Assessment of Renewable Energy Technologies Based on Multicriteria Decision Making Methods (MCDM): Ocean Energy Case

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Abstract. Renewable energy technologies in OECD countries have been highly promoted for the purpose of producing cleaner energy and better life conditions for people in urban areas. However, developing countries require an additional extended analysis to assess the feasibility for their implementation, identify financial risks and settle emissions reduction. In Colombia, in the last several years, there have been more robust public policy strategies to expand alternative energy sources and accomplish the COP 21 limits of 20% GHG reduction before 2030. In this study, a methodology based on Multicriteria Decision Making Methods (MCDM), which is the result of a research project to assess comparatively new renewable energy technologies with renewable energy technologies currently used in the country based on technical, financial, and environmental criteria, has been developed. The methodology allows for the identification of the best and the worst alternatives from the output ranking, considering the numerical value of criteria placed on the decision matrix and the dominance index output. The methodology was tested to assess the comparison of ocean energy technologies in Colombia. Tidal range was identified as the best alternative and ocean current the worst, among the projects evaluated.

Keywords: Multicriteria Decision Making Methods · Ocean energy · Renewable energy

1 Introduction

Globally, in the last decade, a continuous interest in cleaner, cheaper, and scaled up renewable energy alternatives for electricity generation has taken place, considering that an accelerated demographic growth has boosted fossil fuels consumption and affected air quality [1]. The key is to guarantee the quality of life of people and restrain the negative environmental impact of fossil fuels exploitation by promoting matured renewable energy technologies [2].

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To improve energy security programs, OECD countries have been exploring multiple alternatives for the sustainable exploitation of renewable energy sources, such as biomass, hydro, solar, wind, geothermal, ocean current, waves, thermal gradients, salinity gradients, seismic or vibrational, waste and green hydrogen [3]. Through technology and innovation, these kinds of energy sources have been promoted and exploited. In 2018, renewable energy technologies supplied about 26% of the global electricity production [4]. According to REN 21, renewable energy contributing to the final energy consumption supply increased 4% annually between 2013 and 2018, about 7,3 EJ. Among them, 48% of the sources exploited were solar and wind, by photovoltaic cells and wind turbine technologies, respectively [5].

Developing countries are highly dependent on fossil fuels. This dependence requires a thorough analysis to assess the feasibility of the implementation of renewable energy sources using decision making methods which allow to choose the best technological alternatives by identifying financial risks and emissions reduction. In Colombia, 68% of electricity consumption is supplied by hydroelectricity, 31% is supplied by natural gas and coal, and 1% is supplied by renewable energy sources such as solar and wind in the northern region. Considering current issues in Colombia, such as constant high rates of demographic growth, financial challenges, and its environmental commitments of COP 21 in Paris, it is necessary to find strategies for the development of scenarios to expand alternative energy sources. In order to accomplish said goals, the Mining and Energy Planning Unit (UPME) proposed a promotion program for renewable energy technologies with a goal of supplying 17% of the total energy consumption by 2030 [6, 7]. Exploiting renewable energy technologies such as solar photovoltaics, wind turbines, and new renewable energy technologies not included in Law 1715 of 2014, such as ocean energy, vibrational energy, and green hydrogen, could be a way to accomplish that goal.

This study shows a methodology that identifies the feasibility of renewable energy projects by considering technical, financial, and environmental indexes and selects the best alternative among a set of renewable energy technologies by Multicriteria Decision Making Methods (MCDM). Using this methodology, it is possible to compare power generation projects considering technical, financial, and environmental criteria, such as power capacity, technological readiness, investment costs, capacity factor, the reduction of GHG emissions, and Levelized Cost of Energy (LCOE). The methodology was applied to conduct a comparative assessment of ocean energy technologies with solar and wind projects in Colombia in order to establish parameters for developing energy transition strategies aiming toward cleaner energy sources. This kind of comparative theoretical assessment considering ocean energy technologies has yet to be developed in Colombia. Unlike similar traditional methodologies for conducting the assessment of renewable energy technologies for a region by MCDM, this proposed methodology was designed considering the simultaneous computation of three MCDM. In order to validate the results, the integration of technical, financial and environmental indexes was considered so as to adjust the numerical value of criteria in the decision matrix. A complementary algorithm was attached to the main code of the MCDM developed in Python to conduct a financial and performance analysis. This characteristic allows for the establishment of competitiveness thresholds based on the new values of criteria that are being computed.

2 Energy Sources

In the world, energy sources are classified as renewable energy sources and nonrenewable energy sources, according to their availability and the available technologies to exploit them. Renewable energy sources, also known as nonconventional energy sources, have unlimited potential, as these resources are the result of the transformation of solar radiation or the gravitational attraction among planets. In contrast, industrialized countries are highly dependent on nonrenewable resources, also known as conventional energy sources, such as coal, oil and natural gas. According to TRL, nonconventional energy sources such as solar, wind, biomass, and ocean energy, as opposed to conventional energy sources, generally are exploited by non-well-developed technologies at big scales and have low participation in the energy matrix [8]. Likewise, energy sources can be classified on primary and secondary sources. Primary energy sources are obtained directly from nature such as fossil fuels, solar, wind, geothermal and biomass and secondary energy sources, also known as energy vectors(such us hydrogen), are used for storage and transportation of energy [9].

The energy matrix of OCED countries, such as Iceland and Norway, is composed by a high percentage of renewable energy sources, due to the fact these countries have identified, in the last decade, the urgency for developing energy transition strategies aiming toward cleaner energy sources due to climate change issues. Nevertheless, the participation of coal, oil and natural gas continues to be extremely high in most countries. So, the necessity for better, wider, and more effective strategies to reduce the gross annual contaminant and GHG emissions have been identified.

In Colombia, Law 1715 of 2014 defines which energy sources are considered nonconventional. The objective of this law is the promotion of flows of capital on renewable energy projects, which guarantee financial development and environmental sustainability. This law establishes that in Colombia these kinds of resources must be sustainable and must not be widely commercialized and used for large-scale power generation. Nuclear energy, biomass, geothermal, small-scale hydro facilities, wind, solar, and ocean energy are considered nonconventional and are covered by incentives and grants [10]. Today, the Mining and Energy Planning Unit (UPME) of Colombia must identify and evaluate nonconventional energy sources that were not mentioned in the law to include them, if necessary. However, the inclusion of these energy sources necessitates financial and sustainable development, which allow for the guarantee of energy security and energy supplies in all regions. So, the condition that nonconventional energy technologies must be matured and commercialized widely abroad has been identified.

Among the energy sources mentioned by the Law 1715 of 2014 in Colombia, thermal gradients, salinity gradients, waves, tidal and ocean currents have not yet been considered through financed projects despite the existence of their energy potential. On the other hand, geothermal and nuclear energy are sources highly promoted by industrialized countries, but in Colombia the financial, technological, and optimal conditions for their scaled-up implementation have not been established. To classify the best non-conventional energy technologies available for Colombia, the Technology Readiness Levels (TRL), a classification scale of technologies designed by NASA, were considered. Though hydrogen is generally exploited by fuel cells used in power generation, buildings and light duty vehicle applications with TRL 5 to TRL 9, it was identified that the direct comparison with primary energy sources such as solar and wind is not an optimal standard [11, 12]. Unlike fuel cells, vibrational energy technologies were not considered in the assessment due to its TRL 4, an emerging readiness level [13, 14]. This classification is shown in Fig. 1.

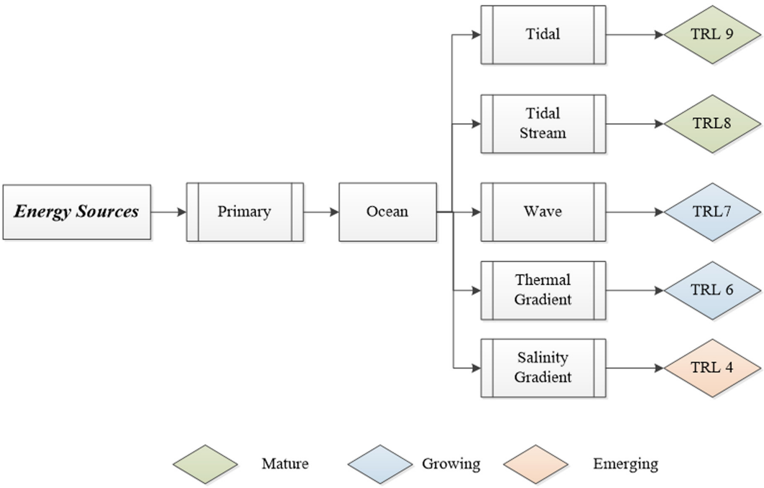

Fig. 1. Technology Readiness Levels (TRL) for ocean energy technologies.

In Colombia, geothermal energy is being evaluated by researchers, and the possibility to initialize its promotion, financing, and research is being considered. However, similar efforts have not been identified for ocean energy, despite it being an energy source with potential in the northern and western regions of Colombia, which could be exploited by technologies with high TRL levels, as presented in Fig. 1. For these reasons, ocean energy technologies considering waves, tidal, and ocean currents were chosen to conduct the assessment [15, 16].

3 Multicriteria Decision Making Methods (MCDM)

According to Ilbahar E, Cebi S y Kahraman C, the Multicriteria Decision Making Methods often used for the evaluation of renewable energy technologies include: *Analytical Hierarchy Process* (AHP), *ELimination Et Choix Traduisant la REalité* (ELECTRE) and *Technique for the Order of Preference by Similarity to Ideal Solution* (TOPSIS). Using these methods, it is possible to set alternatives and integrated strategies for electricity generation, identify optimal locations for infrastructure, and choose the best technological option.

Considering that MCDM can be classified into three groups, Elementary Methods, Unique Criteria Synthesis Methods, and Overcoming Methods, it is necessary to identify which group and which method contain the best characteristics for conducting the evaluation of renewable energy technologies in Colombia. Elementary methods, such as Dominance, *Weighted Sum Model* (WSM), *Weighted Product Model* (WPM), and Weighted Aggregates Sum Product Assessment– WASPAS – are characterized as low-complexity algorithms. Unique Criteria Synthesis methods, such as *Analytic Hierarchy Process* (AHP), *Technique for the Order of Preference by Similarity to Ideal Solution* (TOPSIS), and *VIšekriterijumsko KOmpromisno Rangiranje* (VIKOR) are characterized as medium-complexity algorithms by which it is possible to find optimal and non-optimal solutions. Overcoming methods, such us *Preference Ranking Organization METHod for Enrichment Evaluation* (PROMETHEE) and *ELimination Et Choix Traduisant la REalité* (ELECTRE), are characterized as being algorithms from which it is possible to establish dominance relations among alternatives [17–20].

Using a comparative analysis that considers characteristics such as Ranking, Attribute, and Criteria Weight Calculation, it is possible to select the most appropriate method for the evaluation.

- Ranking: capacity of the algorithm to determine the order of importance among the alternatives by an index which is computed.
- Attribute: capacity of the algorithm to assign the quality positive/negative, desirable/undesirable, or benefit/cost of the criteria. Positive attribute allows criteria to enhance the value of the alternative as much as its value increase. Power capacity and gross annual GHG emission reduction rate are considered positive criteria. On the other hand, Capital Cost Expenditure (CAPEX) and the Levelized Cost of Energy (LCOE) are considered negative criteria.
- Weight: by this criterion, it is possible to assign a dominance value among the selected criteria. Some methods include its computation within the algorithm. This value defines the relative importance among criteria.

In Table 1, the main characteristics of the MCDM considered as criteria for the selection are presented.

Table 1. Characteristics of MCDM algorithms.

MCDM		Ranking	Attribute	Weight
Elementary	Dominance	No	No	Yes
	WSM	Yes	No	Yes
	WPM	Yes	No	Yes
Unique criteria Synthesis	AHP	Yes	No	No
	TOPSIS	Yes	Yes	Yes
	VIKOR	Yes	Yes	Yes
Overcoming	ELECTRE	No	No	Yes
	PROMETHEE I	No	Yes	Yes
	PROMETHEE II	Yes	Yes	Yes

From Table 1, it is observed that TOPSIS, VIKOR and PROMETHEE II contain the capacity of making ranking for the alternatives. These require the definition of attribute for each weight, and the calculation of weights were conducted by an external algorithm, opening the possibility for objective weights. In this study, TOPSIS, VIKOR and PROMETHEE II are computed simultaneously by a code elaborated in Python in order to validate the output ranking. It was found that the assessment could be complemented by the computation of PROMETHEE I, from which an analysis of dominance for the alternatives was conducted.

3.1 Definition of Decision Matrix and Computation of Initial Weights

The calculation of weight w_j can be divided into subjective weight and objective weight. Subjective weight is mainly determined by an expert opinion based on experiences and subjective judgements. In contrast, objective weight is directly drawn from the real data of the alternatives in the decision matrix. An objective method, such as Shannon's entropy, reduces the impact of decision making and increases objectivity [21]. According to the entropy theory, the lower the entropy value, the more the information can be provided. A criterion can be assigned a greater weight if the difference among its values for each alternative is wider. A small numerical difference among values of a criterion for each alternative means a lower probability of obtaining information, higher entropy, and lower weight. The sum of weights must be equal to 1. The computation of Shannon's entropy weight is computed as follows:

a. Assuming m alternatives $(A_1, A_2, \ldots, A_m)$ and n criteria $(C_1, C_2, \ldots, C_n)$, the initial decision matrix is A, as presented in Eq. (1).

$$A = \begin{bmatrix} a_{11} & a_{12} & & a_{1n} \\ . & . & \cdots & . \\ . & . & \ddots & . \\ . & . & \cdots & . \\ a_{n1} & a_{n2} & & a_{mn} \end{bmatrix} = \left[a_{ij}\right]_{mxn} \tag{1}$$

where its elements a_{ij} denote i the alternative of j th criterion.

b. Normalize the decision matrix, where its elements $\hat{r}_{ij}$ are defined as presented in Eq. (2).

$$\hat{r}_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}}, i = 1, 2, \ldots, m \tag{2}$$

c. Compute entropy as presented in Eq. (3).

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} \hat{r}_{ij} \text{ In } \hat{r}_{ij}, j = 1, 2, \ldots, n \tag{3}$$

d. Calculate the weight of each criterion as presented in Eq. (4).

$$w_j = \frac{1 - e_j}{\sum_{i=1}^{n} \left(1 - e_j\right)}, j = 1, 2, \ldots, n \tag{4}$$

4 Methodology

The methodology proposed, aligning with the Colombia energy market, should contain the following characteristics [7]:

a) A tool that supports the development of public policy.
b) The ability to conduct a comparative assessment of the renewable energy technologies considering technical, financial, and environmental criteria simultaneously.
c) The ability to assess multiple scenarios associated with variations of energy markets.

In this study, a methodology for the evaluation of renewable energy technologies in Colombia is proposed. This methodology has been validated by the Mining and Energy Planning Unit (UPME) of Colombia. Figure 2 presents the detailed and schematic diagram of the methodology. This proposal consists of three phases being conducted in the following sequence: a) Mapping the problem, b) Performance assessment and c) Multicriteria Decision Making Method (MCDM).

In Phase I, the evaluation case is defined, and the technical, financial, environmental, social and/or sociopolitical criteria are selected considering which criteria are most used for the assessment of renewable energy technologies. The criteria is selected by the AHP method which considers the judgement of experts from private and public sectors. The scenarios are established, and the assignation of attribute for criteria is conducted.

In Phase II, the financial and technical parameters for each project are defined, such as the electricity exported to grid, electricity export revenue, debt, and equity. Moreover, there are defined financial indexes, such as the Net Present Value (NPV), the Benefit-Cost Ratio (BCR), the Annual Life Cycle Savings (ALCS), the Simple Payback Period (SPP), the Equity Payback (EP), and the Levelized Cost of Energy (LCOE). Additionally, environmental indexes related to GHG such as the Gross Annual GHG emission reduction (GHG_{gr}) are assessed. Based on these indexes a feasibility assessment is conducted.

Note that these indicators are highly dependent on the sales price of energy, *"Annual Rate"*. In other words, there is a guarantee that the projects for this initial simulation are financially viable, given that the sales price of energy for the solar and wind project was calculated at 100 USD/MWh, and the ocean wave, tide, and currents project were calculated at 300 USD/MWh/ 200 USD/MWh, and 600 USD/MWh, respectively. The assumption is that the price at which each project can sell energy is within a reasonable range, which allows them to be competitive within the national energy market. However, despite the fact the levelized cost of energy (LCOE) might appear attractive when compared with estimated typical mean values for a specific technology, it may not be the case due to differences in the order of magnitude in the sales price of energy.

In phase III the comparative assessment of renewable energy technologies for the evaluation case and scenarios is conducted. The weights of criteria are computed by a method based on the calculation of Shannon Entropy. So, by the application of the Multicriteria Decision Making Methods (MCDM), the best and the worst alternatives from the output ranking are identified. Finally, the criteria which cause more variability on decision making by a sensitivity analysis based on the evaluation of scenarios are identified.

Note that criteria used in the MCMD to evaluate alternatives are as follows: Technological Readiness – TRL, Power Capacity – PC, Investment costs – IC, Levelized Cost of Energy – LCOE, and Emission Reduction – ER. Previously, in Phase II, financial indicators with which it is possible to execute an analysis of the financial performance of the projects are used. This allows for the identification of the specific sales price value of energy that guarantees the alternatives that are evaluated in the method.

On the other hand, even though some of the selected criteria to execute the evaluation are interdependent, like LCOE, the capacity factor, and CAPE Diverse studies that have selected these interdependent criteria did not assign importance to this dependence.

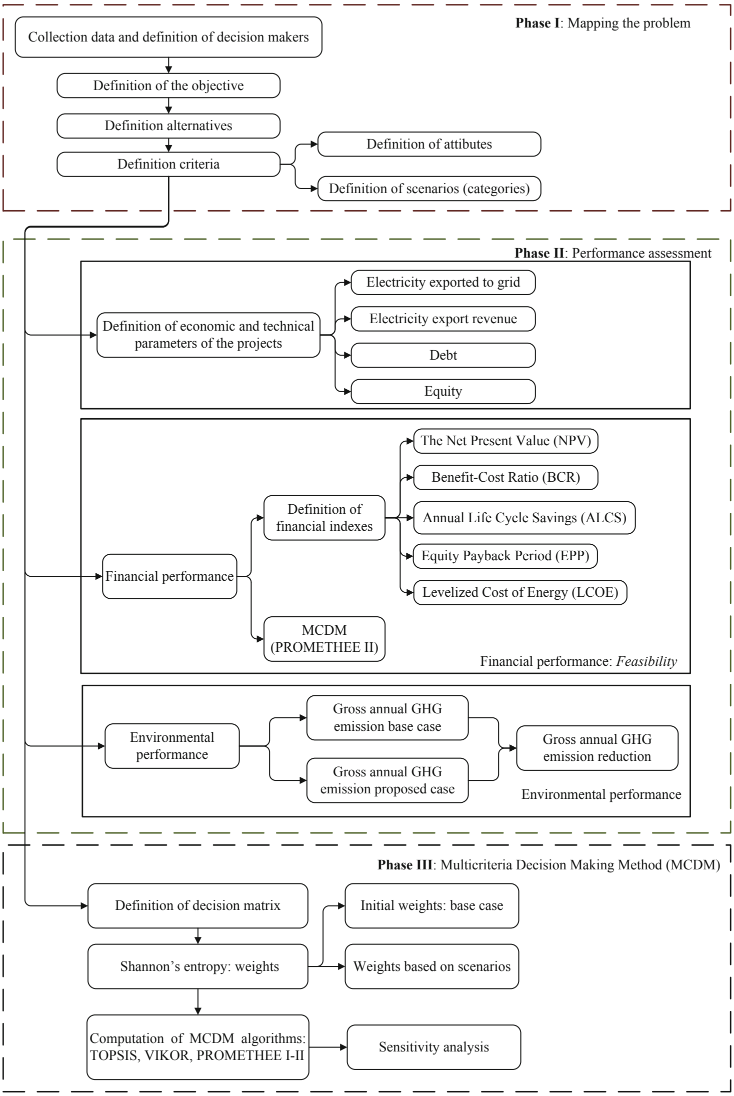

Fig. 2. Detailed steps and schematic diagram of the methodology.

4.1 Mapping the Problem

Definition of Criteria, Attributes, and Scenarios

Previously, the objective, the decision makers, and the alternative energy sources were identified Moreover, according to literature, the evaluation criteria for renewable energy can be divided into four main categories: financial, technical, environmental, and social dimensions. Criteria such as capital cost, O&M cost, Levelized Cost of Energy (LCOE), power capacity, efficiency, job creation/welfare improvement, social acceptability, emission reduction, and land use are commonly considered in renewable energy technologies studies. Among these, capital cost, Levelized Cost of Energy (LCOE), and the gross annual GHG emission reduction were chosen as the criteria for this studied in accordance with the suggestion of the Mining and Energy Planning Unit (UPME) of Colombia. Among these, GHG emission is one of the most widely used criteria in evaluating sustainability of renewables [22]. However, in order to enhance the spectrum of the assessment, the Technology Readiness Levels (TRL) as a measurement of technological readiness the capacity factor as a measurement of technical performance, and the energy potential and source availability of the alternatives were considered. The scenarios were chosen based on the category of criteria, and these were defined according to the numerical values of their weights. So, the following criteria were considered: the financial, technical, and environmental scenarios regarding power capacity; Technology Readiness Levels and capacity factor regarding technology; capital cost and Levelized Cost of Energy (LCOE) in terms of financial criteria; and gross annual GHG emission reduction in terms of environmental impact. The weights of criteria which define them were calculated based on an initial scenario which was defined by the computation of Shannon's entropy. Additionally, a scenario where all the weights own the same value was considered. So, criteria for the assessment of renewable technologies in Colombia based on MCDM is presented in Table 2.

4.2 Performance Assessment

The renewable energy markets involving power generation technologies are not usually balanced. In consequence, energy prices offered from those sources can increase over the total cost during short periods of time when the offer does not grow at the same speed as the demand. In contrast, for periods of surplus, losses can cause a drop in the price of the energy offered below production costs. So, it is necessary to execute a financial assessment of the power generation technology as a way to evaluate its feasibility and its competitiveness in current energy markets [23, 24]. To accomplish that, a two-step subroutine was proposed: a) calculation of financial indexes for the projects and b) comparative assessment by a MCDM. For the second step Table 5 is considered as the decision matrix, weight of criteria are calculated by Shannon's Entropy and data is computed by PROMETHEE II.

Economic and Technical Parameters of the Project

Electricity exported to grid in MWh/year is computed multiplying the capacity factor (CF) and the power capacity (CP) as indicated in Eq. (5).

$$E_{xg} = 0,0876(CF)(CP) \tag{5}$$

Table 2. List of criteria for the assessment based on MCDM.

Criteria		Scenario	Attribute	Unit
TRL	Tech. Readiness	Technical	+	–
PC	Power capacity		+	kW
CF	Capacity factor		+	%
IC	Investment cost	Financial	–	$/kWh
LCOE	LCOE		–	$/MWh
ER	Emission reduction	Environmental	+	tCO_2/year

*TRL: Technological Readiness Levels, PC: Power capacity, CF: Capacity factor, IC: Investment cost, LCOE: Levelized Cost of Energy and ER: Gross annal GHG emission reduction.

Electricity export revenue in USD/year is computed multiplying the electricity export rate and the electricity exported to grid as indicated in Eq. (6). However, it is escalated at the electricity export escalation rate (r_s).

$$E_{xr} = r_e E_{xg} \tag{6}$$

Debt is the fraction of the total investment required for the implementation of the project, and it is financed by a loan. The project debt leads to the calculation of the debt payments and the Net Present Value (NPV). It is calculated multiplying the total initial cost (IC) and the Debt Ratio (f_d). Debt is computed as indicated in Eq. (7)

$$D_b = f_d IC \tag{7}$$

On the other hand, equity is the fraction of the total investment required to finance the project that is funded directly by the facility owners. It is computed as indicated in Eq. (8).

$$E_q = (1 - f_d)IC \tag{8}$$

Financial Performance Assessment

The financial feasibility study of the projects considered is carried out by indexes such as the equity payback, the net present value, the yearly positive cash flow, the benefit-cost ratio, the annual life cycle savings, and the Levelized Cost of Energy [25].

The Net Present Value (NPV) of the project is the difference between the sum of cash inflow and outflow. It is computed by discounting all cash flow, as indicated in the Eq. (9).

$$NPV = \sum_{i=0}^{N} \frac{\hat{C}_n}{(1+r)^n} \tag{9}$$

where,

$\hat{C}_n$: Net cash flow during the period N.

r: Discount rate of the project.

N: Life of the project in years.

The Benefit-Cost Ratio (BCR) provides a measure of the financial desirability of the project. It is expressed as the ratio of the net benefits to the costs of the project. It is computed as indicated in Eq. (10).

$$BCR = \frac{NPV + (1 - f_d)C}{(1 - f_d)C} \tag{10}$$

where,
f_d: Debt ratio.
C: Total initial cost of the project.
The Annual Life Cycle Savings (ALCS) is the levelized nominal yearly savings, having the same life and net present value as the project. It is computed as indicated in Eq. (11).

$$ALCS = \frac{NPV}{\frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right]} \tag{11}$$

The Simple Payback Period (SPP) is the period required for the cash flow to be equal to the total investment. It is computed as indicated in Eq. (12).

$$SPP = \frac{C - IG}{\left(C_e + C_{cap} + C_{RE} + C_{GHG}\right) - \left(C_{O\&M} + C_{comb}\right)} \tag{12}$$

where,
C: Total initial cost of the project.
IG: Incentives and grants.
C_e: Annual energy savings.
C_{cap}: Annual capacity savings.
C_{RE}: Annual renewable energy production credit income.
C_{GHG}: Greenhouse gases reduction income.
$C_{O\&M}$: Annual operation and maintenance cost.
C_{fuel}: Annual cost of fuel or electricity.
The Equity Payback Period (EPP) is the period that represents the length of time that it takes for the owner of a facility to recuperate their initial investment (equity) out of

the cash flow generated by the project. The equity payback considers project cash flow from its inception as well as the leverage (level of debt) of the project, which makes it a better time indicator of the project merits than the simple payback. It is computed as indicated in Eq. (13).

$$EPP = A + \frac{\left|\hat{C}_c\right|}{\hat{C}_A} \tag{13}$$

where,
A: The last period number with a negative cumulative cash flow.
$\hat{C}_c$: Cumulative net cash flow at the end of period A.
$\hat{C}_A$: Net cash flow during the period following period A.

The Levelized Cost of Energy (LCOE) represents the electricity export rate required in order to have a Net Present Value (NPV) equal to 0. It is computed as indicated in Eq. (14).

$$LCOE = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t} \left[\frac{E_t}{(1+r)^t} \right]^{-1} \tag{14}$$

where:
I_t: Annual investment cost.
M_t: O&M annual cost.
F_t: Annual cost of fuel.
E_t: Annual electricity generation, MWh.
r: Discount rate of the project.

Environmental Performance Assessment

The environmental performance study of the projects considered is carried out by calculating? the gross annual GHG emission reduction based on the GHG emission of the base and proposed case. The GHG emission of the base case represents the amount of GHG emitted for the base case system. It is computed by multiplying the emission factor of the base case (EF_{bc}) and the electricity exported to grid, as indicated in Eq. (15).

$$GHG_{bc} = EF_{bc}E_{xg} \tag{15}$$

The GHG emission of the proposed case represents the amount of GHG emitted for the proposed case systems. It is computed multiplying the emission factor of the proposed case (EF_{pc}) and the electricity exported to grid, as indicated in Eq. (16).

$$GHG_{pc} = EF_{pc}E_{xg} \tag{16}$$

The Gross annual GHG emission reduction is based on emissions of both the base case and the proposed case systems on an annual basis. It is computed as indicated in Eq. (17).

$$GHG_{gr} = GHG_{bc} - GHG_{pc} \tag{17}$$

Likewise, the Gross annual GHG emission reduction is commonly established as a percentage reduction. It is computed as indicated in Eq. (18).

$$GHG_{gr(\%)} = \frac{\left|GHG_{pc} - GHG_{bc}\right|}{GHG_{bc}} * 100\% \quad (18)$$

The decision matrix of Colombia's renewable energy technologies is presented in Table 3.

Table 3. Decision matrix on Colombia's renewable energy technologies [26–30].

	TRL	PC [MW]	CF [%]	IC [$/kWh]	LCOE [$/MWh]	ER [tCO_2/year]
Solar	9	86	23	995	46	67,062
Wind	9	19	38	1800	71	26,151
Wave	7	2	30	4900	306	2736
Tidal	9	250	30	3412	196	342,043
Current	8	4	35	11,466	594	6384

The initial weights of the criteria w_j computed by Shannon's entropy algorithm were $w_{TRL} = 0.0002$, $w_{PC} = 0.3392$, $w_{IC} = 0.1344$, $w_{LCOE} = 0.1426$, $w_{ER} = 0.3758$ and $w_{CF} = 0.0060$. These weights are computed based on the numerical values of criteria from Table 3. It was found that the weights of capacity factor and TRL are much smaller than the others. This could be explained considering that a small numerical difference among values of a criterion for each alternative means a lower probability of obtaining information, higher entropy, and lower weight. So, power capacity, investment cost, LCOE, and GHG emission reduction criteria are much better for decision making in this case. Nevertheless, capacity factor and TRL are important for the overall analysis considering that for Colombia this assessment is one of the first steps for the development of a baseline of renewable energy technologies and sources, such as ocean energy which is a renewable energy source not yet considered in the energy matrix.

5 Results

Based on the methodology presented in Fig. 2, the method PROMETHEE II was applied to the data presented in Table 5 in order to conduct a relative comparison of the financial performance of the projects. Likewise, MCDM methods (TOPSIS, VIKOR and PROMETHEE II) were applied to the data presented in Table 3. A sensitivity analysis was conducted based on the weight value of criteria for each scenario, adjusting the sum of criteria of the same category, proportionally. Objective weights of criteria were calculated by Shannon's entropy. It was found that gross annual GHG emission reduction was the most important criterion for the development of ocean energy in Colombia, according to Fig. 3, due to a wider difference among the values of criteria which implies a higher probability for obtaining information, lower entropy, and a greater weight. Unlike gross annual GHG emission reduction, TRL and capacity factor were the less representative criteria during the assessment. In Table 4, Table 5 and Table 6, the economic and technical parameters, the financial performance, and the environmental impact of the alternatives are presented, respectively. The parameters and the results of the financial and the environmental performance assessment were used to grant the numerical values of criteria, such as the LCOE and the gross annual GHG emission reduction. A debt ratio of 70%, a debt interest of 7%, a debt term of 15 years, a discount rate of 9%, and an escalation rate of 2% were considered for the performance assessment of the projects.

Table 4. Economic and technical parameters of the alternatives.

Alternative	E_{xg} [MWh/year]	E_{xr} [$/year]	D_b [$]	E_q [$]
Solar	176,043	17,604,315	49,024,500	21,010,500
Wind	65,026	6,502,636	19,464,900	8,342,100
Waves	5256	1,576,800	6,860,000	2,940,000
Tidal range	657,000	131,400	597,100,000	255,900,000
Ocean current	12,264	7358	9,553,600	4,094,400

Table 5. Financial performance.

Alternative	EPP [years]	NPV [$]	BCR	ALCS [$/year]	LCOE [$/MWh]
Solar	1.8	114,872,774	6.5	12,583,907	46
Wind	2.8	27,356,694	4.3	2,996,829	71
Waves	7.6	2,181,380	1.7	238,962	306
Tidal range	6.9	230,636,658	1.9	25,265,433	196
Ocean current	6.9	12,322,432	1.9	1,349,879	594

Computing the proposed two-step subroutine, the financial indexes for the projects were calculated. The value of the financial indexes for each project is presented in Table 5, which is considered the decision matrix. To conduct the comparative assessment, weight of criteria, in this case, the Net Present Value (NPV), the Benefit-Cost Ratio (BCR), the Annual Life Cycle Savings (ALCS), the Levelized Cost of Energy (LCOE) were calculated by Shannon's Entropy and data was computed by PROMETHEE II. It was found that tidal range has the best financial performance and ocean current the worst. It was identified that the ALCS was the most important criterion for financial performance assessment. On the contrary, the GHG emission of the base and proposed cases were calculated considering an emission factor of 0,548 tCO_2/MWh. The base case was computed considering the power generation by a natural gas thermal power plant, an electricity generation efficiency of 38% and T&D losses of 5%. In Fig. 3 and Table 6 the gross annual GHG emission reduction of the alternatives is presented.

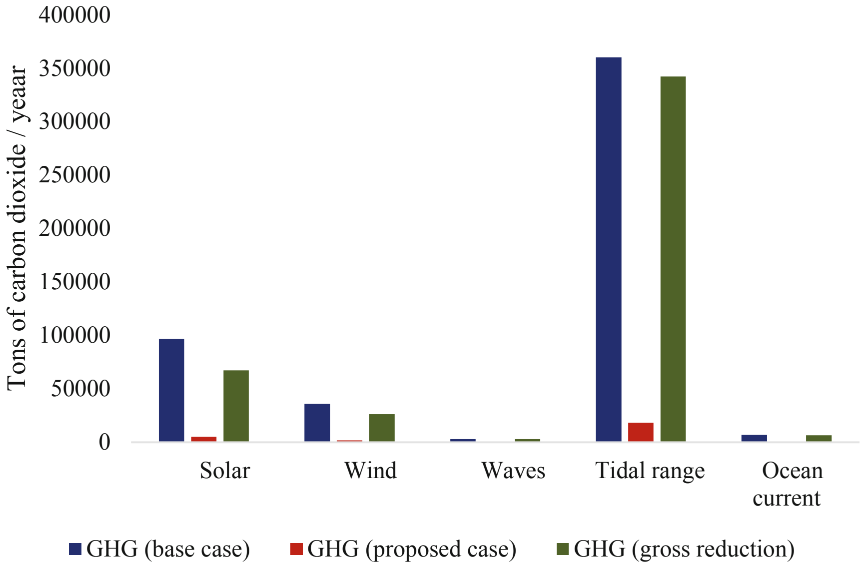

Fig. 3. Gross annual GHG emission reduction.

Table 6. Environmental performance.

Alternative	GHG_{bc}	GHG_{pc}	GHG_{gr}	$GHG_{gr(\%)}$[%]
Solar	96,471	4823	67,062	95
Wind	35,634	1782	26,151	95
Waves	2880	144	2736	95
Tidal range	360,036	17,993	342,043	95
Ocean current	6721	337	6384	95

Based on the data of the decision matrix in Table 3, Shannon's Entropy was used to calculate the relative importance of each criterion. Since the criteria weight significantly cause changes on the rank, a sensitivity analysis was conducted to reveal the ranking alternatives changes due to variation of criteria weights. To accomplish that, the weight value of criteria for each scenario was adjusted to grant 80% of the sum of criteria of the same category, meaning, the remaining 20% for the other scenarios and criteria were reduced or increased proportionally from the base case to complete the sum equal to 1. In Table 7 the weights of the criteria under different scenarios is presented. In Fig. 4 and Table 8, the, in terms of different methods and scenarios, is presented.

Table 7. Criteria weights under different scenarios.

	TRL	PC	CF	IC	LCOE	ER
Base case	0.002	0.339	0.006	0.134	0.143	0.376
Equal	0.167	0.167	0.167	0.167	0.167	0.167
Technical	0.005	0.782	0.014	0.067	0.067	0.067
Financial	0.500	0.500	0.500	0.388	0.412	0.500
Environmental	0.040	0.040	0.040	0.040	0.040	0.800

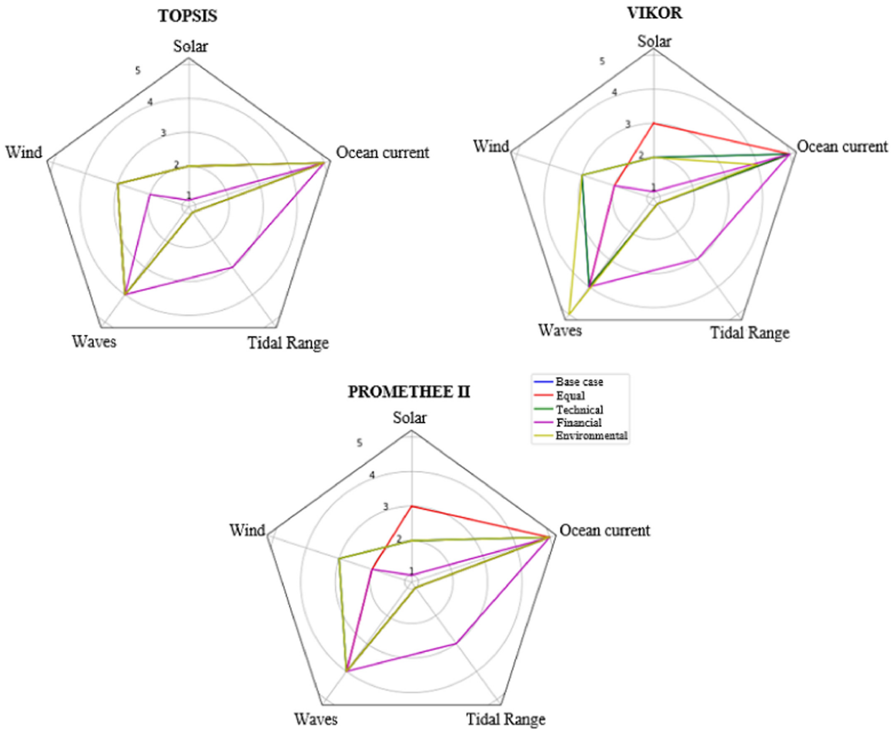

Fig. 4. Radar chart for the ranking in terms of different methods and scenarios.

Table 8. Ranking in terms of different methods and scenarios.

	Method	Rank				
Scenario 1		I	II	III	IV	V
Base case	TOPSIS	4	1	2	3	5
	VIKOR	4	1	2	3	5
	PROMETHEE II	4	1	2	3	5
Scenario 2						
Equal weight	TOPSIS	4	1	2	3	5
	VIKOR	4	1	2	3	5
	PROMETHEE II	4	1	2	3	5
Scenario 3						
Technical	TOPSIS	4	1	2	3	5
	VIKOR	4	1	2	3	5
	PROMETHEE II	4	1	2	3	5
Scenario 4						
Financial	TOPSIS	1	2	4	3	5
	VIKOR	1	2	4	3	5
	PROMETHEE II	1	2	4	3	5
Scenario 5						
Environmental	TOPSIS	4	1	2	3	5
	VIKOR	4	1	1	5	3
	PROMETHEE II	4	1	2	3	5

*1. Solar energy, 2. Wind energy, 3. Waves, 4. Tidal range, 5. Ocean current.

6 Conclusions

The assessment of renewable energy technologies can be conducted by Multicriteria Decision Making Methods considering technical, financial, and environmental criteria as a tool to reduce financial risks and guarantee the objective goals of renewable energy projects. The comparative assessment of ocean energy technologies with renewables such as solar and wind in Colombia was considered. A methodology based on three phases was proposed: I) Mapping the problem, II) Performance assessment, III) Multicriteria Decision Making Method.

During Phase I, there were five defined alternatives: solar, wind, waves, tidal range, and ocean current, and six defined criteria: Technological Readiness Levels, TRL; Power Capacity PC; Capacity Factor, CF; Investment Cost, IC; Levelized Cost of Energy, LCOE; and Gross Annual GHG Emission Reduction, ER. TRL, PC, CF and ER criteria were considered positive as opposed to IC and LCOE, which were considered negative. Likewise, there were five defined scenarios: base case, equal weight, technical, financial, and environmental. For the base case, Shannon's Entropy was used to calculate the relative importance of each criterion. The weights of criteria for the equal weight, technical, financial, and environmental scenarios were calculated adjusting the value of criteria to grant 80% of the sum of criteria of the same category.

In Phase II, financial and environmental assessment of the projects were conducted, and parameters such as electricity exported to grid, electricity export revenue, debt, equity and financial indexes such as Net Present Value, Benefit-Cost Ratio, Annual Life Cycle Savings), Levelized Cost of Energy (LCOE), and gross annual GHG emission reduction were calculated. The results of the financial and the environmental performance assessment were used to grant the numerical values of criteria such as the LCOE and the gross annual GHG emission reduction. It found that the gross annual GHG emission reduction percentage is the same for all the alternatives, but tidal range exhibits increased gross annual emission reduction due to its high-power capacity. Likewise, tidal range exhibits the best financial performance among the alternatives. Unlike tidal range, ocean energy exhibits the worst environmental and financial performance, as presented in Table 8.

Finally, in Phase III, data was computed by three MCDM (TOPSIS, VIKOR, and PROMETHEE II). The ranks obtained from the methods considered were similar, although not entirely equal. However, this issue points out the validity of the algorithms used. According to Table 8 and Fig. 4, tidal range is the best alternative and ocean current the worst for all the scenarios. This could be explained considering the difference in the power capacity, being higher for tidal range. Since higher power capacities eventually imply higher electricity exported to grid for similar capacity factors, and higher electricity exported to grid leads to higher gross annual GHG emission reduction for similar GHG emission factors and lower Levelized Cost of Energy for similar investment cost values. In this study, power capacity is the determining criteria in the assessment. Due to the fact tidal range exhibits the highest power capacity, it would be expected that this alternative was the best. Finally, it can be concluded that for similar power capacities, solar energy would be a better alternative than tidal range considering that solar's financial performance was better than tidal range, even though the power capacity of solar was approximately 65% lower, as shown in Table 3 and Table 8.

References

1. Stern, A.G.: A new sustainable hydrogen clean energy paradigm. Int. J. Hydrogen Energy **43**, 4244–4255 (2018). https://doi.org/10.1016/j.ijhydene.2017.12.180
2. Mitsos, A., Asprion, N., Floudas, C.A., Bortz, M., Baldea, M., Bonvin, D., et al.: Challenges in process optimization for new feedstocks and energy sources. Comput. Chem. Eng. **113**, 209–221 (2018). https://doi.org/10.1016/j.compchemeng.2018.03.013

3. OECD - Better policies for better lives. Data - Organisation for Economic Co-operation and Development n.d. https://www.oecd.org/fossil-fuels/data/. Accessed 6 April 2020
4. REN 21 - RENEWABLES NOW. Global Overview n.d. https://www.ren21.net/gsr-2019/chapters/chapter_01/chapter_01/#fig_4. Accessed 18 July 2019
5. REN 21 - RENEWABLES NOW. Renewables 2020 - Global Status Report n.d. https://www.ren21.net/gsr-2020/chapters/chapter_01/chapter_01/. Accessed 1 Sept 2020
6. Unidad de Planeación Minero Energética - UPME. Plan Energetico Nacional Colombia: Ideario Energético 2050 2015:184
7. Gómez-Navarro, T., Ribó-Pérez, D.: Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia. Renew. Sustain. Energy Rev. **90**, 131–141 (2018). https://doi.org/10.1016/j.rser.2018.03.015
8. Foro Nuclear - Foro de la Industria Nuclear Española. Energía y fuentes de energía n.d. https://www.foronuclear.org/es/energia-nuclear/faqas-sobre-energia/capitulo-1/115488-icomo-se-clasifican-las-fuentes-de-energia. Accessed 5 Mar 2020
9. U.S. Energy Information Administration (EIA). Sources of energy 2019. https://www.eia.gov/energyexplained/what-is-energy/sources-of-energy.php. Accessed 4 May 2020
10. República de Colombia - Gobierno Nacional. LEY No 1715 del 13 de mayo de 2014. TAPPI J 2014;13. https://doi.org/https://doi.org/10.32964/tj13.5
11. International Energy Agency (IEA). The Future of Hydrogen – Analysis - IEA n.d. https://www.iea.org/reports/the-future-of-hydrogen. Accessed 4 Apr 2020
12. Berger, R.: Global consulting. fuel cells and hydrogen applications for regions and cities. Consolidated Technol. Introduction Dossiers **1**, 108–123 (2017)
13. Gholikhani, M., Roshani, H., Dessouky, S., Papagiannakis, A.T.: A critical review of roadway energy harvesting technologies. Appl. Energy **261**, 114388 (2020). https://doi.org/10.1016/j.apenergy.2019.114388
14. Yang, Z., Zhou, S., Zu, J., Inman, D.: High-performance piezoelectric energy harvesters and their applications. Joule **2**, 642–697 (2018). https://doi.org/10.1016/j.joule.2018.03.011
15. Wang, J., Liu, Y., Chen, L., Tang, J.: Using the technology readiness levels to support technology management in the special funds for marine renewable energy. Ocean 2016 - Shanghai (2014). https://doi.org/10.1109/OCEANSAP.2016.7485608
16. International Renewable Energy Agency - IRENA. Ocean energy: technology readiness, patents, deployment status and outlook. Int. Renew. Energy Agency IRENA 76 (2014). https://doi.org/10.1007/978-3-540-77932-2
17. Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H.: Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain. Energy Rev. **13**, 2263–2278 (2009). https://doi.org/10.1016/j.rser.2009.06.021
18. Pradhan, S., Indraneel, S., Sharma, R., Kumar, D., Nathuram, R.: Optimization of machinability criteria during dry machining of Ti-2 with micro-groove cutting tool using WASPAS approach Materials Today : Proceedings Optimization of machinability criteria during dry machining of Ti-2 with micro-groove cutting tool using WASPAS approach. Mater Today Proc (2020). https://doi.org/10.1016/j.matpr.2020.02.972
19. Fontana Viñuanes, M.: Métodos de decisión multicriterio AHP y PROMETHEE aplicados a la elección de un dispositivo móvil (2015)
20. García, J.I.: Las Líneas Estratégicas del Sector Hídrico en México en Materia de Investigación. Una Jerarquización Empleando el Método PROMETHEE, Desarrollo Tecnológico y Formación de Recursos Humanos (2009)
21. Lee, H., Chang, C.: Comparative analysis of MCDM methods for ranking renewable energy sources in Taiwan. Renew. Sustain. Energy Rev. **92**, 883–896 (2018). https://doi.org/10.1016/j.rser.2018.05.007

22. Ilbahar, E., Cebi, S., Kahraman, C.: A state-of-the-art review on multi-attribute renewable energy decision making. Energy Strateg. Rev. **25**, 18–33 (2019). https://doi.org/10.1016/j.esr.2019.04.014
23. International Renewable Energy Agency. Renewable Power Generation Costs 2018 (2018)
24. Himri, Y., Merzouk, M., Kasbadji Merzouk, N., Himri, S.: Potential and economic feasibility of wind energy in south West region of Algeria. Sustain. Energy Technol. Assessments **38**, 100643 (2020). https://doi.org/10.1016/j.seta.2020.100643
25. Lezama-Nicolás, R., Rodríguez-Salvador, M., Río-Belver, R., Bildosola, I.: A bibliometric method for assessing technological maturity: the case of additive manufacturing. Scientometrics **117**(3), 1425–1452 (2018). https://doi.org/10.1007/s11192-018-2941-1
26. World Energy Council. World Energy Perspective - Cost of Energy Technologies 2013:48. ISBN 978 0 94612 130 4
27. Atlantis Resources. MeyGen Tidal Energy Project Phase 1a – Progress Update (2016)
28. Australian Renewable Energy Agency - ARENA. The Tidal Turbine Reef (TTR) Feasibility Study (2018)
29. IRENA International Renewable Energy Agency. Wave energy technology brief. IRENA Ocean Energy Technol. Br. **4**, 28 (2014)
30. Pöyry Management Consulting. Levelised Costs of Power From Tidal Lagoons 2014:38