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A CAR-PROMETHEE-based multi-criteria decision-making framework for sustainability assessment of renewable energy technologies in Morocco

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Abstract
With the goal of becoming a regional leader in clean energy, Morocco has invested heavily in renewable energy mega-projects over the last decade, including the Noor-Ouarzazate complex, the largest concentrated solar power (CSP) plant in the world. To continue accelerating its energy transition and achieve renewable energy targets by 2030, Morocco should focus on small-, medium-, and large-scale projects. However, choosing the most sustainable renewable energy technology (RET) is a complex decision-making problem. This study proposes a novel hybrid multi-criteria decision-making framework for the sustainability assessment of RETs in Morocco. By evaluating the existing RETs (wind, CSP, solar PV, hydro, and biomass) in terms of environmental, economic, technical, and social criteria, the study aims to assist decision-makers in selecting the most sustainable option. The cardinal (CAR) method was used to elicit criteria weights, with economic (30.7% of weight) and environmental (29% of weight) criteria being prioritized. The PROMETHEE method was then used to rank the alternatives, with solar PV emerging as the most sustainable technology, followed by wind, hydro, CPS, and lastly biomass. It should be noted that the PROMETHEE I partial ranking indicated that wind and hydro were both ranked second in terms of sustainability, highlighting the need for careful consideration when choosing between these two options. The study also found that the rankings were similar using both linear and Gaussian preference functions with different thresholds.

Keywords Multi-criteria decision-making · Renewable energy technologies · Sustainability criteria · PROMETHEE method · Cardinal ranking

1 Introduction

Energy has become a crucial factor in maintaining a stable and growing economy in the current era of globalization. Studies have shown that the demand for energy in form of electricity has increased dramatically due to economic growth and urbanization (Rahman 2020; Villanthenkodath and Mahalik 2021). Unfortunately, the majority of the world's electricity is generated from fossil fuels (coal, natural gas, or oil), which has led to a significant rise in carbon emissions and a contributing factor to the unprecedented global warming over the last decade (Balsalobre-Lorente et al. 2018). In response to this, a growing number of nations around the world have set renewable energy targets to ensure universal access to affordable and sustainable energy while combating man-made climate change. According to the international renewable energy agency (IREA), the global energy sector is expected to transition completely from fossil-based to zero-carbon renewable energy technologies (RET) by the mid-century. The existing literature agrees that renewable energy can effectively address both energy security and climate change concerns (Vujanović et al. 2019).

Morocco, like many countries, relies heavily on foreign sources for its energy supply. To reduce this dependency, the Moroccan government has implemented the National Energy Strategy since 2009, which aims to generate 52% of its total electricity production from renewable sources by 2030 (MASEN, Moroccan Agency for Sustainable Energy 2022). This strategy has been supported by targeted legislative and institutional reforms and has been successful in making Morocco one of the most attractive markets for renewable energy. As a result, the dependence on foreign

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sources has decreased from 97.5% in 2009 to 90.51% in 2021 (MEME 2022). The nation currently possesses a diverse portfolio of renewable energy sources, including solar, wind, and hydro anchored in a legislative framework, especially Law No. 13 – 09 on renewable energies. The installed capacity of renewable energy sources, which accounts for about 37% of the electricity mix, has reached 3950 MW, including 750 MW from solar sources, 1430 MW from wind sources, and 1770 MW from hydroelectric sources (MEME 2022). The World Future Council believes that Morocco can achieve even greater success by utilizing its vast potential for renewable energy. This conviction has led to the development of a roadmap for 100% renewable energy in Morocco by 2050 (García and Leidreiter 2016).

From a sustainable development perspective, the goal of achieving a 52% renewable energy system by 2030 or 100% by 2050 should be approached through a strategic energy transition, prioritizing technologies that offer the optimal balance between energy security, environmental sustainability, and economic growth. This means that future investments should be directed towards a more inclusive, sustainable, affordable, and secure energy system that addresses national and global energy-related challenges while creating value for business and society without compromising the balance of the energy triangle (WEF, World Energy Forum 2020). It is well-established that renewable energy systems are more sustainable than conventional energy systems. However, to determine the level of sustainability, both qualitative and quantitative assessments are required to prioritize those with the highest degree of sustainability. A comprehensive sustainability assessment should consider at least the three dimensions of sustainability, namely the environmental, economic, and social dimensions (Purvis et al. 2019). This approach transforms the decision-making process into a multi-criteria decision making (MCDM) problem, where multiple factors are considered to make informed decisions. By considering multiple indicators from each dimension, a more holistic view of the sustainability of a technology can be obtained.

Over the past three decades, MCDM has become a widely used approach for solving real-life problems. When choosing between alternatives based on certain criteria, conflicting issues among the retained criteria should be considered. For example, when selecting a renewable energy alternative, reliability and implementation cost may be two conflicting criteria, as increasing reliability may result in an increase in implementation cost. The selection of a renewable energy alternative is indeed a complex MCDM problem that requires evaluating the advantages and disadvantages of different options based on selection criteria. These criteria make the evaluation process challenging and uncertain. In many decision-making problems, the judgments of the decision-maker (DM) are not crisp, and it can be difficult for the DM to provide precise numerical values for the criteria or attributes (Bohra and Anvari-Moghaddam 2022). This highlights the need for flexible decision-making tools that can accommodate the uncertainty and subjectivity involved in decision-making processes.

According to literature records, Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) has been shown to be efficient in a variety of applications, particularly in situations where there are multiple competing alternatives and multiple conflicting criteria (Bezerra et al. 2021; Corrente et al. 2021; Stanković et al. 2021; da Cunha et al. 2022). One of the key advantages of PROMETHEE is that it allows for the explicit representation and analysis of conflicting criteria, which is often a challenge in traditional MCDA methods. Additionally, PROMETHEE can handle both qualitative and quantitative criteria, and it allows for the incorporation of both preference and indifference thresholds (Tong et al. 2022). PROMETHEE also has the ability to handle both outranking and non-outranking relations between alternatives, which makes it more versatile than some other MCDM methods. It has a clear and transparent decision-making process that can be easily understood by decision-makers. Another advantage of PROMETHEE is that it can be easily combined with other supporting methods, such as the Analytic Hierarchy Process (AHP) (Neofytou et al. 2020; Mohammadi Seif Abad et al. 2021; Dadrasajirlou et al. 2023), to provide a more comprehensive decision-making process. Among thousands of published papers, papers related to PROMETHEE application in the “societal” field represent 57.7% (Mareschal 2022), including environment (Makan and Fadili 2020), energy (Angilella and Pappalardo 2021), water (Ghandi and Roozbahani 2020), public sector (Wati et al. 2018), and health (Miszczyńska 2020). Specifically, the applications of PROMETHEE in the renewable energy field have grown impressively over the last decade. Remarkably, most of these studies have combined PROMETHEE with other supporting methods. For instance, Özkale et al. (2017) selected a power plant running on renewable energy sources (RES) based on the combination of PROMETHEE and the SWOT (strengths, weaknesses, opportunities, and threats) analysis method. Wu et al. (2019) determined the optimal site for parabolic trough concentrating solar power plant applying Fuzzy PROMETHEE II approach combined with a triangular intuitionistic fuzzy generalized ordered weighted averaging (TIFGOWA) operator. Moreover, Chen et al. (2020) developed a multistage framework for choosing the suitable RES alternative by integrating picture linguistic fuzzy numbers (PLFNs), PROMETHEE, and prospect theory (PT). A new framework combining PROMETHEE II and the geographic information system (GIS) was proposed by Sotiropoulou and Vavatsikos (2021) to define the suitable onshore wind farms in Greece. A recent study introduced a novel PROMETHEE method based on the decision-making trial and evaluation laboratory

(DEMATEL) method to select renewable energies (Li et al. 2022). Despite the novel framework they provided, almost all of these studies have given less attention to the precision and robustness of the criteria weights.

Our literature review revealed a lack of research specifically investigating the sustainability assessment of RETs in Morocco using the PROMETHEE method. While a number of studies have employed this method in other countries (Troldborg et al. 2014; Li et al. 2020), there is currently a gap in the literature when it comes to its application in the Moroccan context. Additionally, the criteria used to evaluate the sustainability of RETs vary across studies, with a lack of agreement on the specific indicators to assess criteria such as environmental impact, economic feasibility, and social acceptability. To the best of our knowledge, no study has used PROMETHEE to monitor and evaluate the performance of renewable energy projects in Morocco. In this study, we propose a hybrid MCDM framework, based on the PROMETHEE and the Cardinal Ranking (CAR) methods, to assess RETs in terms of environmental, economic, technical, and social criteria. Herein, the CAR method was chosen to elicit weights because it surpasses its commonly used competitors, such as the simple multi-attribute rating technique (SMART) and AHP (Danielson and Ekenberg 2016; Makan et al. 2022). Moreover, the precision and robustness of the obtained weights are emphasized through the ranking of criteria by preference strength.

The current study has the potential to provide new insights into the use of the CAR-PROMETHEE framework for renewable energy assessment and inform decision-making in this area. It could also inform the development of policies and strategies to promote the deployment of renewable energy in Morocco, providing a comprehensive framework for assessing options based on various criteria and ranking them according to their sustainability. Additionally, the study could provide valuable information for managers and investors to make informed decisions about investing in RETs in Morocco, helping to set priorities, identify potential barriers and opportunities, and develop strategies to overcome the challenges. Overall, this study could make a valuable theoretical and practical contribution to the fields of MCDM, sustainability assessment, and evaluation of renewable energy projects in Morocco.

2 Methods

2.1 Evaluation criteria

Identifying the exhaustive evaluation criteria is a key step in resolving any complex MCDM problem since the inclusion of irrelevant criteria or the disregard of relevant ones can severely affect the final solution. To convey accurate results, this step was carefully undertaken through a comprehensive literature review. Only recent and relevant literature records were considered in this study. A search among published papers in the period of 2014–2021 and indexed in SCOPUS Database were run using the following keywords: ("Evaluation" OR "Assessing") AND "Renewable" AND "Energy" AND "MCDM". Thus, a total of 96 papers were found and reviewed. Table 1 shows the retained references after judicious screening, while Table 2 presents the frequency of citation as well as the categorization of different criteria under four dimensions of sustainability, i.e. environmental, economic, technical, and social. The most cited and most relevant criteria for the Moroccan context were maintained and described in Table 3.

2.2 Renewable energy technologies

Morocco is recognized as one of the most competitive countries in renewable energy potential worldwide, according to a study by Perner and Bothe (2018) and the Economic, Social and Environmental Council (Conseil Économique, Social et Environnemental). This potential is diverse, including hydropower, wind power, and solar power, and growing biomass energy. Given the renewable energy targets set by the country, several projects have already been implemented and are currently operational, while others are either ongoing or planned in the near future. The five main RETs that can be developed and implemented in Morocco are described below.

Wind turbines (WT) The design of large-scale wind turbines is optimized for maximum energy production, and they are typically composed of three main components: the rotor, the nacelle, and the tower. The rotor is the part of the turbine that captures the wind's energy and is made up of blades that are designed to rotate in response to the wind. The nacelle is the housing that contains the generator and other mechanical and electrical components. The tower is the structure that supports the nacelle and rotor, and it is typically made of steel or concrete. Wind turbines typically have a rotor diameter of around 100 m or more, and the blades are made of composite materials such as fiberglass or carbon fiber. These materials provide high strength and stiffness while being lightweight and durable. The rotor diameter and blade length are two key design parameters that determine the turbine's power output and efficiency (Kaushika et al. 2018).

Wind turbines are installed in wind farms, which are collections of wind turbines that are located in areas with high wind speeds. Wind farms can be onshore or offshore. In the latter case, the turbines are built on offshore platforms and are anchored to the seabed to withstand the harsh marine environment. The size of a wind farm can range from a few

Table 1 Retained references among published papers in the period of 2014–2021 after judicious screening

No	Reference	Citations	Applied methods	Objective of the study	Country
1	(Büyüközkan and Güleryüz 2017)	125	DEMATEL, ANP, TOPSIS	Evaluation of renewable energy resources	Turkey
2	(Ahmad and Tahar 2014)	491	AHP	Selection of renewable energy sources	Malaysia
3	(Saleem and Ulfat 2019)	7	AHP	Ranking of renewable energy technologies	Pakistan
4	(Tasri and Susilawati 2014)	180	Fuzzy AHP	Selection among renewable energy alternatives	Indonesia
5	(Büyüközkan et al. 2018)	94	AHP, COPRAS (COmplex PRoportional ASsessment)	Renewable energy selection	United Nations
6	(Yazdani et al. 2018)	55	DEMATEL, ANP	Evaluation and selection of renewable energy technologies	EU
7	(Troldborg et al. 2014)	254	PROMETHEE	Assessing the sustainability of renewable energy technologies	Scotland
8	(Şengül et al. 2015)	425	Fuzzy TOPSIS	Ranking renewable energy supply systems	Turkey
9	(Wu et al. 2018)	171	Triangular fuzzy numbers (TFNs) and AHP	Evaluation of renewable power sources	China
10	(Haddad at al. 2017)	163	AHP	Ranking of renewables for the electricity system	Algeria
11	(Wang et al. 2020)	163	SWOT-Fuzzy AHP	Renewable energy resources selection	Pakistan
12	(Ahmad et al. 2017)	52	AHP	Evaluation of renewable and nuclear resources for electricity generation	Kazakhstan
13	(Abdel-Basset et al. 2021)	26	AHP, VIKOR, TOPSIS	Evaluation of sustainable renewable energy systems	Egypt
14	(Sitorus and Brito-Parada 2020)	36	Integrated Constrained Fuzzy Shannon Entropy (IC-FSE)	Weighting the sustainability criteria of renewable energy technologies	UK
15	(Al Garni et al. 2016)	240	AHP	Evaluation of renewable power generation sources	Saudi Arabia
16	(Li et al. 2020)	48	ANP, WSM, TOPSIS, PROMETHEE, ELECTRE, VIKOR	Ranking of renewable energy	China
17	(Karakaş and Yıldıran 2019)	21	Modified Fuzzy AHP	Evaluation of renewable energy alternatives	Turkey
18	(Saraswat and Digalwar 2021)	28	Shannon's entropy, AHP	Evaluation of energy alternatives	India
19	(Ali et al. 2020)	24	AHP, CODAS (Combinative Distance-based Assessment)	Solving renewable energy technology selection problem	Bangladesh
20	(Yürek et al. 2021)	9	Pythagorean fuzzy sets (PFSs) in AHP-TOPSIS	Evaluation of the hybrid renewable energy sources	Turkey

turbines to several hundred turbines, depending on the location and the expected energy generation.

With an average wind speed of 11 m/s and approximately 3500 km of coastline, Morocco possesses a potential of about 25 GW of onshore wind power (Kousksou et al. 2015). In addition, the offshore wind potential is estimated at 250 GW, of which 6 GW could be installed by 2030 (Benazzouz et al. 2020).

Concentrated solar power (CSP) Different solar power plants are already built in the south of Morocco, and the on-going program for renewable energy aims to reach 13,575 MW of PVS and 2,000 MW of CSP by 2030 (MEME 2022).

In CSP technology, the sun's rays are concentrated on tubes filled with a heat transfer fluid. This technology uses flat (or quasi-planer) mirrors pivoting around a horizontal axis so as to follow the path of the Sun and thus redirect and concentrate the sun's rays towards an absorber tube. The cooling liquid (oil or molten salts) circulating in the tube is heated to a high temperature (over 700 °C) and sent to a steam generator. The steam then turns turbines that drive generators to produce electricity.

Photovoltaic solar (PVS) PVS technology converts sunlight into electricity within semiconductor materials such

Table 2 Frequency of citation and categorization of different criteria

Dimension	Criteria	Reference																				Frequency
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Environmental	Impact on ecosystem	x	x	x		x	x	x		x	x	x		x			x	x	x	x	x	14
	Human health impact						x												x			2
	Greenhouse gas emissions	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x		x	18
	Land requirement	x	x	x	x	x		x	x	x		x	x	x	x	x		x	x			15
	Water consumption														x							1
	Waste, odor, and particulates				x	x							x	x								4
Economic	Affordability of electricity		x			x				x		x				x				x		6
	Capital cost	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		19
	Operational life																		x		x	2
	O&M cost	x	x	x		x	x	x	x	x	x	x		x	x	x	x	x	x	x		17
	Payback period	x			x	x			x	x			x	x					x			8
	Market development					x				x				x								3
	Leveled energy cost																		x		x	2
Technical	Efficiency	x	x	x		x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	18
	Maturity	x	x			x		x	x	x	x	x		x		x	x		x	x		13
	Reliability	x		x	x		x	x	x	x	x		x				x		x	x	x	13
	Safety				x	x	x		x		x		x			x						7
	Local know-how and maintainability				x	x						x				x						4
	Implementation speed		x			x						x	x						x			5
	Distribution grid availability						x					x					x					3
Social	Social benefits	x				x		x	x	x	x					x			x	x		9
	Compliance with national agenda	x				x					x	x	x						x			6
	Social and political acceptance	x	x	x	x	x		x	x	x	x	x	x	x		x		x	x	x		16
	Job creation	x	x	x	x	x	x		x	x		x	x	x	x	x	x	x	x			16
	Visual, noise, and odor nuisances																			x		1

Table 3 Description of criteria

Dimension	Criteria	Description
Environmental	Impacts on ecosystem	Impacts are mainly related to water consumption, noise, visual effects, solid wastes, as well as ground contamination and effects on biodiversity.
	Greenhouse gas emissions	This parameter depicts how a power plant affects the environment and society through reduction in emissions and disturbance in ecological systems due to air pollution. It takes into consideration CO_2 reduction in particular, but also reflects impacts on ozone and global warming.
	Land requirement	The requirement for occupying land for plant installation varies depending on the RET for a given installed capacity. This criterion assesses the land requirements with regard to cost and area for implementing the technology.
Economic	Capital cost	Capital costs are important to the economic viability of energy supply projects and electricity generation. They include land and equipment costs, wages, installation, and infrastructure costs to construct a power plant.
	Operation & Maintenance cost	This criterion consists firstly of operation costs, which cover salaries in addition to expenditures on producing energy and providing services. Secondly, it consists of maintenance costs, which cover the expenditures on ensuring reliable plant operation and preventing failure.
	Payback period	The payback period is the length of time necessary to recover an investment. A shorter recovery period is obviously preferable to a longer recovery period.
Technical	Efficiency	A technology efficiency can be measured by how well it converts its primary energy source into electricity. The ideal efficiency is 100%; however, in reality, it is usually less due to losses. The efficiency reflects the ratio of output to input energy in order to show how effectively a particular technology can obtain electricity from a given energy source.
	Maturity	A technology is considered mature if it has been tested and used in real-world applications for a long enough period of time that it has overcome faults that may occur. The level of widespread availability of a technology is based on how widely it is used locally and internationally as well as its commercial availability.
	Reliability	Reliability is the ability of an energy system to fulfill the necessary functions under specified conditions for a specified period. Essentially, reliability is the probability of failure to occur.
	Safety	The level of safety in an energy system is a key indicator of the degree to which a particular RET causes human death. As a quantitative index, this describes the number of fatal incidents at power plants as a function of time, regardless of the stage of the plant's establishment or its operation.
Social	Social benefits	Energy systems can contribute to the improvement of the local society, especially in underdeveloped regions. Benefits for the local economy can include social welfare as well as local income.
	Social & political acceptance	This parameter qualitatively indicates the anticipated level of satisfaction of the public and politicians and their opinions toward each RET.
	Job creation	This criterion illustrates the potential for the creation of jobs associated with the creation of energy supply systems, from construction to decommissioning, including operations and maintenance.

as silicon. These photosensitive materials have the property of releasing their electrons under the influence of external energy. This is the photovoltaic effect. The energy is provided by photons that strike the electrons and release them, inducing an electric current. This direct current of micro-power calculated in peak watt (Wp) can be transformed into alternating current thanks to an inverter. The electricity produced is available as direct electricity, stored in batteries, or fed into the grid. The performance of a photovoltaic installation depends on the orientation of the solar panels and the sunshine zones in which they are located (Kaushika et al. 2018).

Hydropower (HP) With four perennial rivers and many hydroelectric dams, Morocco can generate a total of more than 5,000 GWh/year (Kousksou et al. 2015).

A hydroelectric power plant uses the force of water to generate electricity. Its principle consists of collecting water and forcing it to drive a turbine connected to a generator. For low gradients, a small dam directs a fraction of the flow to the turbines. For high gradients, pipes following the slope of the mountain bring the water to the turbines. Depending on the flow and the speed of the water flow, the turbine will be different. For low water heights with high flows (an alluvial plain river), vertical axis turbines of Kaplan or Francis type are used. For high falls and low flows (waterfalls or torrents diverted into penstocks), horizontal axis turbines of Pelton or Francis types give best results.

Biomass technology (BM) Recently, Dovichi Filho et al. (2021) assessed the maturity level of current biomass-based electricity generation technologies. They reported two possible routes of biomass conversion into gaseous or liquid energy carriers. The thermochemical conversion includes gasification, pyrolysis, and combustion, while the biochemical conversion comprises fermentation and anaerobic digestion. Gasification and pyrolysis are advanced technologies that have not yet been introduced in Morocco, and combustion is rather a heat generation-oriented technology. As for fermentation and anaerobic digestion, they are emerging technologies in Morocco and are mostly used for the cogeneration of heat and electricity. In the national roadmap for energy recovery from biomass, the Ministry of Energy, Mines, and the Environment estimates by 2030 a cogeneration potential of around 5.0 million MWh of electricity and 7.5 million MWh of heat (MEME, Ministry of Energy, Mining, and the Environment, Morocco 2021). It should be noted that in the case of combined production of heat and electricity, the electrical and thermal efficiencies are estimated at 35% and 40%, respectively.

2.3 Cardinal ranking method

The CAR method is a method that assigns different levels of importance to each criterion and then evaluates the performance of each option based on how well it meets each criterion. The performance of each option is represented by a vector of cardinal values, which are then transformed into a cardinal scale. This scale is used to compare the options and rank them based on their overall performance.

Let us assume that an ordinal ranking of N criteria already exists. If information about how much a criterion outranks or is outranked by other criteria can be made available, then the existing ordinal ranking can be extended into a cardinal ranking. A symbol $>_i$ is used to denote the preference strength (cardinality) between criteria, where $>_0$ is equally important '='; $>_1$ slightly more important; $>_2$ clearly more important; and $>_3$ much more important. The resulting ranking will be in this following form: $w_1 >_{i_1} w_2 >_{i_2} \ldots >_{i_{n-1}} w_n$. Then, the statements of the decision-makers can be converted into cardinal weights following the instructions of Danielson and Ekenberg (2016).

1. An ordinal number is assigned to each importance scale position, starting with the most important position as number 1.
2. Let $Q = \sum s_i + 1$, where $i = 1, \ldots, N-1$, be the total number of importance scale positions. Each criterion i has the position $p(i) \in \{1, \ldots, Q\}$ on this importance scale, such that for every two criteria c_i and c_j, whenever $c_i >_{s_i} c_j$, $s_i = |p(i) - p(j)|$. The position $p(i)$ then denotes the importance as stated by the decision-maker.
3. The cardinal weights w_i^{CAR} of a ranking can be obtained using Eq. (1).

$$w_i^{CAR} = \frac{\frac{1}{p(i)} + \frac{Q+1-p(i)}{Q}}{\sum_{j=1}^{N} \left(\frac{1}{p(j)} + \frac{Q+1-p(j)}{Q} \right)} \quad (1)$$

2.4 PROMETHEE method

This section summarizes the systematic approach followed to implement the PROMETHEE method according to Brans and Mareschal (2005) guidelines.

Step 1. *Pairwise comparison*
Compare pairs of alternatives for each criterion g_j. Recall that a discussion with the decision-makers should help to determine, for each g_j, a specific preference function P_j and a weight w_j, so that P_j can model the deviation between the alternatives for a given criterion j, and w_j represents the weight assigned to this criterion. Select P_j from the six proposed basic types that cover a wide range of practical situations: (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) linear criterion, and (6) Gaussian criterion (Ostovare and Shahraki 2019).
Step 2. *Preference index*
Calculate the aggregated preference index, π, for each pair of alternatives, i.e. the degree to which the alternative a is preferred over the alternative b.

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b).w_j \quad (2)$$

where $\pi(a,b) \approx 0$ implies a weak global preference of a over b, and $\pi(a,b) \approx 1$ implies a strong global preference of a over b.
Step 3. *Outranking flows*
Compare each alternative to the others, and then calculate the positive outranking flow φ^+ (strength of an alternative over all the others) and the negative outranking flow φ^- (weakness of an alternative over all the others) according to Eq. (3).

$$\begin{cases} \varphi^+(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a,x) \\ \varphi^-(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x,a) \end{cases} \quad (3)$$

where n denotes the number of alternatives and A is the set of alternatives.
Step 4. *Rankings*
The intersection of the positive and negative outranking flows will create the PROMETHEE I partial ranking, while the net outranking flow $\varphi(a) = \varphi^+(a) - \varphi^-(a)$ will create the PROMETHEE II complete ranking.

$$\begin{cases} aP^I b \iff \begin{cases} \varphi^+(a) > \varphi^+(b) \text{ and } \varphi^-(a) < \varphi^-(b), \text{or} \\ \varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(a) < \varphi^-(b), \text{or} \\ \varphi^+(a) > \varphi^+(b) \text{ and } \varphi^-(a) = \varphi^-(b); \end{cases} \\ aI^I b \iff \varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(a) = \varphi^-(b); \\ aR^I b \iff \begin{cases} \varphi^+(a) > \varphi^+(b) \text{ and } \varphi^-(a) > \varphi^-(b), \text{or} \\ \varphi^+(a) < \varphi^+(b) \text{ and } \varphi^-(a) < \varphi^-(b). \end{cases} \end{cases} \quad (4)$$

$$\begin{cases} aP^{II} b \iff \varphi(a) > \varphi(b) \\ aI^{II} b \iff \varphi(a) = \varphi(b) \end{cases} \quad (5)$$

where P^I, I^I, and R^I stand for preference, indifference and incomparability, respectively.

2.5 MCDM framework

The MCDM framework under which this study was conducted is displayed in Fig. 1. It consisted of a hybrid MCDM method combining PROMETHEE and CAR methods. In this framework, two surveys were initiated. The first survey aimed to prioritize the criteria based on preference strengths, while the second targeted the scoring of alternatives. Both surveys complied with the CAR method guidelines. Following a formal protocol, several national/international academic/professional experts were invited to participate in ranking criteria and alternatives. Fourteen of them provided their rankings according to the prepared questionnaires. The received rankings from Survey 1 and Survey 2 were converted respectively into cardinal weights (criteria) and cardinal scores (alternatives) using the CAR method. Subsequently, the PROMETHEE matrix was completed by setting convenient preference functions and thresholds. Finally, the Decision Lab software was executed, and the PROMETHEE I and II rankings were generated.

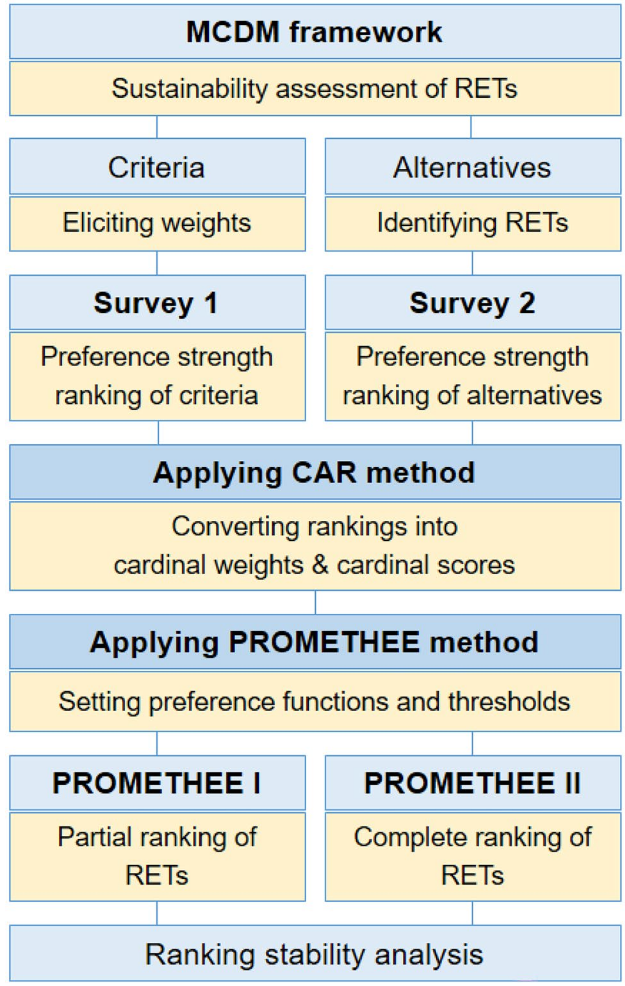

Fig. 1 MCDM framework adopted in this study

3 Results and discussion

3.1 Criteria prioritization

In the criteria prioritization step (Survey 1), each expert provided five rankings; one ranking of the sustainability dimensions and four rankings of the criteria within each dimension. The received rankings were then converted into numerical weights using Eq. (1). The final criteria weights (W_F) were obtained by multiplying the dimension weight (W_D) and the criterion weight in its dimension (W_C). Table 4 displays the final weights for all criteria. This step revealed that impact on ecosystem, greenhouse gas emissions, capital cost, O&M cost, and payback period are the top priority criteria to consider when assessing the sustainability of RETs. The lowest priority criteria were found to be efficiency, maturity, safety, social benefits, and political acceptance.

3.2 Performance of alternatives

Since the evaluation criteria involved both quantitative and qualitative criteria, the performance of the alternatives with regard to each criterion was determined differently. Performance against the quantitative criteria was established based on reported data, as shown in Table 5. Whereas, for the qualitative criteria, the invited experts were requested to rank the performance of the alternatives according to Survey 2. Subsequently, the obtained rankings were converted into numerical scores using Eq. (1). The detailed results are presented in Table 6.

3.3 Preference functions and thresholds

For comparison purposes, two preference functions were used to model pairwise deviations, namely linear and Gaussian functions. Each preference function requires the DM to set one or more specific thresholds. An indifference

Table 4 Dimension weights W_D, criteria weights W_C, and final weights W_F

Dimension	% W_D	Criteria	% W_C	% W_F
Environmental	29.0	En1: Impact on ecosystem	36.7	10.64
		En2: Greenhouse gas emissions	37.8	10.96
		En3: Land requirement	25.5	7.39
Economic	30.7	Ec1: Capital cost	35.8	10.99
		Ec2: Operation & Maintenance cost	34.2	10.50
		Ec3: Payback period	30.0	9.21
Technical	21.7	T1: Efficiency	21.7	4.71
		T2: Maturity	22.2	4.82
		T3: Reliability	28.7	6.23
		T4: Safety	27.4	5.95
Social	18.6	S1: Social benefits	30.2	5.62
		S2: Social & political acceptance	29.8	5.54
		S3: Job creation	40.0	7.44

threshold (Q) and a preference threshold (P) should be defined with the linear shape, while a single threshold (S) is required with the Gaussian shape (Behzadian et al. 2010). Herein, a rate of 10% of the deviation between the highest and lowest score (d_{max}) was used to determine the associated Q (Makan and Fadili 2020). For P, both higher and lower preference degrees were considered. Thus, rates of 30% and 70% of d_{max} were used to express higher preference degrees (P1) and lower preference degrees (P2), respectively (Ostovare and Shahraki 2019; Makan and Fadili 2021). Similarly, for the Gaussian thresholds, S1 corresponding to weak preference degrees was set to 50% of d_{max}, while S2 reflecting strong preference degrees was taken as the standard deviation of the scores (Oberschmidt et al. 2010; Phillis et al. 2021).

3.4 PROMETHEE analysis

The main PROMETHEE analysis consisted in calculating the outranking flows using the linear preference function and the P1 threshold. On the one hand, the positive and negative flows allowed to generate the PROMETHEE I partial ranking shown in Fig. 2a. It is clear that solar PV technology is ranked as the most sustainable RET because of its highest φ^+ (0.52) and lowest φ^- (0.14). Conversely, biomass technology is ranked as the least sustainable RET due to its lowest φ^+ (0.16) and highest φ^- (0.67). Moreover, two clusters of technologies emerged in this partial ranking. The first cluster comprises wind turbine and hydropower technologies, while the second cluster contains only CSP technology. Both clusters are ranked in the second position of sustainability due to incomparability conditions (Eq. 4). It should be noted that within the first cluster, the wind turbine slightly outperforms the hydropower in terms of φ^+, but they have the same φ^-. On the other hand, the PROMETHEE II complete ranking was generated based on the net outranking flow, as depicted in Fig. 3a. This ranking allowed to overcome the incomparability encountered in partial ranking. It revealed that wind turbine is more sustainable than hydropower, which in turn is more sustainable than CSP technology. The overall ranking of RETs in terms of sustainability can be presented as follows, from the most to the least sustainable technology: Solar PV, wind, hydro, CPS, and lastly biomass. Note that the net outranking flows for wind, hydro, and CSP technologies are pretty close to each other,

Table 5 Performance of alternatives with regard to quantitative criteria

	En2	En3	Ec1	Ec2	T1	S3
Unit	gCO_2eq/kWh	m^2/kW	USD/MWh	USD/MWh	%	person yr/MW
Reference	(Troldborg et al. 2014)	(Troldborg et al. 2014)	(Rutovitz and Atherton 2009)	(Rutovitz and Atherton 2009)	(Rutovitz and Atherton 2009; MEME 2022)	(Rutovitz and Atherton 2009)
WT	15	200	48.5	13.2	40.0	10.5
PVS	60	150	70.7	9.9	20.0	73.5
CSP	40	40	186.6	43.3	25.0	32.0
HP	20	500	57.5	8.5	11.2	15.5
BM	100	4000	44.9	14.9	83.0	45.5

Table 6 Performance of alternatives with regard to qualitative criteria

	En1	Ec3	T2	T3	T4	S1	S2
WT	19.27	23.77	21.41	19.05	18.29	17.11	17.84
PVS	22.79	24.68	21.13	20.94	25.19	24.88	29.25
CSP	24.34	19.23	20.08	20.24	22.64	22.20	21.91
HP	20.91	16.76	22.21	23.41	18.59	20.00	17.63
BM	12.69	15.55	15.17	16.36	15.28	15.80	13.37

which translates into one alternative being good on a set of criteria on which the others are weak and vice versa. This is in fact the reason for the incomparability in PROMETHEE I, which is prudent and would not decide which action is best.

Using the linear preference function but this time with lower preference degrees (P2), the complete and partial rankings were the same, and they were identical to the complete ranking obtained with P1. It is clear from Fig. 2b that the partial ranking did not result in any incomparability. This finding suggests that by decreasing preference degrees, a partial ranking will always converge toward a complete ranking. The same result is observed with the Gaussian preference function and S1 threshold, as displayed in Fig. 2c. Nevertheless, by changing the Gaussian threshold to S2, one incomparability appeared in the partial ranking, which involved the second position of sustainability (Fig. 2d). As shown in Fig. 3d, wind and hydropower technologies have almost the same net outranking flow, but their φ^{+} and φ^{-} do not verify the comparability conditions in Eq. (4). They were both ranked as the most sustainable after solar PV and before CSP (Fig. 2d).

In a recent study in Egypt, Abdel-Basset et al. (2021) reported a ranking inconsistent with that found in this study, although they also prioritized environmental and economic dimensions. They claimed that CSP was more sustainable than PVS using a hybrid MCDM approach. This may be due to the small number of experts (only 3 experts) involved in

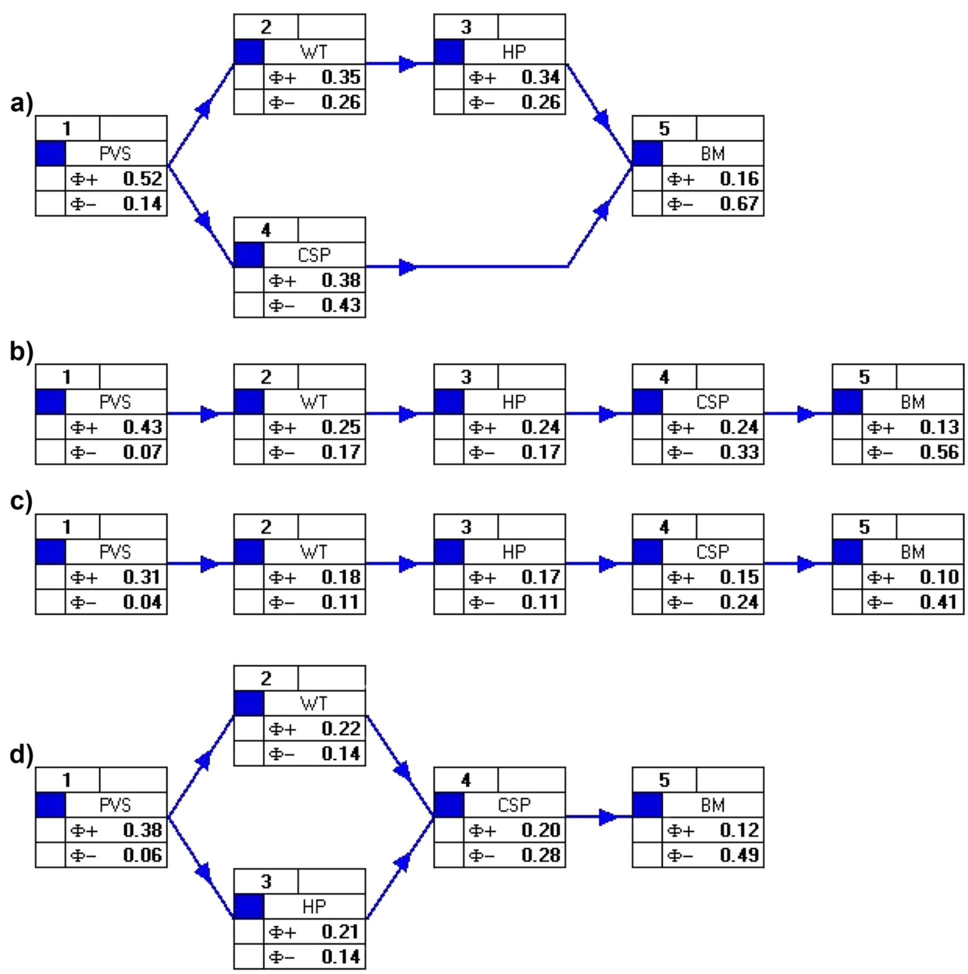

Fig. 2 PROMETHEE I partial ranking of RETs using: **a** linear preference function and P1 threshold, **b** linear preference function and P2 threshold, **c** Gaussian function and S1 threshold, **d** Gaussian function and S2 threshold

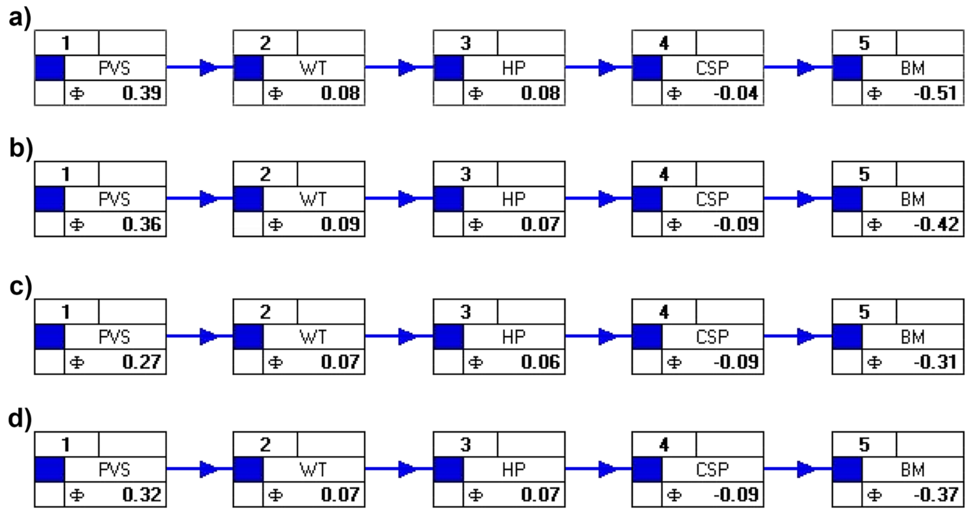

Fig. 3 PROMETHEE II complete ranking of RETs using: **a** linear preference function and P1 threshold, **b** linear preference function and P2 threshold, **c** Gaussian function and S1 threshold, **d** Gaussian function and S2 threshold

the decision-making process, which made their judgment not accurately representative. On the other hand, studies in Turkey reported conflicting findings. One study believed that the hydropower is the best alternative for Turkey (Şengül et al. 2015), while a second recommended the geothermal-based power (Büyüközkan and Güleryüz 2017). However, the most recent study determined a ranking in perfect agreement with that of this study. It ranked the renewable energy alternatives as solar, wind, geothermal, hydropower, and biomass in descending order (Karakaş and Yıldıran 2019). Excluding hybrid technologies from their ranking, Yürek et al. (2021) provided an almost identical ranking. In the Algerian context, solar and wind were ranked first and second sustainable energies, respectively. Even if the type of solar energy was not specified, this ranking can be considered consistent with that in the Moroccan context. The geographical location of Saudi Arabia, which is not open to the ocean, and the limited speed of wind (3.1–4.8 m/s) made wind energy rank third after solar PV and CSP (Al Garni et al. 2016). In contrast, the geographical position of Morocco and its Sahara are favorable for both solar and wind technologies.

In similar contexts as Morocco, studies in different countries have produced almost the same results. Although their rankings may show some changes, solar energy and wind energy were found to be the most sustainable RETs in most studies. Since the final ranking is largely related to the selected criteria and their allocated weights, one might wonder whether a change in weights would affect the final ranking. To address this question, stability intervals of different criteria weights not compromising the obtained ranking were determined. Table 7 presents the stability intervals for the non-compromised first-ranked alternatives. For the first action, It can be revealed that the weight stability intervals of all criteria are wider than [0, 30%], indicating that any change in criteria weights within this interval will not affect

Table 7 Stability intervals for not compromising the ranking

	Weight (%)	First action		Two first actions		Three first actions		Whole ranking	
		Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)	Min (%)	Max (%)
En1	0.00	10.64	67.25	0.00	12.12	0.00	12.12	0.00	12.12
En2	10.96	0.00	30.19	4.76	29.39	4.76	29.39	4.76	29.39
En3	7.39	0.00	95.85	0.00	87.28	0.00	76.97	0.00	76.97
Ec1	10.99	0.00	60.29	4.53	60.29	4.53	60.29	4.53	33.62
Ec2	10.50	0.00	79.06	0.00	12.66	1.93	12.66	1.93	12.66
Ec3	9.21	0.00	100.00	8.91	100.00	8.91	23.84	8.91	23.84
T1	4.71	0.00	33.69	4.24	33.69	4.24	26.64	4.24	26.64
T2	4.82	0.00	50.17	0.00	6.70	0.00	6.70	0.00	6.70
T3	6.23	0.00	32.56	0.00	6.57	0.00	6.57	0.00	6.57
T4	5.95	0.00	100.00	0.00	18.75	0.00	18.33	0.00	18.33
S1	5.62	0.00	100.00	0.00	6.22	0.00	6.22	0.00	6.22
S2	5.54	0.00	100.00	0.00	21.48	0.00	20.32	0.00	20.32
S3	7.44	0.00	100.00	0.00	15.88	0.00	15.88	0.00	15.88

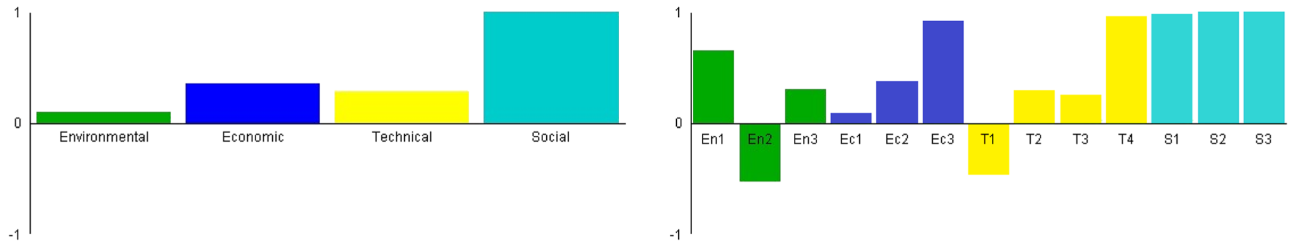

Fig. 4 Effect of individual criteria and sustainability dimensions on solar PV performances

the first-ranked alternative (PVS). However, a weight change outside of this interval, e.g., a change in En2 weight from 10.96 to more than 30.20%, will affect the final ranking of RET. This finding is better than that previously reported by Makan et al. (2022) who obtained stable weights within an interval of [0, 18.84%]. This confirms the robustness and high precision of the CAR method in eliciting weights. When assessing RESs using ANP and PROMETHEE method, Li et al. (2020) reported similar results. In fact, they found that the ordering of alternatives remained unchanged even by changing the criteria weights up to ±50%. On the other hand, the two first actions may be affected if changing the weights of some criteria outside tighter stability intervals. For instance, a change in En1 weight from 10.64 to more than 12.2% or in T3 weight from 6.23 to more 6.6% will compromise the two first-ranked alternatives. As the intervals are tighter, the PVS first position cannot be compromised, but the second position will be. Consequently, hydropower technology will rank second, and wind turbines will rank third. This is due to the fact that they have almost similar net outranking flows and are incomparable by PROMETHEE I. Besides, the stability intervals for the three first actions are almost identical to those for the two first actions. It can be noted that the stability intervals of criteria weights without compromising the whole ranking remained almost unchanged.

Figures 4, 5, 6, 7 and 8 show how individual criteria and sustainability dimensions affect the RET performances. For instance, despite the negative effect of greenhouse gas emissions (E2) and efficiency (T1) on PVS performances, the overall effects of all sustainability dimensions remained positive, allowing it to rank the highest in terms of sustainability. This is supported by the findings of Wu et al. (2018) who concluded that the integration of photovoltaic technology into the power sector reduces greenhouse gas emissions, and that its efficiency has improved over time. On the other hand, Haddad et al. (2017) found that the high capital cost of photovoltaic systems may hinder their widespread adoption, which aligns with the negative effect of capital cost (Ec1) on the PVS performances.

For the WT, the study found that all environmental criteria, except for the impact on ecosystem (En1), positively affected its performance, and their overall effect was still in favor of its sustainability (Fig. 4). All economic criteria positively affected the WT performances. However, all social criteria acted against its sustainability. The technical dimension presented no overall sustainability response toward the WT performances, as T1 and T2 affected it positively, while T3 and T4 impacted it negatively (Fig. 5). The literature supports this, with studies such as Büyüközkan et al. (2018) finding that WT has a low impact on the environment and is considered a highly sustainable source of energy. In Pakistan, Saleem and Ulfat (2019) reported that social and political acceptance (S2) is a major challenge to the widespread adoption of wind energy. Additionally, Troldborg et al. (2014) concluded that WT is technically mature, but its reliability (T3) and safety (T4) are still areas of concern.

The environmental and technical dimensions were in favor of the HP performances. However, the HP sustainability was hindered by social perceptions. The overall effect of the economic dimension was almost negligible, with moderately positive Ec1 and Ec2 effects and extremely negative Ec3 effect (Fig. 6). This is supported by the findings

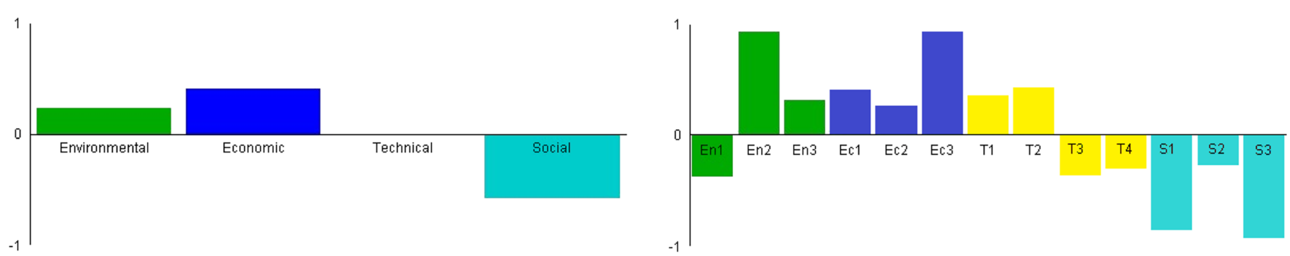

Fig. 5 Effect of individual criteria and sustainability dimensions on wind turbine performances

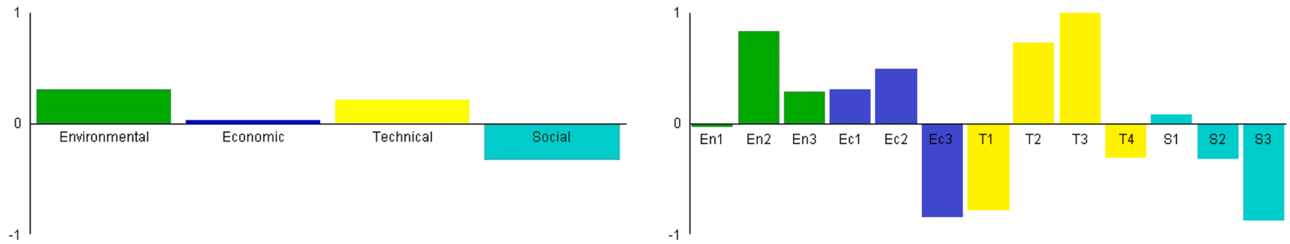

Fig. 6 Effect of individual criteria and sustainability dimensions on hydropower performances

of Şengül et al. (2015), who concluded that HP is environmentally friendly and technically efficient. According to Saraswat and Digalwar (2021), social acceptance (S2) is a challenge to the widespread adoption of HP. Moreover, Ali et al. (2020) concluded that hydropower projects can be economically viable, but the high capital cost (Ec1) and long payback period (Ec3) are areas of concern.

For the CSP technology, it is found that the overall effect of all dimensions, except for the economic dimension, supported its sustainability (Fig. 7). This aligns with the findings of Abdel-Basset et al. (2021), who concluded that CSP technology is environmentally friendly and technologically advanced. However, the study also found that the negative individual effects of efficiency (T1) and maturity (T2) decreased the overall positive effect of the technical dimension. Again, this is supported by the findings of Sitorus and Brito-Parada (2020), who reported that the efficiency and maturity of CSP technology need to be improved for widespread adoption.

For the least sustainable technology (BM), the overall effects of all dimensions were against its sustainability despite the positive effect of Ec1, Ec2, T1, and S3 (Fig. 8). This may be due to the fact that the BM technology is newly introduced in Morocco and has not yet been mastered at all levels. Besides, it is not yet mature and has not been widely accepted socially (Wang et al. 2020).

Overall, the CSP and HP can be considered environmentally friendly technologies since they generate fewer environmental impacts. This finding is consistent with Wu et al. (2018) stating that the CSP was inclined towards environmental criteria. The WT followed by PVS are economically the most preferred RETs because they provide shorter payback period. Again, this result is in agreement with Wu et al. (2018), who found that solar PV ranks first in economical criteria. Even though the PVS technology exhibits lower efficiency, it is technically the most preferable due to its maturity, reliability, and high level of safety. The result obtained by Saleem and Ulfat (2019) is in line with this study, affirming that solar energy has become more technically mature. It is also shown that the PVS is socially the most preferable and acceptable RET followed by CSP.

It was revealed also from this study that talking about hydropower sustainability may seem a bit controversial since this technology is primarily dependent on the water potential in the country, which has become limited due to the continuous periods of drought and precipitation fluctuations observed in recent decades. These constraints may indeed constitute hindering factors for the expansion of this technology. On the other hand, to compete for sustainability, biomass technology still needs more progress in terms of technical processes, professional skills, and maturity. Finally, and parallel to what other countries have achieved in the field of renewable energy, it should be noted that technologies based on other renewable energy sources, such as geothermal energy, offshore wind energy, and wave energy, are worth exploring in Morocco.

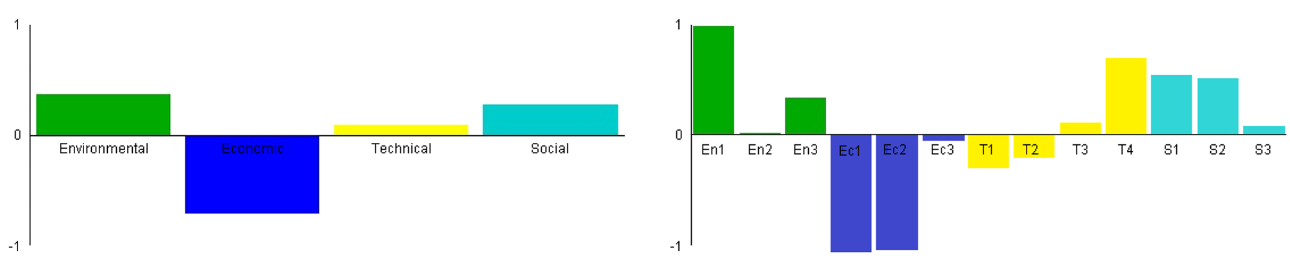

Fig. 7 Effect of individual criteria and sustainability dimensions on concentrated solar power performances

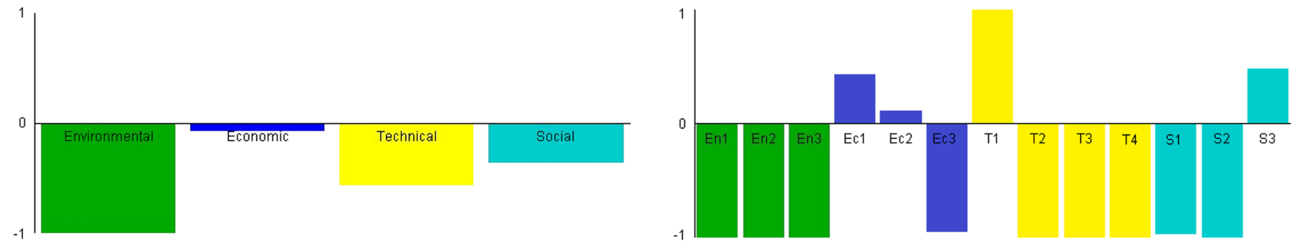

Fig. 8 Effect of individual criteria and sustainability dimensions on biomass performances

4 Conclusion

The study provides valuable insights into the sustainability of renewable energy technologies (RETs) using a novel CAR-PROMETHEE-based multi-criteria decision-making framework. The criteria prioritization step highlights the importance of considering a range of factors when assessing the sustainability of RETs, including impact on ecosystem, greenhouse gas emissions, capital cost, O&M cost, and payback period. The results of the PROMETHEE analysis, which showed that solar PV technology is ranked as the most sustainable RET and biomass technology is ranked as the least sustainable RET, are consistent with current trends in the industry, where solar PV and wind energy are rapidly growing in popularity, while biomass and CSP are less common.

It is important to note that the study has some limitations, for instance, the PROMETHEE method is based on pairwise comparison, which may not fully capture the complexity of sustainability assessment. Furthermore, the results of the study are based on the criteria and weighting chosen by the authors, so different results may be obtained if different criteria or weighting were used.

Additionally, the study's knowledge cut off is in 2021, since then the renewable energy industry has been rapidly evolving, with the cost of renewable energy decreasing, the deployment of renewable energy increasing, and new technologies emerging. Therefore, it is important to keep in mind that the findings of the study may not reflect the current state of the renewable energy industry.

Despite these limitations, the study provides a useful framework for assessing the sustainability of RETs, and the results can help decision-makers identify the most sustainable options for investment. The framework can also be used as a monitoring and evaluating tool for the renewable energy projects in Morocco. It would be interesting to see further studies that apply this method to a broader range of RETs and that consider more recent data and technologies.

Declarations

Conflicts of interest The authors have no relevant financial or non-financial interests to disclose. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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