

The role and challenges of clean energy technologies and embedded critical raw materials in the energy sustainability

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Abstract: Given the increasing pattern of sustainability challenges such as climate change, carbon footprint, biodiversity loss and its sensitivity to energy policies, developing a holistic perspective is essential to enhance the further integration of energy sustainability into environmental issues. As the green transition to energy sustainability, it requires mineral-intensive energy technologies. Mineral requirements are expected to increase at unprecedented rates and could bring about the supply risks. One of the fundamental strategies is including the critical raw materials (CRMs) as variables in the energy sustainability, as the dependencies on CRMs for clean energy technologies. To address the issues related to energy sustainability and raw materials, Hesitant Fuzzy AHP (HF-AHP) is used to assess the clean energy technologies related to raw materials with the simultaneous consideration of economic, environmental, technological, and social pillars of sustainability perspective. The results are compared with the Best-Worst Method (BWM) to validate the obtained solutions. Computational results reveal that technological and environmental metrics are evaluated as the most critical dimensions. Mineral intensity as a technological metric and emissions as an environmental dimension are the most important sub criteria to evaluate the energy technologies. In Türkiye, while the hydraulic energy has the highest share due to its installed capacity and accessibility, solar panels and wind turbines hold high promise to combat climate change, obtained results also address the EVs and battery storage technologies. Ultimately, this enables all stakeholders to understand that involving of raw materials into energy sustainability could guide the compatibility policies between raw materials and sustainability energy models.

1. Introduction

The Green Deal approach by European Union (EU) following the Paris Agreement (2015) presented a roadmap to combat the climate change. The UN sustainable development goals are also aims to reduce the climate crisis, emissions, and carbon footprints. The green initiatives, prioritizing energy sustainability, have led to the supply risk of CRMs used in renewable energy resources and energy storage systems. CRMs are of critical importance in zero carbon and green technologies, ecological balance and human welfare, which are important in the context of local policies and global goals. It is associated with the country's energy and development policies (Göçmen-Polat, 2024). The use of more sustainable energy sources for critical raw materials is considered one of the main ways to reduce emissions and achieve future goals. Sustainable energy sources including solar, hydrogen, wind, nuclear, hydroelectric, geothermal, biomass energy are known to have less environmental impact than fossil fuel-based energy production. The use of sustainable energy sources is an important step to reduce environmental impacts and achieve international goals (Martin et al., 2022). As the

global energy economy shifts toward sustainability, countries are racing for sustainable development through a mix of political and economic strategies (Cozzi et al., 2020). With the spread of sustainable energy sources, CRM demand is increasing, and these increases are closely related to green and digital development. Therefore, it is important to carefully monitor and manage the relationship between sustainability and technological change. According to the International Energy Agency, the clean energy sector's demand for minerals such as cobalt, natural graphite and lithium is expected to increase by twenty to forty times in the next twenty years (IEA, 2023). The goal of achieving net zero CO₂ emissions by 2050 will require a transformation from a fossil fuel-dominated economy to one led by renewable energy technologies. This transformation will increase the production and international trade of various raw materials. Renewable energy technologies generally require more intensive use of minerals. The green transition process will reduce the dependence on fossil fuels, while putting pressure on the production and international exchange of other raw materials. Therefore, the sustainable production and efficient use of raw materials will become a global priority and will require various strategies. In this process, the determination and implementation of global standards are also important. As a result, the sustainable production and efficient use of raw materials in the green economy transition process is critical to the transformation of the global economy to renewable energy technologies. Investing more in renewable energy sources nationwide, enhancing energy efficiency, and enacting policies to cut carbon emissions will support Turkey in adopting a sustainable energy strategy. Given the rising energy demands and the environmental damage caused by fossil fuels, it is essential for all countries, including Turkey, to shift towards renewable energy and implement measures to lower carbon emissions. This transition will eliminate reliance on environmentally damaging fossil fuels and foster the development of a sustainable energy policy. Figure 1 demonstrates the installed capacity values of renewable energy sources in Türkiye. Hydraulic sources have the highest share and wind turbines also have increased. With technological transformations, it is expected that the share of solar and wind energy in total capacity could increase in the long term.

Installed Renewable Capacity by Source (2006–2023)

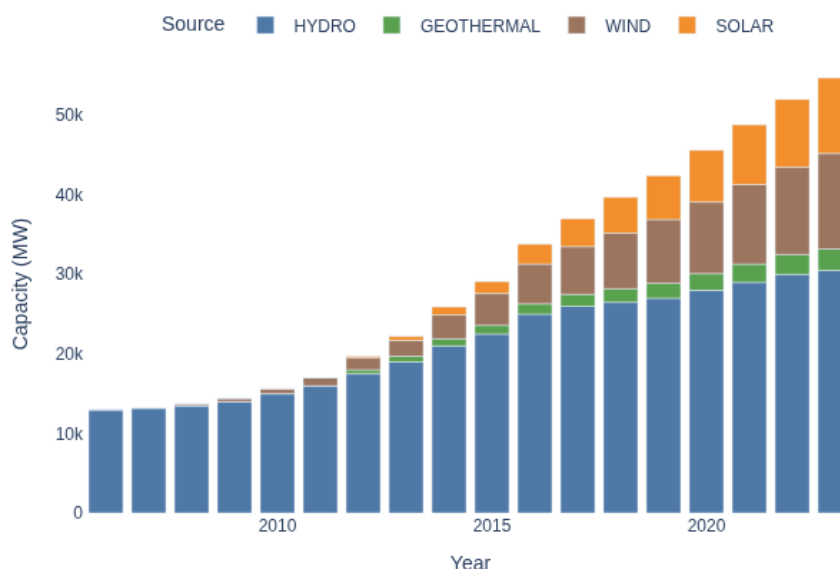


Figure 1. Installed capacity values of clean energy types in Türkiye (megawatt) (TEİAŞ, 2024)

To optimally determine the criticality of raw materials in energy sustainability and to reveal Turkey's potential in this field, it is necessary to address the issue with a system approach. Criticality analysis is mainly handled with the economic importance and supply risk. While the usage rates of raw materials in the manufacturing sector or high-tech

applications are examined, it is planned to include their use in energy sustainability in the methodology. In addition to physical dimensions, non-physical dimensions such as the existence of other sectors competing for the same strategic raw materials, new technologies expected in the coming years, politically unstable supplier countries should also be considered for evaluation studies (Ortego et al., 2020). With recent policy changes (Xie et al., 2023), it is crucial to assess raw materials considering the impacts of air and water pollution, climate change (Salvi et al., 2023), agriculture, biodiversity, and the principles of secondary production and the circular economy. In addition to the mentioned criteria, price, demand scenarios and socio-economic indicators and energy metrics could be included to the assessments. The rapid advancement of sustainable energy systems is crucial for protecting the environment, enhancing human health, and supporting the development of a circular economy. As reliance on CRMs grows in low-carbon technologies, it is essential to assess these materials within a comprehensive framework. Technologies such as wind turbines, solar panels, and electric vehicles play a vital role in low-carbon transitions, with green growth largely driven by these strategic raw materials. Consequently, the scarcity of these materials impacts energy sustainability and is significant for addressing climate change (Pommeret et al., 2022). Turkey has outlined policies and targets related to green growth and recognizes the crucial role of these strategic raw materials in its development plans. Given Turkey's increasing emphasis on renewable energy and green technologies, the demand-supply gap for these materials is anticipated to widen significantly. The novelty of this paper lies in its utilization of HF-AHP and BWM to holistically evaluate clean energy technologies by integrating CRMs into the energy sustainability assessment framework. This approach addresses the often-neglected reliance on raw materials and provides a multidimensional analysis including economic, environmental, technological, and social pillars. By emphasizing mineral intensity and emissions as critical sub-criteria, the paper offers a comprehensive evaluation of energy technologies while highlighting how CRM considerations can inform and align energy policies with sustainability goals. This advanced methodology and focus on CRM integration represent a significant advancement in assessing and guiding energy sustainability strategies.

1.1. Renewable energy systems for CRMs

Batteries for electric vehicles and energy storage highly use the lithium, solar batteries focus on high amounts of silicon, permanent magnet technologies used in wind turbines contain REEs. Some external factors limit the static operation of renewable energy systems and therefore cause the fluctuation of the resulting energy (Guo et al., 2018). Hybrid energy systems emerged due to the inability to obtain fixed and orderly from renewable energy systems over time. For instance, the use of solar energy in the evening is not possible, but it can be provided by combining energy sources such as wind energy and wave energy to obtain energy at other times of the day. García et al. (2013) discuss converting wind turbine and photovoltaic solar panels into a hydrogen and battery-based energy storage system. This system has the correct performance and better performance than the conventional energy management system for the hybrid system examined. Battery based energy storage systems require high amounts of the CRMs. Biomass energy is obtained by burning industrial waste, sewage waste, organic waste (animal waste, agricultural waste, domestic waste, etc.), etc. Biomass energy is one of the most focal energy sources used in developing countries and has a key role in industrial countries (Hall, 1991). Also, biomass energy has important potentials such as increasing energy security with low fossil fuel reserves and reducing net carbon emissions into the atmosphere per unit of energy obtained (Field et al., 2008). Solar energy is the oldest type of source and is the root of almost all fossil and renewable species (Azadeh et al., 2008). It is obtained by collecting the energy emitted by the solar panels and converting it into energy (Kabir et al., 2018). It is a superior renewable energy source in terms of usability, cost-effectiveness, accessibility, capacity, and

efficiency (Kannan and Vakeesan, 2016) and has a wide range of applications from small systems to large-scale power plants (Ferreira et al., 2018). Solar energy is critical to reduce greenhouse gas emissions and climate changes and most prominent source in Turkey due to the optimal location and solar radiation (Seker and Kahraman, 2021). New challenges have been conducted that combination of solar modules ensure the installation of high-power solar panels and solar power plants. Given this, solar technologies have contributed to the environmental science (Kwak et al., 2020). Geothermal energy is the energy source obtained by the underground heat that emerges in hot water, steam, and gas. Geothermal energy is environmentally friendly and countries without heat sources do not have geothermal energy potential (Nasruddin et al., 2016). Pipes, boilers, turbines and other equipment used in geothermal power plants are usually made of elements such as Iron, Copper, Aluminium. Elements such as lithium, potassium, magnesium are used during the processing and purification of geothermal waters. Geothermal energy has the potential for sustainable mineral extraction and energy production and draws a positive projection for the future of energy conversion and critical raw material management (Szanyi et al., 2023). Nickel, Iron, Scandium are used in the production of alloys with high strength, and these alloys can be used in turbines used in thermal power plants. In addition, elements such as Chromium and Cobalt are used in boilers and pipelines in thermal power plants due to their high temperature resistance. Turbines, dams, and other structural components used in hydroelectric power plants are usually made of steel. Copper and aluminium are often used in power plants, generator windings, and electrical conductors. China, which has mostly CRM reserves, is not effective for wind energy before the Renewable Energy Law. However, it has increased the installed capacity after this law (Yang et al., 2020).

In the European Commission's 2020 report, critical raw materials were classified according to supply risk and associated with their application areas (Figure 2). In this classification, it is noteworthy that REEs are the raw materials with the highest supply risk and are the most important components of wind turbines and electric motors.

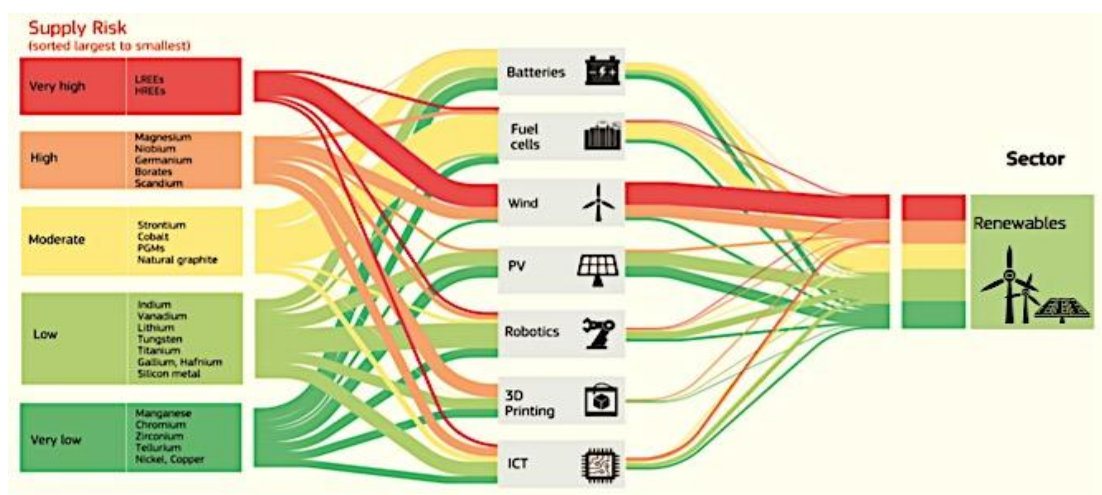


Figure 2. Materials relevant to the renewable energy sector (Bobba et al., 2020)

David and Koch (2019) focused on smart city energy field and the smart city-critical raw material-energy connection. The paper presented that CRMs are important materials for smart city applications such as energy production, energy distribution and energy allocation. Cristóbal et al. (2020) presented future projections of CRMs in the context of solar and wind energy shows that future demand for Tellurium, Indium and Selenium exceeds current reserves. Pommeret et al. (2022) presented the main metrics of energy transition and raw material dependence for this transition. In addition, political economy constraints on social acceptability, recycling technology were incorporated into the paper. Nate et al. (2021) presented the supply-demand scenarios of CRMs regarding energy technologies. Cobalt, graphite, and lithium were obtained as lowest material

availability. Lewicka et al. (2021) assessed the importance of CRM deposits for renewable energy technologies and assessed that wind turbine generators as most cost-efficient technology for clean energy production, requiring boron, dysprosium, niobium, neodymium and praseodymium. Platias et al. (2023) emphasized that high purity quartz critical raw material, which is a rare element formed under geological conditions with chemical and physical parameters can be applied in energy sectors such as photovoltaic solar cells. Peiró et al. (2022) developed approaches for incorporating material-specific life cycle assessments into energy system models to more accurately evaluate raw material needs and their environmental effects. Their case studies on wind turbines and solar photovoltaic panels highlight notable differences in global warming potential, energy demand, and supply risks across various technologies. Li and Iammarino (2024) investigated the role of domestic production of CRMs as a strategy to mitigate global supply chain risks and enhance local renewable energy development. Focusing on wind and solar energy sectors, the study assessed how domestic CRM supply capabilities impact the competitiveness of RE sectors and technological innovation. Karali and Shah (2022) explored how circular economy strategies can address the CRM supply challenges associated with scaling up low-carbon technologies to meet Paris Agreement climate goals. The findings indicate that while circular economy approaches could significantly contribute to CRM supply, improvements are needed in collection systems, recycling technologies, and product design to fully realize these benefits. Rabe et al. (2017) examined the European Union's reliance on Chinese supplies of five critical raw materials-tellurium, gallium, indium, neodymium, and dysprosium-that are essential for its solar and wind industries. The study, informed by expert interviews, reviewed China's industrial policies affecting these materials and assessed the EU's and the industries' short- and long-term strategies to address potential supply issues. Additionally, the study highlighted that the solar industry, with more supply options, faces fewer risks from supply bottlenecks and price volatility compared to the offshore wind sector. Jones et al. (2020) analysed the impact of mass EVs adoption on the demand for critical raw materials. It predicts substantial increases in demand for base metals, including a 37-fold rise in cobalt and an 18-fold rise in lithium compared to 2015 levels. The study also anticipates significant demand growth for copper, chrome, and aluminium. Song et al. (2019) created a critical raw material (CRM) evaluation model to analyse the supply risks and economic significance of materials essential for the Chinese lithium-ion battery sector. Their study employed dynamic materials flow analyses combined with a trade-linked model to assess material criticality and refine materials flow analysis. The findings revealed that a substantial share of the material flow for lithium, nickel, cobalt, and graphite is retained in active use stocks. In Türkiye, the role of the CRMs has not previously been widely investigated for the energy sustainability. Raw material criticality considering some environmental, economic, technical and social indicators such as supply risk, economic importance, biodiversity, price, human health is evaluated in Turkey (Polat et al., 2023). In addition, the challenges of the raw materials for the sustainable development goals (SDGs) are analysed through positive and negative impacts and the most important goals for the CRMs are obtained in this study (Polat, 2023). Sustainability metrics are also investigated by using Hesitant-fuzzy based decision-making method to evaluate the CRMs (Göçmen-Polat, 2024).

2. Materials and Methods

To tackle the challenges of energy sustainability and raw materials, HF-AHP is employed to evaluate clean energy technologies, integrating considerations of economic, environmental, technological, and social factors within a comprehensive sustainability framework. In this section, HF-AHP is introduced through steps and formulations. For energy sustainability, material-intensity clean technologies (Figure 3) are evaluated with the four main dimensions and sixteen sub dimensions, shown in Figure 4.

These material-intensity technologies and material relation are summarized in the following:

- **Solar PV:** Solar panels including silicon material are a very popular technology in Türkiye. Silicon, the main material for solar PVs, is the most abundant material, however, silver, tin, cadmium telluride, indium embedded in solar panels can pose a supply risk (Urbina, 2022). Perovskite solar cells and gallium arsenide technology could be adopted to combat these external and internal factors.

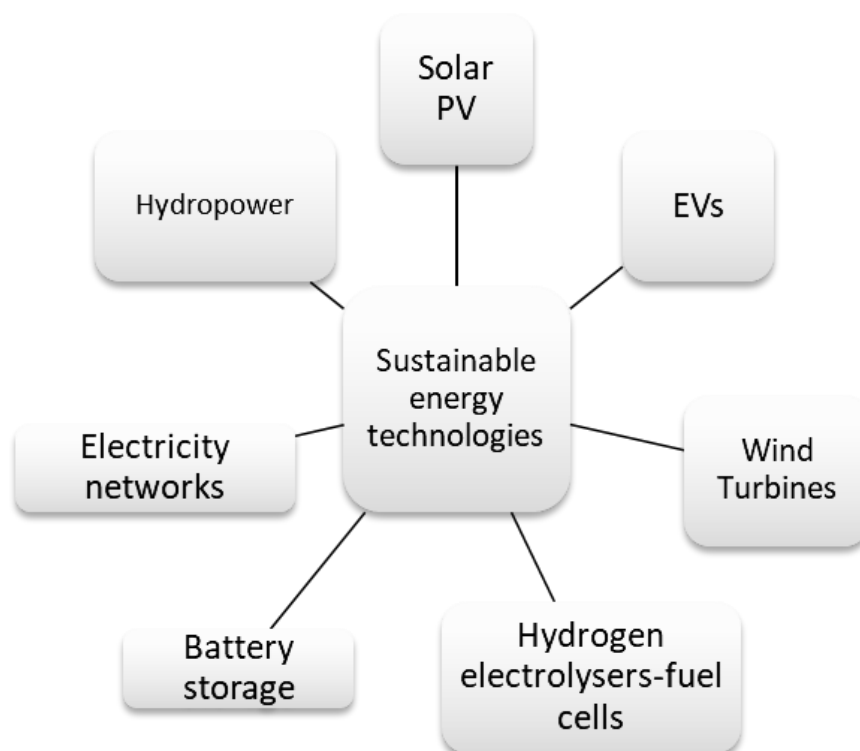


Figure 3. Material-intensity clean technologies

- **Wind Turbines:** EU wind industry struggles the supply risks of the raw materials such as REE since it is used both in the permanent magnets and EVs (Rabe et al., 2017). Neodymium, Dysprosium, Praseodymium, Terbium are used in permanent magnets of the wind turbine generator. The most appropriate CRMs for wind turbines are also listed as borate, gallium, germanium, indium and silicon metal (Lewicka, 2021). Constrained REE supply is important problem for all countries.

- **Electricity networks:** Electricity networks require copper and aluminium due to its characteristics with lower conductivity, corrosion resistance and strength for underground cables. Researchers have investigated the substitution relation of copper and aluminium, and they can imperfect or complementary substitutes. Aluminium production has increased and continue to growth in the next years, comparing to the copper production (Bartoš and Šanderová, 2022).

- **EVs:** Increasing demand of the CRMs for EVs could lead to lithium production up to six times and three times for cobalt (Maisel et al., 2023). The lithium-ion batteries used in EVs require high number of raw materials and result the supply chain risks. Circular economy strategies can reduce the primary extraction of cobalt (Baars et al., 2021). Some EVs companies prefer nickel as an option for cobalt due to the politically instable main supplier country (Varga and Fodor, 2019). Silicon-rich anode and all-solid-state batteries are future technologies for the EVs. In

addition, some countries have presented new pathways for EVs on a national scale, increasing trend of the lithium for the global market (Hache et al., 2019)

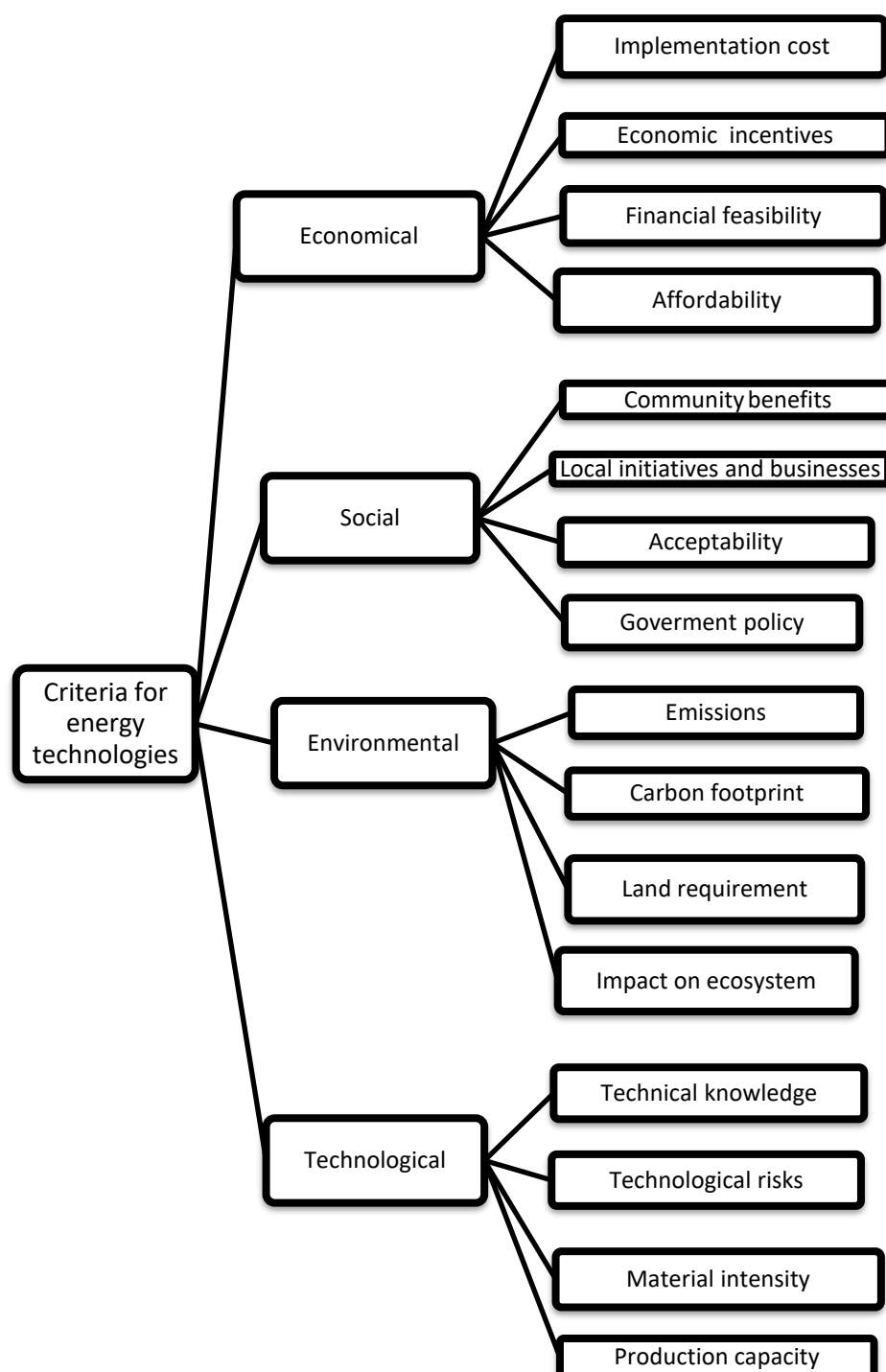


Figure 4. Main criteria and sub criteria for sustainable energy technologies

- **Battery storage:** The electricity storage through renewable energies and the energy required for EVs increases the importance of batteries. The technology used by batteries in electric vehicles or energy-storage is lithium-ion, which contains both lithium and cobalt. In addition to lithium-ion battery, new battery type named post-lithium-ion battery also requires a high raw material requirement. Wentker et

al. (2019) develop a methodology to assess the supply risk lithium-ion and post-lithium-ion battery technologies. Lithium-ion technologies, mostly based on lithium, manganese, nickel and cobalt, post-lithium-ion technologies based on lithium and sodium-based cathodes are evaluated in the study. Post-lithium-ion technologies mainly have lower supply risk than lithium-ion technologies. Home energy storage and vanadium flow batteries could be adopted as options.

Table 1. Definitions of criteria

Criteria	Sub criteria	Code	Description
Economical	Economic incentives	M1	Economic incentives include low interest, tax credits, etc. to ensure the adaptation of sustainable energy applications.
Economical	Implementation cost	M2	This includes building facilities, and energy processes, set up.
Economical	Financial feasibility	M3	This includes carbon credit and other financial instruments that support the energy sustainability.
Economical	Affordability	M4	Affordability involves balancing high initial capital costs with long-term economic benefits.
Social	Community benefits	M5	This can be achieved through educational programs that support sustainable energy practices.
Social	Local initiatives and businesses	M6	Supporting local initiatives and businesses can help build sustainable communities by promoting local production, creating local jobs.
Social	Acceptability	M7	Acceptability can be increased for the society through workshops, events, posters and advertisements.
Social	Government policy	M8	This involves creating regulations, incentives, and frameworks that support the equitable transition to clean energy.
Technological	Technical knowledge	M9	Advanced technologies can require professional experts and knowledge for the implementation.
Technological	Production capacity	M10	Capacity is essential to optimize energy management processes and increase efficiency in energy applications.
Technological	Technological risks	M11	Insufficient experienced or skilled labor available to develop the technologies.
Technological	Material intensity	M12	Materials embedded in energy technologies provide the demand and supply projections in the future.
Environmental	Emissions	M13	This refers to the pollutants released into the atmosphere associated with energy technologies to minimize these emissions compared to fossil fuels. creates a market for sustainable energy and encourages decision-makers to develop more sustainable practices.
Environmental	Carbon footprint	M14	This refers to the total greenhouse gas emissions associated with energy technologies to minimize these emissions compared to fossil fuels.
Environmental	Impact on ecosystem	M15	The disruption of the ecological balance and global warming is important to evaluate the technologies.
Environmental	Land requirement	M16	This refers to the amount of land needed for the installation and operation of energy systems. Rising shares of the energy technologies raise concerns over their land-use requirements.

- Hydrogen electrolyzers and fuel cells: In Türkiye, green hydrogen production potential is essential from the onshore and offshore wind power. Turkey can use its position in the hydrogen economy by using this renewable energy infrastructure for hydrogen energy production (Karayel et al., 2023). Increasing trend of hydrogen as an energy carrier has led to demand growth for nickel and zirconium for electrolyzers, and for platinum-group metals for fuel cells. Hydrogen electrolyzers are promising technologies for the usage of renewable and nuclear electricity applications. CRMs are essential for fuel cells, electrolyzers, and separation, storage of hydrogen and ensure sustainable and effective hydrogen energy systems (Eikeng et al., 2024). CRMs embedded in hydrogen technologies are investigated to highlight the hydrogen potential linked with the raw materials (Faye et al., 2022; Dutta, 2014).
- Hydropower: Hydropower technology requires lower raw material than other renewable sources. About 2% of the total demand of copper is considered for the hydropower (IEA, 2021). Hydropower turbines also require nickel material in the stainless steel, providing durability and sustainability.

2.1. HF-AHP

The HF-AHP method is a sophisticated approach that combines several advanced fuzzy decision-making techniques to determine the weights of various criteria in multi-criteria decision analysis. This method integrates Hesitant Fuzzy Sets (HFS), which allow for the consideration of uncertainty and hesitation in decision-making, Hesitant Fuzzy Linguistic Sets (HF-LS) for capturing linguistic terms, and the traditional Fuzzy AHP (F-AHP) method for pairwise comparisons. The steps of the HF-AHP method are detailed below:

Defining Linguistic Terms: A set of linguistic terms, denoted by $D = [D_0, D_1, \dots, D_M]$ are established to express qualitative judgments about the criteria. These linguistic terms represent different levels of importance or preference, such as "very low," "low," "medium," "high," and "very high," which will be used in the pairwise comparisons of criteria.

Binary Comparisons Using HF-LS: Pairwise comparisons are made between the dimensions or criteria using HF-LS. This allows the decision-makers to express their hesitation or uncertainty by providing a range of possible linguistic terms rather than a single crisp value. The hesitant fuzzy set allows flexibility in expressing the uncertainty associated with each comparison.

Generation of Data Envelopes: Data envelopes $env[d_{ij}]$ are generated for each pairwise comparison, which include the expressions for criterion i in dimension j . These envelopes hold the hesitant fuzzy linguistic values derived from the decision-makers' judgments.

Conversion to Triangular Fuzzy Numbers (TFNs): The linguistic expressions in the data envelopes are converted into TFNs. TFNs are widely used in fuzzy set theory to represent imprecise information. Each TFN is characterized by three parameters-lower, medium, and upper values-which reflect the range of possible values for each comparison.

Transformation to TFN Data Envelopes: The data envelopes $env[d_{ij}]$ are now transformed into envelopes that involve TFNs, ensuring that the hesitant fuzzy expressions are represented in a numeric form that is compatible with the fuzzy arithmetic operations used in later steps.

Mean of TFNs: For each data envelope, the mean of the TFNs is calculated. This step is essential to aggregate the fuzzy comparisons and prepare them for further analysis.

Geometric Mean for Each Criterion: For each criterion i , the geometric mean of the fuzzy comparisons is calculated as $r_i = (\sum_{j=1}^n d_{ij})^{1/n}$ $i = 1, 2, \dots, n$ where n represents the number of comparisons made for that criterion. This step summarizes the relative importance of each criterion based on the pairwise comparisons.

Fuzzy Weights Calculation: The fuzzy weights for each criterion are calculated using the geometric mean values. The weight of each criterion w_i expressed as a fuzzy number

$$w_i = r_i \otimes (r_1 \otimes r_2 \otimes \dots \otimes r_n)^{-1} = (lw_i, mw_i, uw_i) \text{ where:}$$

lw_i is the lower weight of the criterion,

mw_i is the medium weight (most likely value),

uw_i is the upper weight (maximum possible value).

This allows for a range of values to reflect the uncertainty in the importance of each criterion.

Clarification of Fuzzy Numbers: To simplify the fuzzy weights, they are clarified using the area center method. This method computes a single representative value for each criterion based on the lower, medium, and upper bounds of the fuzzy weights. The formula used is: $M_i = \frac{lw_i + mw_i + uw_i}{3}$ This process reduces the fuzzy weights to a single value while retaining the essence of the uncertainty captured by the triangular fuzzy numbers.

Normalization and Weight Calculation: Finally, the clarified weights are normalized to ensure that the sum of all criteria weights equals 1. The normalized weight for each criterion N_i is calculated using the formula: $N_i = \frac{M_i}{\sum_{i=1}^n M_i}$

Normalization ensures that the final weights are proportional and can be used for further analysis in decision-making.

2.2. BWM

The method used for criterion weighting is based on the idea of comparing two criteria. A total of $(2n-3)$ pairwise comparisons are made, where n is the number of criteria. This method was introduced into the literature in 2015 by Jafar Rezaei. The steps of the model are as follows (Rezaei, 2015):

Step 1: Selection and Definition of Criteria: Criteria are chosen through literature review, expert opinions, and other sources.

Step 2: Identifying Best and Worst Criteria: The best (most important) and worst (least important) criteria are selected based on the expert judgments.

Step 3. Preference Matrix for Best Criterion: A preference matrix is created, comparing the best criterion against all others using a numerical scale from 1 to 9. (Eq. 1). $A_b = (a_{1B}, a_{2B}, a_{3B}, \dots, a_{nB})$

Step 4. Preference Matrix for Worst Criterion: Similarly, a matrix is developed to compare all criteria against the worst criterion, again using a scale from 1 to 9. (Eq. 2). $A_w = (a_{1w}, a_{2w}, a_{3w}, \dots, a_{nw})$

Step 5. Calculation of Weights: The optimal weights for the criteria ($w_1^*, w_2^*, w_3^*, \dots, w_n^*$) are determined by solving an optimization model. The goal is to minimize the maximum deviation between comparisons of best and worst criteria to all others, ensuring consistency. (Eq. 3).

$$\text{Minmax}_j \{ |(w_B - a_{Bj} w_j)|, |(w_j - a_{jww})| \}$$

$$\text{s.t. } \sum_j w_j = 1$$

to find optimum weights ($w_1^*, w_2^*, w_3^*, \dots, w_n^*$) and optimum confidence level (ξ^*):

$$\text{Min } \xi$$

$$|w_B - a_{Bj} w_j| \leq \xi \text{ for all } j$$

$$|w_j - a_{jww}| \leq \xi \text{ for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0 \text{ for all } j$$

w_B and w_w represent the weights assigned to the best (most important) and worst (least important) criteria, respectively. a_{Bj} indicates how much more preferred the best criterion is compared to criterion a_{jw} reflects how much more preferred criterion j is compared to the worst criterion.

Step 6. Estimating the consistency ratio to verify the reliability of pairwise comparisons using Consistency ratio = ξ^*/CI

A consistency index (CI) as shown in Table 3 assists in determining the consistency ratio.

Table 2. CI values for BWM method

aBW	1	2	3	4	5	6	7	8	9
CI (max ξ^*)	0	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

HF-AHP handles hierarchical structures, making it effective for weighting multiple criteria and sub-criteria. BWM is designed to obtain highly consistent pairwise comparisons with fewer inputs. Using both HF-AHP and BWM provides a balanced, complementary approach. HF-AHP represents uncertainty thoroughly, and BWM ensures consistency and efficiency in expert evaluations. The outputs from each method can be compared that rankings are not method dependent. Results are compared because HF-AHP and BWM reflect two different strengths-hesitant judgments versus highly consistent judgments and comparing them verify whether the prioritization of criteria remains stable with different decision-making conditions.

3. Results

In this section, computational results of the HF-AHP and BMW methodologies are presented. Both methods present a comparison of local and global weights for various criteria under Economical, Social, Technological, and Environmental Metrics and sub criteria.

3.1. Results of the BWM

To evaluate the criteria used in the clean energy technologies with the BWM, expert opinions were first consulted. Experts were initially asked to identify the most important criterion and the least important criterion. Then, they were asked to evaluate how much more important the most important criterion is compared to the other criteria, and how much more important the other criteria are compared to the least important criterion, using a 1-9 evaluation scale. Since each expert's evaluation was quite lengthy, only the evaluation results of Expert 1 are shown in Table 3-4.

Table 3. The BWM vectors of the criteria

Strategies	Preferences for the Best Environmental	Preferences for the Worst Social
Economical	3	2
Social	4	1
Technological	2	3
Environmental	1	4

Table 4 shows the preferences for various metrics (Economical, Social, Technological, and Environmental) by comparing the best and worst criteria. For Economical Metrics, M1 and M2 are equally preferred as the best, while M3 and M4 are rated lower, with M4 being the least important. In Social Metrics, M6 and M7 are the best, and M5 and M8 are less preferred, with M5 as the least. For Technological Metrics, M11 and M12 are rated best, while M9 and M10 are rated worse, with M10 having the lowest preference. Lastly, in Environmental Metrics, M13 and M16 are seen as the best, while M14 and M15 are less important, with M15 as the least preferred.

After the evaluations for Expert 1, other three experts evaluated the criteria. The average of the four experts' evaluation results was taken to obtain the final criterion weights. Instead of using arithmetic mean, the geometric mean was preferred to

eliminate the extreme values. The criterion weights based on the geometric mean of each experts' evaluations and the average criterion weights are shown in Table 5.

Table 4. The BWM vectors of the sub-criteria

Economical Metrics	Preferences for the Best M1 and M2	Preferences for the Worst M3 and M4
M1	1	3
M2	1	4
M3	3	1
M4	4	1
Social Metrics	Preferences for the Best M6 and M7	Preferences for the Worst M5 and M8
M5	3	1
M6	1	3
M7	1	3
M8	3	1
Technological Metrics	Preferences for the Best M11 and M12	Preferences for the Worst M9 and M10
M9	3	1
M10	5	1
M11	1	5
M12	1	3
Environmental Metrics	Preferences for the Best M13 and M16	Preferences for the Worst M14 and M15
M13	1	3
M14	3	1
M15	3	1
M16	1	3

Table 5. Ranking of the BWM method

Criteria	Local Weights	Global Weights	Rank
Economical Metrics	0.092	-	4
M1	0.65	0.058	10
M2	0.125	0.013	14
M3	0.210	0.025	13
M4	0.225	0.035	12
Social Metrics	0.178	-	3
M5	0.458	0.1042	4
M6	0.125	0.0284	11
M7	0.125	0.0284	11
M8	0.2	0.0356	7
Technological Metrics	0.278	-	2
M9	0.417	0.1143	3
M10	0.125	0.0352	8
M11	0.122	0.0346	9
M12	0.458	0.1284	2
Environmental Metrics	0.387	-	1
M13	0.375	0.1457	1
M14	0.123	0.0472	5
M15	0.123	0.0472	5
M16	0.125	0.0483	6

Table 5 provides a ranking of various criteria, and their sub-criteria based on local weights and global weights. The Environmental Metrics is the highest-ranked criterion

with a local weight of 0.387, and M13 has the highest global weight of 0.1457, ranked 1st. Technological Metrics follows as the 2nd criterion with a local weight of 0.278, where M12 ranks 2nd with a global weight of 0.1284, and M9 is ranked 3rd with 0.1143. Social Metrics is ranked 3rd overall, with M5 being the top sub-criterion under this category, ranking 4th with a global weight of 0.1042. Economical Metrics, which is ranked 4th, has M1 as its best sub-criterion, ranked 10th with a global weight of 0.058. Other sub-criteria are ranked between 5th and 14th, showing the relative importance of each metric.

3.2. Results of the HF-AHP

Table 6. Fuzzy weights of each criterion

Dimension	w_i		
Economical	0.036	0.054	0.082
Social	0.110	0.155	0.220
Technological	0.013	0.018	0.027
Environmental	0.035	0.051	0.077

Step 9: Clarification of the fuzzy numbers with the area center method and Normalization of the clarified numbers and calculation of each criterion weight are presented in Table 7.

In both tables, Environmental Metrics is ranked the highest, with M13 being the top sub-criterion, but Table 5 assigns a higher global weight (0.1457) compared to Table 8 (0.045). Similarly, Technological Metrics ranks 2nd in both tables, with M12 as the leading sub-criterion, though the global weight is higher in Table 5 (0.1284) than in Table 8 (0.039). In Social Metrics, M5 is the highest ranked in Table 5, while M7 leads in Table 8. For Economical Metrics, M1 has the highest global weight in Table 5 (0.058), but M2 leads in Table 8 (0.007). Overall, while the sub-criteria rankings remain mostly consistent, Table 5 assigns generally higher global weights than Table 8, reflecting variations in the perceived importance of criteria across evaluations. These variations illustrate how HF-AHP and BWM capture expert judgments differently: HF-AHP tends to assign higher absolute weights, whereas BWM distributes importance more conservatively across criteria. Overall, although the ranking order of most sub-criteria remains consistent, the shifts in global weight reflect methodological differences between HF-AHP and BWM.

Table 7. De-fuzzified (M_i) and normalized (N_i) relative weights of criteria

Dimension	M_i	N_i
Economical	0.057	0.055
Social	0.162	0.156
Technological	0.019	0.218
Environmental	0.054	0.352

All weights of all dimensions and maturity items are demonstrated in Table 8. Total weights are obtained by multiplying the dimensions' weight and item weights.

Based on the application of the HF-AHP to evaluate clean energy technologies with respect to raw materials and energy sustainability, Solar Panels and Wind Turbines are the most important technologies from an environmental perspective, as they score highest under the dominant criteria of emissions. Likewise, EVs and battery storage emerge as top technologies under the technological dimension, driven by their high mineral intensity. The material intensity for the technologies is demonstrated in Figure 5. EVs and battery storage are the most material-intensity technologies. Thus, the most influential criteria and sub-criteria identify these four technologies as the leading options in the sustainability assessment. The following key results were obtained:

Solar Panels and Wind Turbines: Solar panels and wind turbines were identified as highly promising technologies for addressing climate change. They are deemed effective

in reducing greenhouse gas emissions and have considerable potential for future development and deployment in renewable energy strategies.

Mineral Intensity: This metric, reflecting the demand for CRMs required for technology deployment, was highlighted as a crucial factor in assessing the sustainability of energy technologies. High mineral intensity can pose supply risks and impact long-term feasibility.

Table 8. Item and total weights

Dimensions	Sub dimensions	Local Weights	Global Weights
Economical (0.055)	M1	(0.046)	(0.003)
	M2	(0.120)	(0.007)
	M3	(0.032)	(0.002)
	M4	(0.035)	(0.005)
Social (0.156)	M5	(0.097)	(0.006)
	M6	(0.128)	(0.003)
	M7	(0.235)	(0.009)
	M8	(0.032)	(0.004)
Technological (0.218)	M9	(0.069)	(0.001)
	M10	(0.214)	(0.004)
	M11	(0.105)	(0.002)
	M12	(0.036)	(0.039)
Environmental (0.352)	M13	(0.043)	(0.045)
	M14	(0.102)	(0.005)
	M15	(0.113)	(0.006)
	M16	(0.033)	(0.012)

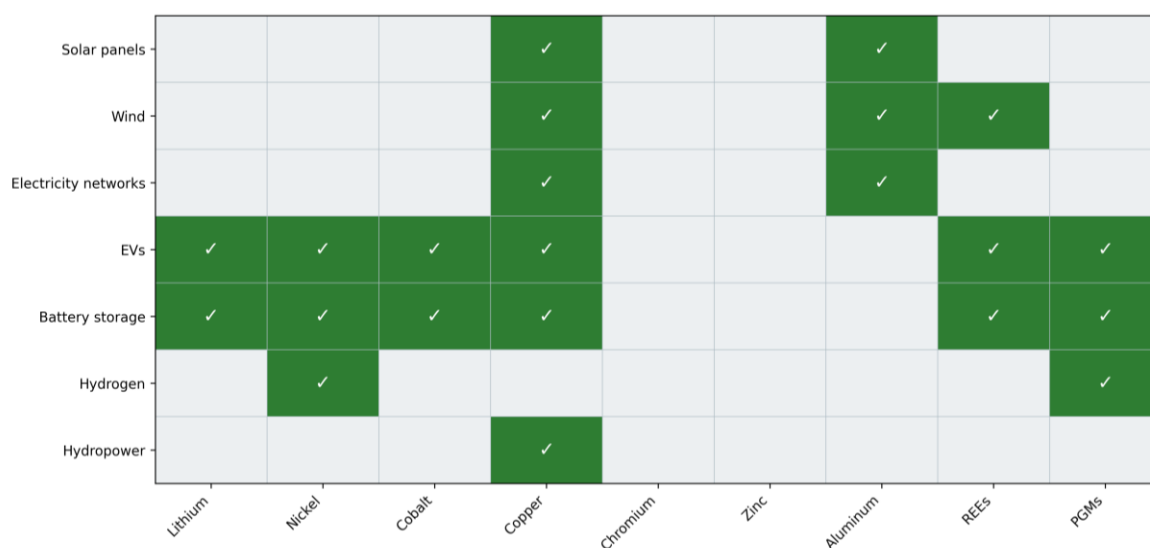


Figure 5. Material requirement of technology

Emissions: The environmental impact, particularly emissions generated during the lifecycle of energy technologies, was identified as another critical criterion. Reducing emissions is essential for minimizing the carbon footprint and achieving environmental sustainability goals.

Policy Guidance: Incorporating CRMs into the evaluation of energy sustainability helps to develop policies that balance raw material management with energy sustainability. This approach supports the creation of compatibility policies that ensure sustainable practices in both raw material extraction and energy technology deployment.

Installed Capacity and Accessibility: Hydraulic energy emerged as the most prominent technology, largely due to its high installed capacity and widespread

accessibility. This positions hydraulic energy as a leading option in the context of current energy systems and their capacity to provide substantial energy output.

4. Discussion

The increasing complexity of sustainability challenges such as climate change, carbon footprint and biodiversity loss necessitates a comprehensive approach to integrating energy sustainability. Green energy technologies increase the demand for minerals, which are critical for these technologies. The use HF-AHP evaluates the clean energy technologies in the context of raw material dependencies, considering multiple sustainability pillars-economic, environmental, technological, and social. The computational results highlight the importance of integrating raw materials into energy sustainability models. While solar panels and wind turbines are highly promising for addressing climate change, the findings also highlight the significant role of EVs and battery storage, particularly given their strong dependence on critical raw materials. The dependence on CRMs for these technologies focuses on the need for policies that ensure the sustainable management and supply of these materials. Addressing the supply risks associated with CRMs is vital to maintaining the viability of green technologies and achieving long-term sustainability goals. To enhance the security of silicon supply, crucial for Solar PV, there is an urgent need to manage the silicon supply chains, especially from mineral extraction to end-of-life management in Türkiye. The dependence on these materials, considering the emissions and carbon footprint, also could overshadow the SDG 7 and SDG 13 due to additional carbon emissions because of primary mining processes. Thus, the circular economic strategies such as reuse and recycling from the electronic waste could be preferred to obtain the CRMs to use in the energy technologies. Incorporating circular economy practices not only helps to alleviate the environmental burden of mining but also supports the transition towards more sustainable and closed-loop systems. By focusing on the recycling of electronic components, we can reduce the reliance on virgin materials, decrease carbon emissions from mining operations, and lessen the overall environmental impact of energy technologies. This approach aligns well with the principles of SDG 12 (Responsible Consumption and Production), as it promotes efficient use of resources and reduces waste.

The emphasis on mineral intensity as a technological metric and emissions as an environmental dimension reflects their critical roles in evaluating energy technologies. Mineral intensity determines the feasibility and sustainability of deploying energy technologies, given the finite and often geographically concentrated nature of CRMs. Meanwhile, emissions data offer insights into the environmental impacts of energy technologies, helping to assess their overall sustainability. Thus, a balanced approach that considers both the technological and environmental aspects is essential for effective decision-making. Involving raw materials in energy sustainability assessments helps stakeholders understand the interplay between material dependencies and sustainability objectives. By highlighting the importance of CRMs, this approach encourages the development of compatibility policies that align raw material management with sustainability goals. It also prompts a more comprehensive view of the sustainability landscape, integrating economic, environmental, technological, and social factors into policy formulation. In summary, the integration of CRMs into energy sustainability assessments is crucial for addressing the complexities of the green transition. By considering technological, environmental, economic, and social dimensions, stakeholders can develop more informed and effective policies that support sustainable energy development while managing raw material dependencies. Moreover, incorporating CRMs into sustainability assessments supports national and regional energy planning by revealing potential supply bottlenecks and resource vulnerabilities. This enables policymakers to align long-term energy strategies with secure and resilient material supply frameworks, ensuring that the transition to clean energy remains both feasible and sustainable.

5. Conclusions

Energy sustainability plays a key role in the move toward reducing carbon footprint. The trends of the energy sustainability have propelled unprecedented growth in the CRMs demand. Increasing electric car sales, energy storage systems, solar PV and wind power installations have led to a significant requirement for raw materials. This study guides the presentation of renewable energy technologies, allowing more sustainable energy utilizing a range of CRMs. Addressing the intricate relationship between energy sustainability and CRMs is crucial for advancing clean energy technologies. The use of HF-AHP and BWM has provided a comprehensive evaluation of these technologies across economic, environmental, technological, and social dimensions, highlighting the significant role of mineral intensity and emissions in assessing their viability. The findings indicate that while hydraulic energy shows considerable potential due to its established infrastructure, solar panels and wind turbines also offer substantial benefits in mitigating climate change. By integrating raw materials into the sustainability framework, stakeholders can develop more informed and effective policies that align raw material dependencies with sustainable energy goals, ultimately fostering a more resilient and environmentally friendly energy future.

While this study provides valuable insights into the relationship between energy sustainability and CRMs, several limitations must be acknowledged. One significant limitation is the variability and accuracy of the data used in the evaluation. The quality and availability of data on CRMs and renewable energy technologies can fluctuate, potentially affecting the reliability of the findings. Additionally, the dynamic nature of CRMs demand poses a challenge; as technological advancements and market conditions evolve, the study's findings might not fully capture these rapid changes and their implications for energy sustainability.

Another limitation is the scope of the technological assessment. Although the study covers a range of established renewable energy technologies, it may not include emerging technologies that could significantly influence future CRM demands and sustainability outcomes. Furthermore, the analysis may not fully account for regional differences in CRM availability, energy infrastructure, and environmental regulations, which can affect the relevance of the findings in various geographic contexts. Lastly, the methodologies used in the study rely on certain assumptions and subjective judgments, which could introduce biases and affect the accuracy of the sustainability assessment. Future directions can further enhance the integration of CRMs into energy sustainability frameworks and improve the advancement of clean energy technologies. Technologies such as advanced nuclear reactors, geothermal, and next-generation energy storage systems could significantly impact CRM demand and sustainability. Including these technologies in future evaluations will ensure a more holistic understanding of their implications for raw materials and energy sustainability. By pursuing these future directions, stakeholders can better align CRM dependencies with sustainable energy goals, ultimately advancing the development of resilient and environmentally friendly energy systems.

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