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Bilevel Prioritization within the Energy Transition Framework for Diversified Portfolios of Green Hydrogen Production for Export

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ABSTRACT

Green hydrogen has been proposed as an alternative to incorporate into energy portfolios and as an export product to address the economic and social challenges derived from the energy transition, especially in hydrocarbon-exporting countries; however, this energy carrier faces economic challenges associated with the cost of electricity used in its production process. This research aimed to prioritize renewable generation portfolios within the framework of an energy transition, considering attributes related to export, sustainability, and source diversity, to ensure supply continuity and reduce dependency in green hydrogen production for export. To achieve this, bilevel multicriteria analysis and an unsupervised classification algorithm were employed, based on a set of electrical projects. The results obtained highlight the importance of evaluating indicators at both project and portfolio levels in a differentiated manner, paying special attention to diversity as an essential criterion. Through the development of analysis threads, it was identified that robustness does not necessarily imply greater diversity; in this sense, in addition to scenarios with variation in criteria weights, it was necessary to construct source participation scenarios that would directly influence diversity.

Keywords: Green Hydrogen, Energy Transition, Generation Portfolios, Diversification, Bilevel Prioritization, Export
JEL classifications: Q42, C61, L94, Q48

1. INTRODUCTION

In recent decades, given the changes in people's lifestyles and in the operational methods of economic sectors, there has been significant growth in energy demand, primarily marked by fossil fuel consumption. This has led the energy sector to increase its contribution to Greenhouse Gas (GHG) emissions, contributing to atmospheric warming and the crisis caused by climate change (Banco Mundial, 2024; IEA, 2023a; United Nations Development Programme, 2002).

In order to generate commitments to address the situations experienced regarding this issue, various agreements, treaties, and summits have been developed worldwide, primarily highlighting the Sustainable Development Goals (SDGs) and the Paris Agreement. Globally, what is now known as the energy transition has emerged, with the topic beginning to take on special relevance in academic circles in 2012 (SCOPUS, 2025), motivated by the contribution it could make to fulfilling the various commitments acquired regarding the reduction of GHGs caused by fossil fuels. According to the International Energy Agency (IEA), achieving a total reduction in global pollution by 2050 requires transformation in various sectors (IEA, 2023b; IEA, 2021) such as the energy sector, which in 2021 represented 74% of GHGs generated worldwide (ClimateWatch, 2025).

In this regard, green hydrogen is being considered as an energy carrier and a crucial clean fuel alternative within the energy transition to deeply address decarbonization, especially in those economic sectors that are difficult to decarbonize and make intensive use of fossil fuels (Flah et al., 2025; Angelico et al., 2025; Müller et al., 2024).

The worldwide relevance that green hydrogen has acquired is related to the potential benefits identified in technical, social, environmental, and economic terms, among which the following stand out: Potential to improve grid stability through the utilization of renewable sources and the storage of their generated energy, contributing to energy security; facilitator of the integration of different energy systems, allowing it to reach even hard-to-decarbonize sectors; creation of new employment sources through the diversification and revitalization of the economy given new investments in the sector; decoupling the energy sector from dependency on fossil fuels; and the possibility of addressing other challenges inherent to the energy transition. These elements also provide it with the potential to fulfill the various commitments regarding the reduction of GHG emissions (Przybyla et al., 2025; Angelico et al., 2025; Flah et al., 2025; Hassan et al., 2024; Pereira Nunes and Gonçalves, 2024; Hine et al., 2024; Nemmour et al., 2023; Nadaleti et al., 2022).

Authors such as Oliveira et al. (2021) suggest that the transition to a hydrogen economy presents an opportunity to decarbonize approximately 18% of global energy sectors; this suggests that in the future, the green hydrogen trade will gain relevance and participation in covering the growing demand for carbon-free hydrogen, where fossil fuel exporting countries with renewable electricity generation potential can leverage these resources through investment in green hydrogen production for both domestic use and export, allowing them to address, through economic diversification, the challenges posed by climate change and the transition to sustainable energy systems (Müller et al., 2024; Lal and You, 2024; Hassan et al., 2024; Nadaleti et al., 2021).

However, as an emerging market and industry, it faces challenges of different nature. Authors point out that among the topics to investigate, the following are relevant: competitive profitability of green hydrogen, political support mechanisms that allow the implementation of solid infrastructure for its deployment at national and international levels, regulatory framework that enables investment, consideration of social aspects and community perceptions regarding renewable energy projects, and guarantee of green hydrogen supply security (Angelico et al., 2025; De Sá, 2024; Lal and You, 2024; Hassan et al., 2024; Pereira Nunes and Gonçalves, 2024; Hine et al., 2024; Nadaleti et al., 2022).

Particularly and within the framework of energy transition, studies regarding green hydrogen have considered the analysis of technologies associated with different links in the supply chain; the estimation of hydrogen production potential in various countries; and the analysis of hydrogen policies and their impact on energy transition.

Authors such as Pereira Nunes and Gonçalves (2024) analyze the regulatory challenges and impacts faced by BRICS countries within the framework of the green hydrogen sector. Based on the obtained results, they highlight, as do Angelico et al. (2025), the potential of green hydrogen to contribute to decarbonization efforts in the context of energy transition, emphasizing the importance of international collaboration for this purpose; a conclusion that is also presented by Flah et al. (2025).

On the other hand, authors such as Przybyla et al. (2025); Hassan et al. (2024); Müller et al. (2024); Bairrão et al. (2023); Nadaleti et al. (2022) and Nadaleti et al. (2021) focus their research on estimating the potential for green hydrogen production in countries like Saudi Arabia, Algeria, Portugal, and South American countries, concluding that green hydrogen plays a relevant role in energy transition and therefore, it is necessary to rapidly expand renewable energies in order to meet emission reduction objectives, considering strategic alliances between countries and the diversification of the energy portfolio.

Among the most important challenges in incorporating green hydrogen into energy portfolios are the high costs of its production (Angelico et al., 2025; Lal and You, 2024; De Sá, 2024; Pereira Nunes and Gonçalves, 2024; Hassan et al., 2024; Nemmour et al., 2023; Bairrão et al., 2023), specifically associated with capital expenditures, the price of electrolyzers, and the cost of renewable electricity, which is a requirement in the production process through electrolysis to be classified as “Green Hydrogen” (Athia et al., 2024; Kotowicz et al., 2024; Choi and Kang, 2023; Clark and Rifkin, 2006; Stojić et al., 2003).

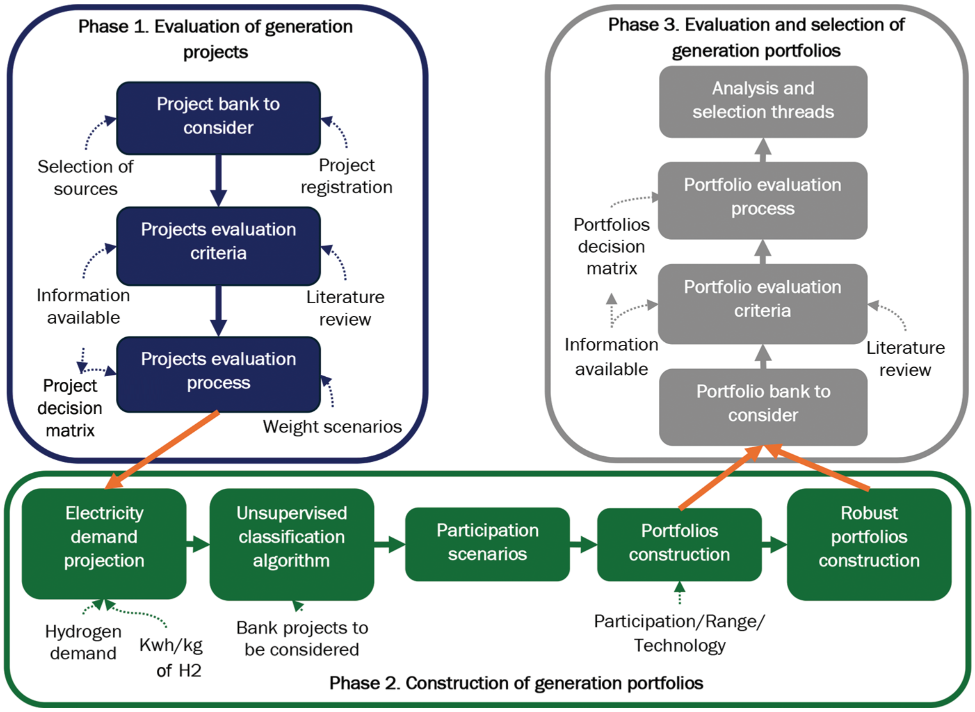
The above highlights the need for efficient renewable electricity generation infrastructure, since as established by Santana et al. (2024); Lal and You (2024); Hassan et al. (2024); Kotowicz et al. (2024); Martínez de León et al. (2023); Choi and Kang (2023); Bairrão et al. (2023) y Nemmour et al. (2023) and reaffirmed by IRENA (2022), the largest component of green hydrogen production cost is linked to the cost of electricity. As this aspect is of great interest, one of the mechanisms for cost reduction is diversification; as proposed by Casas Ferrús et al. (2024), technological and location diversification generates significant cost mitigation; on one hand, the technological portfolio reduces costs by 39% compared to the average, while the location portfolio has an impact of up to 21%.

Acknowledging what has been previously presented, this research seeks to configure and prioritize renewable electricity generation portfolios for green hydrogen production with export purposes from a set of generation projects, simultaneously considering in the evaluation attributes related to diversification, exportation, as well as sustainability criteria, within the framework of an energy transition. The rest of the document is structured as follows: section 2 presents the method and input data considered in the research; section 3 presents the obtained results, and their discussion based on four proposed analysis threads, and finally, conclusions regarding the research are presented.

2. METHOD AND DATA

Figure 1 graphically outlines the methodology implemented to obtain electricity generation portfolios that are both diversified and exhibit high performance in indicators related to technical aspects,

Figure 1: Methodological approach



Source: Authors' elaboration

sustainability, and export. This methodology was structured into three phases: Phase 1. Evaluation of generation projects, Phase 2. Construction of generation portfolios, and Phase 3. Evaluation and selection of generation portfolios.

Each of the stages presented in Figure 1 is described in detail below:

2.1. Phase 1. Evaluation of Generation Projects

2.1.1. Project bank to consider

2.1.1.1. Selection of sources

The sources utilized for green hydrogen production must be renewable. Previous research specifically has largely focused on solar and wind sources, a combination of these two, and occasionally hydroelectric sources; nevertheless, having a wide range of alternatives provides the opportunity to construct diversified generation portfolios and therefore mitigate the risk of electrical supply shortages, seeking to guarantee continuous supply through heterogeneity in sources. For this purpose, the reports from GIZ, (2023) and IRENA (2024b), were taken as reference, where renewable generation is defined as that derived from bioenergy and biofuels, geothermal energy, hydroenergy, ocean, solar energy and wind energy.

2.1.1.2. Projects registration

Generally, studies associated with electricity generation portfolios provide the participation percentages that each source/technology should have, based on information directly related to them. This research begins with the premise that countries or entities have declared generation intentions, not only through expectations of source/technology participation at a strategic level but also through the declaration of potential electricity generation projects at a tactical level; therefore, the latter are those considered in the construction of electricity generation portfolios.

Acknowledging the potential generation projects and their associated information, Colombia's generation project registry was used as a database. This is a voluntary and informative mechanism through which service promoters present their intention to develop an electric generation project through registration, which provides information on the various project initiatives that serve as input for planning processes (UPME, 2018; UPME, 2025).

The report on the registration of generation projects generated by the Unidad de Planeación Minero Energética - UPME that was utilized was the one issued in week 25, with data as of June 24, 2024. To establish the bank of projects for consideration, projects with active status and declaring photovoltaic, wind, hydraulic, or geothermal as their implementation technology were defined.

2.1.2. Project evaluation criteria

The evaluation of electricity generation projects was established based on elements that are crucial for energy transition and export processes.

With regard to energy transition, the following articles were reviewed: Constantin (2024) [1]; Daoudi (2024) [2]; Gao (2023) [3]; Romero-Castro et al. (2023) [4]; (Liu et al. (2023) [5]; Lillo et al. (2021) [6]; Ryszawska et al. (2021) [7]; Lee et al. (2021) [8]; French (2020) [9]; Angelakoglou et al. (2020) [10]; Martinez and Komendantova (2020) [11]; O'Neill-Carrillo et al. (2019) [12]; Perlaviciute et al. (2018) [13]; Frei et al. (2018) [14]; Safarzyńska and Van Den Bergh (2013) y [15]; Mah et al. (2013) [16]. Regarding exportation, the following articles were examined: Lopes et al. (2020) [17]; Ingason et al. (2008) [18] y Wietschel and Hasenauer (2007) [19].

Based on the results of the analysis derived from the literature review, the application of each element within the research framework, and the availability of information per project, the criteria and categories detailed in Table 1 were established.

2.1.2.1. Technical

2.1.2.1.1. Knowledge regarding technology

It indicates the extent of knowledge available concerning technology. Thus, each project is assigned a value based on the number of worldwide patents associated with its registered utilization technology. This information was derived from IRENA (2024a) in its "Patents Evolution" statistics.

2.1.2.2. Social

2.1.2.2.1. Social acceptance

This refers to how willing or unwilling a community is regarding the development of an energy project in their territory. For this assessment, the "Social Criticality" reported by UPME for Colombia was considered as a measure, which takes into account variables such as: "Indigenous reservations; community councils; intervention in Afro territories; intervention in indigenous territories; peasant reserve zones; documented social conflicts related to different development projects (mining, hydroelectric, etc.) and POMCA where prior consultation processes with communities are indicated" (UPME and Universidad de Antioquia, 2024), thereby determining the level of impedance at the location. The value assigned to each project for this criterion is linked to the municipality it registers. This information was based on what was indicated by UPME in its report "Map of socio-environmental criticalities/restrictions for the National Interconnected System."

2.1.2.2.2. Employment generated

This refers to the number of jobs that can be generated per project. For its calculation and approximation, data reported by IRENA and ILO (2023) and IEA (2023c) in terms of the total number of jobs generated by technology for a specific year were considered; and were divided by the installed capacity reported by IRENA (2025) regarding each technology for the said year. This provided an approximation of the number of jobs/MW according to technology, which was multiplied by the capacity (MW) reported by each project.

2.1.2.3. Economic

2.1.2.3.1. LCOE

"The Levelized Cost of Electricity (LCOE), is an economic measure used to compare the lifetime costs of generating electricity through various generation technologies" (Raikar and Adamson, 2020). The LCOE values for each of the generation projects were obtained through the GeoLCOE application, by indicating the particular characteristics of each project in terms of its location (Municipality), capacity (MW) and utilization technology (UPME and Universidad de Antioquia, 2017).

2.1.2.4. Environmental

2.1.2.4.1. Required space

This refers to the land area that the generation project would potentially occupy. To estimate this space, the information reported by UNECE (2022) regarding total land occupation (agricultural and urban) in m^2/year/MWh for each technology was used. The data extracted from this report were multiplied by the energy that each project is capable of generating annually according to its capacity and plant factor.

2.1.2.4.2. Generated emissions

This refers to the volume of GHG that each project may generate in its annual operation. For this calculation, data provided by NREL in its report "Life Cycle Emissions Factors for Electricity Generation Technologies" (Nicholson and Heath, 2021) were used. The data extracted from this report were multiplied by the energy that each project is capable of generating annually according to its capacity and plant factor.

2.1.2.5. Export

2.1.2.5.1. Availability of transportation infrastructure

This indicates the availability of transportation infrastructure in a specific territory. For this assessment, the "Infrastructure" reported by the UPME for Colombia was considered as a measure, which takes into account the existence of: "Roads, oil pipelines, polyducts, electric transmission lines, railway lines, etc." (UPME and Universidad de Antioquia, 2024), thereby determining the level of impedance at the location. The value assigned to each project for this criterion is linked to the municipality it registers. This information was based on what was indicated by UPME in its report "Map of socio-environmental criticalities/restrictions for the National Interconnected System."

2.1.2.5.2. Average distance to ports

This refers to the average distance from the project location to the various ports in the country. For this calculation, the distance between points was calculated using the coordinates of each origin location and each destination location. The value assigned to each project for this criterion is based on the municipality it registers.

Table 1: Criteria and categories - project evaluation

Category	Criterion	Scale	Objective	Source
Technical	Knowledge regarding technology	# of patents	Maximize	[1], [2], [3], [6], [15]
Social	Social acceptance	1-10	Minimize	[3], [4], [5], [6], [7], [8], [11], [13]
	Employment generated	# of jobs	Maximize	
Economic	LCOE	USD/MWh	Minimize	[3], [4], [5], [6], [7], [8], [15]
Environmental	Required space	m^2 year	Minimize	[1], [3], [4], [6], [7], [8], [9], [13], [14]
	Generated emissions	TON CO_2 year	Minimize	
Export	Availability of transportation infrastructure	1-10	Minimize	[17], [18], [19]
	Average distance to ports	Km	Minimize	

Source: Authors' elaboration

2.1.3. Project evaluation process

2.1.3.1. Projects decision matrix

Once the bank of generation projects and the criteria to be considered for evaluating each of these were established, the decision matrix was developed, which contains information for each project (alternative) against each evaluation criterion. This information was obtained through national and international entities related to the energy sector, which were presented together with the explanation of each evaluation criterion addressed.

2.1.3.2. Weights scenarios

Considering that information was available by project for each evaluation criterion, the objective multicriteria Shannon Entropy method was used. This method allows the definition of the weights of the criteria according to the behavior of the decision matrix. Lower data variability for a criterion results in lower weight (Shannon, 1948; Wu et al., 2011). Additionally, recognizing the sensitivity of the method to the ranges of criteria and that low variability does not necessarily represent low importance, scenarios were proposed prioritizing each evaluation criterion and a scenario of balance between them, as presented in Table 2.

To evaluate the generation projects against the established criteria considering each of the designed weight scenarios, the multicriteria method known as Technique for Order of Preference by Similarity to the Ideal Solution - TOPSIS was used. This approach developed by Hwang and Yoon (1981), establishes the principle that the chosen alternative should have the shortest distance to the positive ideal solution and the longest distance to the negative ideal solution (Alguliyev et al., 2016).

2.2. Phase 2. Construction of Generation Portfolios

2.2.1. Electricity demand projection

According to the GIZ (2023) document, the potential hydrogen-importing regions worldwide are Germany, South Korea, and Japan, whose total hydrogen demand for 2030 is estimated at 10 million tons, of which they expect to import between 40% and 90%. Specifically, Colombia expects to supply 1% of the hydrogen to be imported by each potential region. Assuming a consumption of 48 kWh/kg of H_2 (IEA, 2024; IRENA, 2020), the electricity requirements are 2'880.000 MWh/year to produce 60.000 tons of green H_2 for export. The details of the calculations are presented in (Table 3).

2.2.2. Unsupervised classification algorithm

Initially, all current projects were grouped according to the declared technology. For each set, a squared distance matrix was created between projects based on the reported capacity (MW).

This information was used as input data in the mathematical model, with the purpose of grouping projects by technology into three clusters representing: Large capacity, medium capacity, and small capacity projects; seeking to minimize their squared distance. The model was executed for each set of projects by technology with cardinality greater than one.

2.2.2.1. Model

The K-means method was developed to identify clusters and ranges by technology according to the capacity of each project; and participation based on the energy capable of being generated by range (Table 4 shows the analysis of the results produced by the mathematical model).

2.2.2.2. Set

I: Set of projects, indexed by the subscript i ϵ I.

2.2.2.3. Parameter

dis_{ij}: Squared distance between project i and project j.

2.2.2.4. Variable

X_{ij}: 1 if project i is assigned to cluster j, 0 otherwise.

Table 2: Scenarios of variation in the weighting of evaluation criteria

Evaluation Criterion	Shannon Entropy (%)	Sce. 1 (%)	Sce. 2 (%)	Sce. 3 (%)	Sce. 4 (%)	Sce. 5 (%)	Sce. 6 (%)	Sce. 7 (%)	Sce. 8 (%)	Sce. 9 (%)
Social acceptance	1.29	30	10	10	10	10	10	10	10	12.5
Employment generated	8.33	10	30	10	10	10	10	10	10	12.5
Knowledge regarding technology	1.23	10	10	30	10	10	10	10	10	12.5
Required space	39.29	10	10	10	30	10	10	10	10	12.5
Generated emissions	43.23	10	10	10	10	30	10	10	10	12.5
LCOE	4.13	10	10	10	10	10	30	10	10	12.5
Availability of transportation infrastructure	2.06	10	10	10	10	10	10	30	10	12.5
Average distance to ports	0.45	10	10	10	10	10	10	10	30	12.5

Source: Authors' elaboration

Table 3: Green hydrogen and electricity demand

Demand		Germany	South Korea	Japan
Total H_2 demand (MT*)		3	4	3
Amount of H_2 to be imported (MT*)		2-3	2	1
H_2 demand to be supplied (MT*)		0.03	0.02	0.01

	% to cover	(MT*)	TON of H_2	KWh/year	MWh/year
2030	1	0.06	60,000	2,880,000,000	2,880,000

MT*: Million tons

Source: Authors' elaboration

2.2.2.5. Performance function

Minimize the squared distance of the clusters.

$$Z_{\min} : \sum_{i \in I} \sum_{j \in I} X_{ij} * dis_{ij} \tag{1}$$

2.2.2.6. Restrictions

1. Each project i must be assigned to a single cluster j.

$$\sum_{j \in I} X_{ij} = 1 \forall i \in I \tag{2}$$

2. The main diagonal must sum to 3, meaning that only 3 clusters should be generated.

$$\sum_{i \in I} X_{ii} = 3 \tag{3}$$

3. Project i is assigned to cluster j, only if cluster j is active.

$$X_{ij} \leq X_{jj} \ \forall \ I \in I, j \in I \tag{4}$$

2.2.3. Participation scenarios

Diversification is a crucial element in portfolios to mitigate risk and address fluctuations that may occur in the alternatives that constitute it. Particularly in electricity generation portfolios, diversity is represented by the consideration of different generation sources. In this context, we start from the hypothesis that it is not sufficient to generate variations in the weights of evaluation criteria to obtain diversified portfolios, and therefore it is essential to establish participation scenarios; thus, the following scenarios associated with variations in technology participation were proposed, considering the total generation potential of each (Table 5 summarizes the participation scenarios considered):

- Scenario without participation: Takes the best projects until reaching the required demand.
- Scenario$_i$: Technology i has the highest participation.
- Balance scenario: Attempts to make the participation of different technologies as similar as possible to each other (particularly, considering the data in question, this scenario coincides with Sce. Geoth).
- Current portfolio scenario: Technology participation representative of the country's current generation portfolio.
- Bank representative scenario: Technology participation representative of the generation project bank.

2.2.4. Construction of portfolios and robust portfolios

2.2.4.1. Participation/range/technology

In this case, diversification is mediated by the participation of technologies through projects and their capacities. For this purpose, it was specifically established how much energy each technology should supply based on the participation in terms of electricity of each of its ranges, according to the results of steps 2.2.1 and 2.2.2. for each participation scenario designed in step 2.2.3.

With these specifications, each portfolio was constructed by filtering projects by technology and range, and selecting the best ranked ones until reaching the energy that each range in each technology should supply, according to the results obtained and presented in Table 6. Following this approach, ten portfolios were obtained (one associated with each variation in weights) for each participation scenario.

The idea of robust portfolios is proposed as a strategy to have a generation portfolio considered good across the different weight scenarios proposed.

For each of the participation scenarios with their ten portfolios, the victories that each selected project had against

Table 4: Ranges and participation by technology

Ranges (MW)/Cluster	Representation in generated energy (%)	Ranges (MW)/Cluster	Representation in generated energy (%)	Ranges (MW)/Cluster	Representation in generated energy (%)
Onshore Wind		Photovoltaic		Reservoir	
6.6-150	24.70	0.01-65	25.25	19.9-19.9	2.00
200-378	57.35	70-240	65.73	20-200	19.60
500-500	17.95	750-750	9.02	200.1-800	78.40
Offshore Wind		Geothermal		Run-of-river hydropower	
50-50	56.41	10-10	100.00	0.95-21	36.70
50.1-99.9	43.59			45-75	34.70
				90-98	28.60

Source: Authors' elaboration

Table 5: Scenarios of variation in technology participation

Technology	Sce. without participation	Sce. OnW (%)	Sce. OffW (%)	Sce. Photo. (%)	Sce. Geoth. (%)	Sce. Reser. (%)	Sce. River. (%)	Sce. Balan. (%)	Sce. Current. (%)	Sce. Bank (%)
Onshore Wind	Takes the best projects until reaching the required demand	50	18	12	19	12	12	19	0.45	16.6
Offshore Wind		12	24	12	19	12	12	19	0.11	2.5
Photovoltaic		12	18	50	19	12	12	19	9.54	41.7
Geothermal		3	3	3	3	3	3	3	0.00	0.3
Reservoir		12	18	12	19	50	12	19	84.54	22.7
Run-of-river hydropower		12	18	12	19	12	50	19	5.36	16.2

Considering that the Sce. Geoth. and the Sce. Balan have the same participation, they will be treated as a single scenario henceforth

Source: Authors' elaboration

the others were calculated. These victories were summed, and a new ordering was established from highest to lowest according to these sums. The construction of each robust portfolio was done according to its participation scenario (Table 6). At this level, there were eleven portfolios for each participation scenario, which constituted the portfolio bank to be considered.

2.3. Phase 3. Evaluation and Selection of Generation Portfolios

2.3.1. Portfolio evaluation criteria

The categories and evaluation criteria for generation portfolios included those implemented in the project evaluation, and diversity was established as an additional category, as this is a relevant element that can only be measured at the portfolio level and not in projects individually. Table 7 presents the particular details of each category and criterion.

2.3.1.1. Diversity

This refers to how the participation is distributed among the technologies that constitute the generation portfolio in terms of the energy capable of being generated. The more equitable the participation of technologies in the portfolio, the more diverse it is. For the calculation of such diversity, the following equations were considered according to the literature on the subject (Wu et al., 2011; Zhang et al., 2018):

HHI: Herfindahl-Hirschman Index

$$HHI : \sum_{i \in I} X_i^2 \qquad (5)$$

X_i: Participation of technology i in the generation portfolio.

SWI: Shannon-Wiener Index

$$SWI : -\sum_{i \in I} X_i \ \ln(X_i) \qquad (6)$$

Table 6: Energy to be supplied by range by technology in each participation scenario

Ranges (MW)/Cluster	Representation in generated energy (%)	Sce. OnW	Sce. OffW	Sce. Photo.	Sce. Geoth. and Balan.	Sce. Reser.	Sce. River.	Sce. Current.	Sce. Bank
		2030	2030	2030	2030	2030	2030	2030	2030
Onshore Wind		1.440	526	338	558	338	338	14	479
6.6-150	24.70	356	130	83	138	83	83	3	118
200-378	57.35	826	302	194	320	194	194	7	275
500-500	17.95	258	94	61	100	61	61	2	86
Offshore Wind		338	689	338	558	338	338	3	72
50-50	56.41	191	389	191	315	191	191	2	40
50.1-99.9	43.59	147	300	147	243	147	147	1	31
Photovoltaic		338	526	1.440	558	338	338	275	1.200
0.01-65	25.25	85	133	363	141	85	85	69	303
70-240	65.73	222	346	946	367	222	222	180	789
750-750	9.02	30	47	130	50	30	30	25	108
Geothermal		87	87	87	87	87	87	-	9
10-10	100	87	87	87	87	87	87	-	9
Reservoir		338	526	338	558	1.440	338	2.435	653
19.9-19.9	25.25	7	10	7	11	28	7	47	13
20-200	65.73	66	103	66	109	282	66	477	128
200.1-800	9.02	265	412	265	438	1.129	265	1.910	512
Run-of-river hydropower		338	526	338	558	338	1.440	154	467
0.95-21	36.70	124	193	124	205	124	529	57	171
45-75	34.70	117	183	117	194	117	500	54	162
90-98	28.60	96	150	96	159	96	411	44	133

The scenario values are presented in GWh
Source: Authors' elaboration

Table 7: Criteria and categories - portfolios evaluation

Category	Criterion	Scale	Objective	Source
Diversity	HHI - Portfolio Diversity	1/n - 1	Minimize	[10], [12], [14], [16]
	SWI - Portfolio Diversity	0 - Ln (n)	Maximize	
	e - Portfolio Diversity	0-1	Maximize	
Technical	Weighted average knowledge regarding technologies	# of patents	Maximize	[1], [2], [3], [6], [15]
Social	Weighted average social acceptance	1-10	Minimize	[3], [4], [5], [6], [7], [8], [11], [13]
	Total jobs generated	# of jobs	Maximize	
Economic	Weighted average LCOE	USD/MWh	Minimize	[3], [4], [5], [6], [7], [8], [15]
Environmental	Total required space	m^2 year	Minimize	[1], [3], [4], [6], [7], [8], [9], [13], [14]
	Total emissions generated	TON CO_2 year	Minimize	
Export	Weighted average availability of transportation infrastructure	1-10	Minimize	[17], [18], [19]
	Weighted average distance to ports	Km	Minimize	

Source: Authors' elaboration

e: Entropy

$$e : -k \sum_{i \in I} X_i \ \ln(X_i) \qquad (7)$$

$$k : \frac{1}{\ln(n)} : Normalization\ constant\ .$$

n: Number of technologies.

Each of the criteria presented below maintains the same conception that was considered in the framework of the evaluation of generation projects; however, here the value is taken globally by the portfolio from the projects that constitute it. For the calculation of each of these criteria, the following equations were used:

2.3.1.2. Technical

Weighted average knowledge regarding technologies.

$$CPPT : \sum_{i \in I} \frac{E_i}{\sum_{i \in I} E_i} * pt_i \qquad (8)$$

E_i: Energy generated by project i.

pt_i: Number of patents linked to project i.

2.3.1.3. Social

Weighted average social acceptance.

$$ASPP : \sum_{i \in I} \frac{E_i}{\sum_{i \in I} E_i} * as_i \qquad (9)$$

as_i: *Social acceptance linked to project i.*

Total jobs generated.

$$EmpTG : \sum_{i \in I} Emp_i \qquad (10)$$

Emp_i: *Jobs generated by project i.*

2.3.1.4. Economic

Weighted average LCOE.

$$LCOEPP : \sum_{i \in I} \frac{E_i}{\sum_{i \in I} E_i} * LCOE_i \qquad (11)$$

$LCOE_i$: *Levelized cost of generation linked to project i.*

2.3.1.5. Environmental

Total required space.

$$EspTR : \sum_{i \in I} Esp_i \qquad (12)$$

Esp_i: *Space required by project i.*

Total emissions generated.

$$EmiTG : \sum_{i \in I} Emi_i \qquad (13)$$

Emi_i: *Emissions generated by project i.*

2.3.1.6. Export

Weighted average availability of transportation infrastructure.

$$DPPIT : \sum_{i \in I} \frac{E_i}{\sum_{i \in I} E_i} * dit_i \qquad (14)$$

dit_i: *Availability of transportation infrastructure linked to project i.*

Weighted average distance to ports.

$$DPPP : \sum_{i \in I} \frac{E_i}{\sum_{i \in I} E_i} * dpp_i \qquad (15)$$

dpp_i: *Average distance to ports of project i.*

2.3.2. Portfolio evaluation process

2.3.2.1. Portfolios decision matrix

Once generation portfolio bank and the criteria to be considered for evaluating them were established, the decision matrix was constructed according to each of the established analysis threads. This matrix contains information for each generation portfolio (alternative) measured against each evaluation criterion. This information was derived from the data associated with the set of projects that constitute each portfolio, applying the equations presented in step 2.3.1. The method considered for the evaluation of generation portfolios was TOPSIS.

3. RESULTS AND DISCUSSION

The results of the designed methodology and their discussion are presented through analysis threads, with the aim of identifying the behavior of different portfolios when variations are made in the "Diversity" category, which is considered a critical element in the portfolios. This analysis considers the particularities of the designed participation scenarios and the proposed threads.

Analysis thread 1. The best generation portfolio among the best portfolios from each participation scenario.

From the evaluation of the eleven portfolios in each of the nine participation scenarios, the best generation portfolio was selected in terms of weight (for this case, the portfolio evaluation criteria had equitable weight). Subsequently, with these nine portfolios, a tenth was designed based on victories. These ten generation portfolios were evaluated through TOPSIS.

The best generation portfolios from each participation scenario and the resulting victories portfolio that were considered in the multicriteria evaluation are those presented in Table 8.

Graph 1 demonstrates that when diversity is not accorded sufficient importance, the best generation portfolio is provided by the scenario without participation (Sce. without parti.), which can be explained by considering that this scenario selects the best projects until the required demand is met. This position is maintained even when equal weight is assigned across all categories of criteria, as the projects constituting this portfolio are of such high quality (in terms of criteria other than diversity) that its lack of diversity becomes inconsequential. This behavior is sustained for diversity importance values between 0% and 26.4%, beyond which this portfolio begins to occupy other positions, eventually reaching the penultimate position (9), when the first position is taken by the Sce. OffW, in which Offshore Wind technology has the greatest participation. This result is congruent insofar as this scenario is sufficiently balanced regarding technology participation, given that Offshore Wind cannot achieve participation greater than 24% due to the number of projects utilizing this technology and their respective capacities.

Analysis thread 2. The best generation portfolio from robust portfolios.

This analysis thread focused exclusively on the robust generation portfolios from each participation scenario (Table 9), created by counting the victories of each project across weight scenarios.

For this analysis thread, as observed in Graph 2, the best robust portfolio initially is also provided by the scenario without participation (Sce. without parti.) when the importance of diversity is between 0% and 21.8%. When diversity assumes an importance between 21.9% and 27%, the best robust portfolio is delivered by the Sce. Photo, that prioritizes the participation of photovoltaic technology; between 27.1% and 98% the best portfolio is provided by Sce. Geoth. and Balan, which seeks balance among technology participation and particularly coincides with the scenario that prioritizes geothermal technology participation; this explains its diversity insofar as it favors similar participation across technologies. Finally, for importance values between 98.1% and 100%, the best portfolio is delivered by Sce. OffW, in which Offshore Wind technology has the greatest participation.

Table 8: The best generation portfolios/participation scenario

Scenario	Best Portfolio	Scenario	Best Portfolio
Sce. without parti.	Sce. 8	Sce. Reser.	Sce. 6
Sce. OnW	Sce. 6	Sce. River.	Sce. 10 - Victories
Sce. OffW	Sce. 6	Sce. Current.	Sce. 10 - Victories
Sce. Photo.	Sce. 3	Sce. Bank	Sce. 9
Sce. Geoth. and Balan.	Sce. 6	Sce. Victories	Victories of the above

Source: Authors' elaboration

Table 9: Robust generation portfolios/participation scenario

Scenario	Robust Portfolio	Scenario	Robust Portfolio
Sce. without parti.	Sce. 10 - Victories	Sce. Reser.	Sce. 10 - Victories
Sce. OnW	Sce. 10 - Victories	Sce. River.	Sce. 10 - Victories
Sce. OffW	Sce. 10 - Victories	Sce. Current.	Sce. 10 - Victories
Sce. Photo.	Sce. 10 - Victories	Sce. Bank	Sce. 10 - Victories
Sce. Geoth. and Balan.	Sce. 10 - Victories		

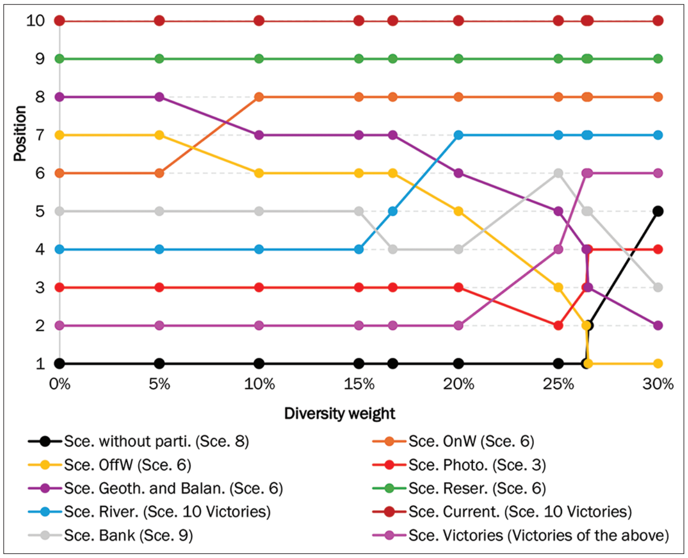
Source: Authors' elaboration

As in analysis thread 1, when diversity is not considered a truly important element in portfolio evaluation, the multicriteria analysis method will select the generation portfolio that performs best in the other metrics, considering that the projects constituting each portfolio were evaluated and ranked based on them. In this case, one would have a robust portfolio, but not necessarily a diverse one, hence the importance of analyzing and establishing at what diversity weight one can begin to guarantee not only robustness but also diversity in the portfolios.

Analysis thread 3. The best generation portfolio from balanced portfolios.

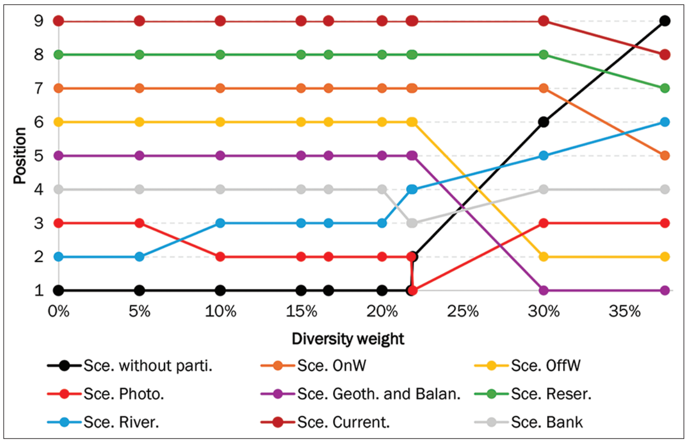
This thread considered only the balanced generation portfolios from each participation scenarios (Table 10), that is, those constructed considering equal weights in the evaluation criteria. With this set of nine portfolios, a tenth was designed based on victories.

Graph 1: Rankings analysis thread 1 - impact of the "diversity" category



Source: Authors' elaboration

Graph 2: Rankings analysis thread 2 - impact of the "diversity" category



Source: Authors' elaboration

Table 10: **Balanced generation portfolios/participation scenario**

Scenario	Balance Portfolio	Scenario	Balance Portfolio
Sce. without parti.	Sce. 9	Sce. Reser.	Sce. 9
Sce. OnW	Sce. 9	Sce. River.	Sce. 9
Sce. OffW	Sce. 9	Sce. Current.	Sce. 9
Sce. Photo.	Sce. 9	Sce. Bank	Sce. 9
Sce. Geoth. and Balan.	Sce. 9	Sce. Victories	Sce. 9

Source: Authors' elaboration

Balance suggests equality in weightings. As shown in the Graph 3 in this case, it is also evident that when diversity is not given relevant importance, variations in the ranking are minimal or nonexistent. For example, in the range between 0% and 24.1% importance in diversity, variations occur in only five of the scenarios, and in all cases, the scenario without participation (Sce. without parti.) maintained the first position. However, when the importance of the category is between 24.2% and 35.8%, the best-balanced portfolio is delivered by Sce. Bank, which is representative of the project bank; between 35.9% and 96.4%, the best portfolio proves to be from the Sce. OffW, in which Offshore Wind technology has the greatest participation; for importance values between 96.5% and 99.4%, the best portfolio is determined to be the one delivered by Sce. Victories, constituted by the victories of all balanced portfolios; finally, between 99.5% and 100%, the best portfolio is delivered by the Sce. Geoth. and Balan, that seeks balance among participation and which, in this context, coincides with the scenario that prioritizes geothermal technology participation. Notably, the scenario without participation reaches the worst position (10) when the importance of diversity is 37.4% and above.

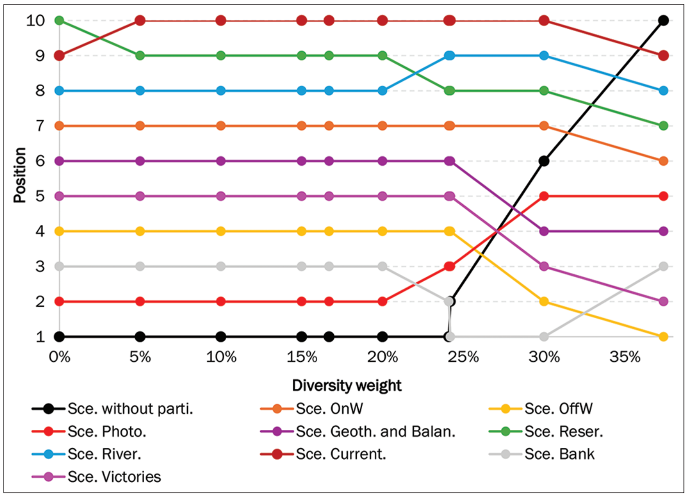
In analysis threads 1, 2, and 3, the generation portfolios that prove to be the best immediately after transitioning from the scenario without participation to one with participation, given the increases in the importance of diversity, demonstrate better performance against the economic evaluation criterion, in this case the LCOE, which is consistent with findings reported by Casas Ferrús et al. (2024), who assert that diversity has a positive impact on portfolio costs.

Analysis thread 4. Weight scenario with best performance in each participation scenario**.**

This analysis began with the evaluation of the eleven portfolios from each of the nine participation scenarios, considering the established generation portfolio evaluation criteria and equal weight in each category. With this, the best generation portfolio in terms of weight was selected through the presented multicriteria analysis method. The results were presented on Table 8.

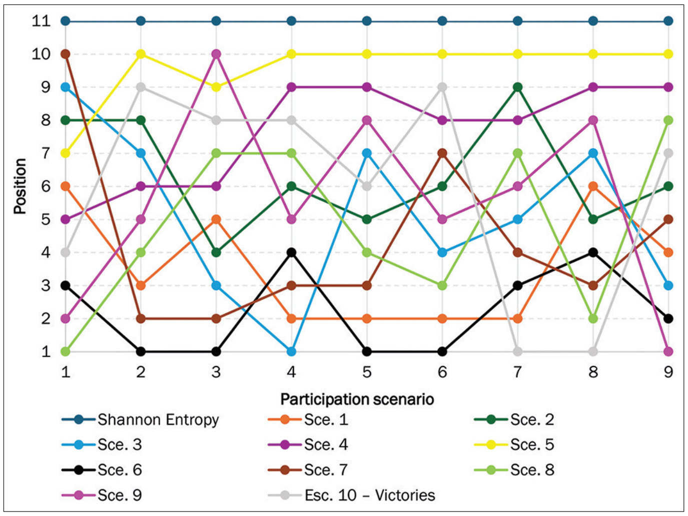
As observed in Graph 4, for the participation scenarios Sce. OnW (2), Sce. OffW (3), Sce. Geoth. and Balan (5) and Sce. Reser. (6), the best generation portfolio is the one that favors portfolio cost, that is, Sce. 6; for the participation scenarios Sce. River (7) and Sce. Current (8), the best portfolio is the one with robust characteristics, that is, Sce. 10 - Victories. Finally, the portfolio that favors average distance to ports (Sce. 8), the one that favors knowledge regarding technology (Sce. 3) and the one that favors balance among criteria (Sce. 9), were selected in at least one of the participation scenarios, which in this case were Sce. without parti. (1), Sce. Photo (4) and Sce. Bank (9) respectively.

Graph 3: Rankings analysis thread 3 - impact of the "diversity" category



Source: Authors' elaboration

Graph 4: Rankings/participation scenario - analysis thread 4



Source: Authors' elaboration

Particularly in this analysis thread, across all participation scenarios, the generation portfolio that exhibited the worst performance with respect to the portfolio evaluation criteria was the one that considered the weights assigned by the Shannon Entropy Method.

4. CONCLUSION

Multicriteria analysis methods are effective tools that support the decision-making process in complex contexts, considering multiple alternatives and criteria. Specifically in this study, these methods were implemented for the definition of weights and the evaluation of electricity generation projects and portfolios.

Considering the relevance of diversity in portfolios, the analysis in the selection process focused on the impact on ranking when variations occur in the importance of the "Diversity" category, while also considering that the remaining evaluation criteria were included in the project evaluation process, and therefore, projects that constitute each portfolio are already sufficiently good within their technology and generation range, according to these metrics.

The results allow us to conclude that in all analysis threads, portfolios without participation are efficient when evaluated against criteria that do not consider diversity. Therefore, the weight of the "Diversity" criterion must be very carefully analyzed and established for electricity portfolios, as minimal relevance generates minimal or no variations in the ranking, and thus it is necessary to determine the preference threshold at which diversity begins to play an important role in the decision.

Based on the results derived from the analysis threads, the relevance of diversity in the evaluation is evident, as significant modifications in the ranking only begin to appear when this portfolio characteristic plays an important role in their evaluation. Specifically, according to the analysis threads, this importance of the category begins to have an impact on the ranking when it reaches weights above 21.9% (thread 2) and 26.5% (thread 1).

It was also observed through analysis thread 4 that in all participation scenarios, the portfolio with the worst performance was the one that considered the weightings provided by the Shannon Entropy method for project evaluation; this may suggest that it is not advisable to bias or make decisions considering only an objective approach to the importance of criteria, since in practical applications—if there is no community acceptance regarding the project development, for instance—the project simply cannot be executed, despite the fact that according to the method, this criterion has a weighting of only 1.29%.

Furthermore, it can be concluded that generating scenarios of criteria weights and jointly evaluating the behavior of projects against these makes it possible to obtain robust portfolios, but not necessarily diverse ones. Therefore, it is important to consider participation scenarios to induce a level of representativeness by technology within the portfolio, with heterogeneity in project capacities.

A fundamental and differentiating element in this study is that aspects associated with energy transition and export are proposed and considered as central focuses in the evaluation process of both projects and portfolios. This, bearing in mind the current need to transition towards cleaner energies and the particular situation faced by some fossil fuel exporting countries regarding this transition.

Additionally, the methodology proposed in this research considers generation projects as input data in the construction of portfolios, which enables evaluations and estimations of green hydrogen production potential based on already declared renewable energy generation intentions at the national level.

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