributes used to evaluate alternatives. These criteria often include both quantitative and qualitative aspects, such as cost, quality, and environmental impact (Albayrak & Erensal, 2004). After identifying the decision criteria, the decision-maker lists the possible options, which serve as the options in the evaluation process, e.g., different projects, investment opportunities, policies, and technologies. Each option is assessed in terms of each criterion, and the score value reflects how well the option performs with respect to each criterion. The evaluation process can involve expert judgments, or data analysis, or a combination of the two. After criteria weighting and alternative scoring, an aggregation method is used to calculate the overall assessment (Henig & Buchanan, 1996; Zeleny, 2011).

For case study 1, we present a MCDM framework that allows organizations and policymakers to evaluate and rank EEP concerning sustainability. We employ a new set of evaluation criteria validated by a group of energy efficiency experts. Several MCDM techniques are combined for the assessment and prioritization of EEPs in a petrochemical complex: Fuzzy Analytic Hierarchy Process (FAHP) for the determination of evaluation criteria weights and four methods for ranking and prioritizing the options VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR); Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS); Weighted Aggregated Sum Product Assessment (WASPAS); and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). Our comparative analysis using the four MCDM ranking methods shows that the results obtained using VIKOR and TOPSIS were consistent, robust, and simple to implement. In our case study of a petrochemical complex, EEPs related to operation and maintenance measures, especially steam systems, were ranked highest.

For the second case study, we adopt a FAHP model-based MCDM approach for the prioritization and evaluation of HPT alternatives in the context of Egypt. HPTs play a significant role in developing a hydrogen economy strategy. On the other hand, selecting among current HPTs is regarded as a MCDM problem, and it is essential to involve several incompatible evaluation criteria. Due to the rapid development of HPT and the small number of projects that have been implemented on a commercial scale worldwide, it may not be easy to use crisp numbers for the evaluation criteria. Linguistic values and expert judgments can be used for the evaluation process. The proposed FAHP framework allows two groups of subject-matter experts (SME), national (Egyptian) and international to participate in the evaluation process, so as to address the uncertainty and vagueness surrounding the decision-making problem.

Results:

This study highlights the different pathways towards achieving decarbonized and SES, considering the role of EE and hydrogen economy. EE can maximize the output of energy services while minimizing energy consumption and GHG emissions. The development of hydrogen economy can play a significant role towards the energy transition by offering a clean energy carrier that can be used in various sectors, including transportation, industry, and electricity generation. Emphasizing EE and harnessing the capabilities of a hydrogen economy stand out as essential approach, not only to advance the shift towards decarbonization but also to effectively tackle numerous challenges across various energy sectors.

The MCDM evaluation framework of EEP uses a combination of the FAHP method and four MCDM methodologies, with consideration of sustainability dimensions (economic, environmental, socio-political, and technological prospects). Through a literature review, we identified the most relevant EEP evaluation criteria; these criteria were validated by group of international EE experts. In our case study of an Egyptian petrochemical complex, Egyptian petrochemicals firm decision-makers determined the weighting assigned to the criteria. The procedure was repeated for two additional companies—one based in Qatar and the other in Ireland. All three companies have given high score to economic and environmental criteria. The variation among the three results underlines the importance of internally establishing evaluation criteria for each organization. Internal identification of the evaluation criteria is essential in light of a number of factors such as corporate culture, national policies, strategic objectives, financial status, and sector-specific regulations. Those factors emphasize the need for policymakers to consider these diverse variables when formulating EE policies and regulations.

In our assessment of the proposed ranking methodologies, we recommend employing the FAHP-VIKOR and FAHP-TOPSIS methods, given their simplicity, consistency, and flexibility. FAHP-WASPAS yielded a different ranking from the other MCDM applied in this study, and the procedural steps of FAHP-PROMETHEE were more longer when dealing with a large number of EEPs. In our examination of a petrochemical complex, and based on the final ordering of EEP evaluations, we found that maintenance and operational measures ranked highest in term of enhancing energy performance.

For the selection of optimum HPT in the development of Egypt's hydrogen economy strategy, an FAHP model based MCDM framework is adopted here. The FAHP model hierarchy structure includes four main sustainability criteria, with each main criterion divided into two sub-criteria, for prioritizing HPTs alternatives. We assessed five HPTs as follows: steam methane reforming (SMR); biomass gasification (BG); PV-electrolysis (PVE); wind-electrolysis (WE); and grid-electrolysis (GE). Two groups (national and international) of subject-matter experts (SME) were invited to participate in the evaluation process. Our results indicate that PVE is the optimum HPT for the Egypt case, and SMR was ranked third by both SME groups. For the national group, GE was ranked the second-best HPT option, while WE was ranked second by the international group, this variance in ranking was due to the different weights for environmental and economic criteria between the two groups. WE rated fourth by the national group and SMR was rated fourth by the international group. Both groups rated BG fifth. Additionally, a sensitivity analysis was conducted for the five scenarios; sensitivity analysis showed that in four scenarios (out of five) PVE was ranked as the first HPT option, while changing criteria weights had an impact on other ranking of HPTs.

Conclusion:

The findings of this study highlight the different pathways towards achieving decarbonized SES. We adopted a multicriteria decision-making (MCDM) approach in the two case studies reported here: (a) energy efficiency project (EEP) evaluation of a petrochemical complex; and (b) the evaluation of hydrogen production technologies (HPT) for the development of Egypt's hydrogen economy strategy. The work presented here clarifies the role of MCDM in overcoming the uncertainty and complexity of sustainable energy projects decision-making. Given an appropriate evaluation of EEP and

HPT, stakeholders can make well-informed decisions that promote sustainability, energy security, and climate resilience. This study contributes to the development of a framework to support the ongoing energy transition, and provides a tool to empower the selection of strategies and technologies that align with the goal of a more sustainable and decarbonized future.

Through its systematic application of our MCDM framework with diverse sustainability criteria and results analysis, this study provides valuable insights into the complex decision-making processes associated with energy projects and decarbonization policy. The findings point to the importance of considering multiple factors including economic, socio-political, environmental, and technical aspects, in determining effective and sustainable solutions. The comprehensive MCDM analysis presented here, contribute to a broader research area: examination of the complexities of the decision-making process.

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