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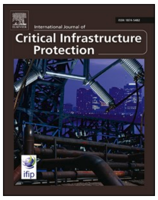

Assessment of cross-border electricity interconnection projects using a MCDA method

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ABSTRACT

The European Union is promoting cross-border electricity interconnection projects to achieve energy objectives, reduce the current fragmented European market, and eradicate the isolation of the most disadvantaged areas. However, selecting these projects is a complex task because there are multiple objectives, criteria, participants and alternatives involved. This paper aims to develop a multi-criteria decision analysis (MCDA) method for appropriately assessing and prioritizing cross-border electricity interconnection projects considering technical, economic, environmental and social criteria. Additionally, this work analyzes interconnection effects on the resilience of interconnected power systems. To verify its validity, this method is applied to prioritize new Spain-France interconnection infrastructure projects. From the results obtained, the technical and environmental criteria have proven to be the most important, since cross-border electricity interconnection projects are aimed at better market-coupling, less congestion and higher reliability while minimizing environmental impacts. In short, the proposed methodology provides a comprehensive view of the impact of these projects.

1. Introduction

The European Union (EU) aims at balancing sustainable development with competence and electricity supply security. In the context of an increasingly complex geopolitical environment and the fight against climate change, in recent years, the EU has promoted an ambitious energy policy based on the following three main objectives: promoting energy efficiency, applying measures for reducing greenhouse gas emissions and developing renewable energy sources [1].

Since the EU strongly depends on external gas and oil for its energy supply security, electricity interconnections play a key role in ensuring the functioning of a fully integrated internal energy market that guarantees affordable energy prices. Electricity interconnections also contribute to electricity supply security, facilitating support functions between neighboring systems and reducing dependence on gas from third countries. Another advantage of cross-border interconnections is to improve the use of renewable energy by enabling countries with excess renewable capacity to export this energy, thereby avoiding the need to restrict renewable sources that cannot be used locally and reducing the reserve generation capacity [2,3].

Despite the numerous benefits of cross-border interconnections, the development of new interconnections is slow for political (interests of different agents involved in electricity systems, such as operators, regulators, and producers) and financial reasons, among others [4–6]. Accordingly, the EU has introduced a category of projects called Projects of Common Interest (PCIs), which are crucial for developing its transport, storage and smart grid infrastructure and achieving its energy goals to become climate neutral by 2050 [7]. These projects must have a significant impact on energy markets in improving their competence and common energy security through the diversification of sources and the integration of renewable energy. In addition, PCI projects can benefit from faster administrative procedures, adequate environmental assessment and possible financial assistance for their implementation.

Traditionally, Cost-Benefit Analysis (CBA) tools have been used to find strategic solutions in the electricity sector. This analysis focuses on the economic justification of investments. Everything that can be translated into monetary units is tallied. However, by using these tools some impacts of the projects are difficult to assess, such as environmental impact, electricity system security, and social impact, among others. In recent years, Multi-Criteria Decision Analysis (MCDA) methods have been chosen to structure and analyze more complex problems and conflicting contexts. These planning techniques may help decision makers assess and prioritize projects under several criteria without having to express them as monetary units. In other words, these

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criteria can be expressed in quantitative or qualitative values using various scales. In addition, all interested parties of a project can participate in MCDA, leading to a reliable and realistic assessment. Another advantage is the possibility to perform a sensitivity analysis of the most influential factors in decision making [8–10].

Some studies review multi-criteria decision-making (MCDM) methods used in previous papers on energy resource planning to identify the basic concepts of these methods and understand their advantages and limitations, criteria assessment, and applications [11–13]. Work [11] assesses different mathematical methods used for electrification planning in rural remote areas between 1970 and 2013. This is a consequence of the fact that energy planning problems are complex and involve multiple decision criteria. Therefore, it is necessary to use methods that include the other complementary aspects of economic or technical criteria, such as environmental and social criteria, and overcome the limitations of one-dimensional planning. The authors of [12] present an overview of various MCDM techniques for RES-based energy planning. According to this article, AHP method is flexible, intuitive and allows to deal with criteria qualitatively and quantitatively, although it could become more complex when applied to several criteria. It is mainly applied in energy storage planning problems, power quality, energy allocation, optimal dispatch and sustainability in the field of renewable energy. On the other hand, ELECTRE methods are mainly used in applications related to the choice of energy allocation on the demand side. These methods represent the decision-maker's preferences over the set of alternatives. It is a model that uses various mathematical functions to indicate the degree of dominance of one alternative over another. ELECTRE is the least versatile method. Paper [13] analyzes previous studies to identify trends in the renewable energy literature from 2009 to 2019. According to this article, the most commonly used methods are the following: AHP, ELECTRE and TOPSIS. It points out the same features of the AHP and ELECTRE methods of works [11,12]. TOPSIS method allows decision-makers to obtain the best alternative that is as close as possible to the positive ideal solution and as far as possible from the negative ideal solution. This model is inadequate to assess qualitative criteria and is used with other methods such AHP or ANP, among others. In short, the reviewed articles indicate that all methods have their strengths and weaknesses and their use will depend on the required application.

Regarding the application of these decision-making techniques to power systems, the authors of [14] propose a hybrid MCDM method, simultaneously combining two techniques, Analytic Network Process (ANP) and Benefits, Opportunities, Costs and Risks (BOCR), to assess and prioritize energy strategies in Turkey. The work [15] combines the technique Fuzzy Analytic Hierarchy Process with Grey Relational Analysis to study the electricity supply sustainability and security in different countries (Brazil, Russia, India, China and South Africa). The authors of [16] apply the Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS) to compare different Institute of Electrical and Electronics Engineers - Reliability Test System 96 (IEEE-RTS-96) topologies based on reliability and vulnerability criteria. The study [17] also uses this technique to study the sustainability of the electricity sector in European Union countries in 2017.

According to cross-border interconnections, previous works have focused on the analysis of their economic impact, such as those on Spain-France [18] and Korea-Japan [19] cross-border electricity interconnection and on West Africa's interconnected electricity network [20]. The article [18] quantifies the potential revenue to a cross-border interconnector using a stochastic model of domestic spot prices. The authors of [19] propose an energy-economic model to assess the impact of interconnections on CO_2, NOx and SOx emissions and on electricity cost, whereas the paper [20] also studies the impact on electricity generation cost, rapidly growing demand and cross-border electricity trade.

Based on literature review, previous works use multi-criteria methods for energy planning related to the assessment of renewable sources, energy policies or the selection of the best site for the installation of renewable power plants. In order to analyze cross-border electricity interconnection projects, the cost-benefit analysis has been mostly applied [21–23]. As mentioned above, CBA tool does not include all the criteria involved in cross-border interconnection projects (technical, economic, social and environmental criteria). When using cost-benefit analysis, there are benefits of a project that may be difficult to quantify in monetary terms, for example, environmental or social aspects, which can lead to subjective valuations. In this context, it is necessary to use a multi-criteria technique that involves all the participants and criteria to improve decision-making in the development of a cross-border electricity interconnection project and to obtain greater reliability of the results obtained.

Therefore, the gaps in the literature are the following:

- Limited application of multi-criteria techniques in the assessment of cross-border electricity interconnection projects.
- Previous works do not study all the criteria related to this type of projects.

In this regard, the paper's main strength lies in its relevance to an important topic related to cross-border electricity interconnection projects. The inclusion of technical, economic, environmental, and social criteria ensures a comprehensive assessment of the interconnection projects.

Energy transition and energy security are linked, since there is concern about the stability and reliability of the electricity supply with the growing integration of renewable generation sources into power systems. Cross-border electricity interconnections play a crucial role in advancing the energy transition and ensuring energy security in an ever-changing world, as they make it possible to share surplus energy generated and diversify energy sources between countries in the event of sudden interruptions or crises in energy supply. Therefore, interconnections lead to a robust and reliable electricity system with high share of renewables that allows for real-time balancing of supply and demand. In this regard, to overcome the previous gaps, this article aims to develop and apply a MCDA methodology to study and prioritize cross-border electricity interconnections in the European electricity transmission network under technical, economic, environmental and social criteria. The proposed use of a MCDA method for the assessment and prioritization show promise in providing valuable insights for decision-making in the energy sector. Additionally, this paper identifies and analyzes the indicators included in cross-border electricity interconnection projects that are related to the resilience of interconnected power systems. The proposed method is applied to assess new Spain-France electricity interconnection projects funded by the European Union under the program of key cross-border infrastructure projects, also known as PCIs.

In summary, the main contributions of this paper are the following:

- The development of a multi-criteria methodology for the analysis and assessment of cross-border electricity interconnection projects.
- The incorporation of the social, economic, technical and environmental criteria involved in cross-border electricity projects.
- The analysis of indicators to study the reliability, robustness and restoration of power systems.

The remainder of this paper is organized as follows: Section 2 presents the selected multi-criteria method and the proposed methodology. Subsequently, Section 3 explains the indicators selected to apply the MCDA technique. Section 4 applies the methodology to a case study. Section 5 discusses in depth the relationship of specific indicators with the reliability, robustness and restoration of power systems. Lastly, Section 6 summarizes the major conclusions drawn from this article.

2. Description of the proposed methodology

The purpose of this work is the planning of a multidimensional decision process that considers economic, technical, social and environmental aspects to assess and prioritize adequately a portfolio of electricity interconnection projects. The selection of the most cost-effective project among a set of alternatives is one of the major difficulties faced by network managers, so the application of the multi-criteria analysis technique proposed in this paper can serve as a support tool in decision-making.

2.1. Research methodology

This section outlines the steps considered for this research.

(1) As a first step, an exhaustive search of articles using multicriteria techniques for decision making in energy planning problems had to be carried out in different journals and databases. The search was mainly focused on papers published in indexed journals due to their higher quality.
(2) It was found that there are hardly any articles where multicriteria methods are applied to problems of selection and prioritization of cross-border electricity interconnection projects.
(3) Subsequently, a challenge is the selection of criteria in this complex issue with multiple objectives (economic, environmental, social and technical).
(4) From the literature reviewed, the AHP method was selected due to its multiple advantages. The hierarchical structure of the method allows for a detailed analysis, the possibility of integrating quantitative and qualitative criteria and the integration of the experts' specialized knowledge enables well-founded decisions, and the verification of the consistency of the judgments leads to ensure that the assessment is coherent and reliable.
(5) Finally, a sensitivity analysis was performed by varying the weights of the criteria to verify the validity of the method.

2.2. AHP method

First, in order to select the multi-criteria method, the characteristics of the planning of cross-border electricity interconnections have been considered. This process includes various criteria of different nature, such as costs, transmission capacity, environmental impact, security and reliability of the system, among others. Therefore, a combination of technical expertise, environmental experience, strategic considerations, etc. is required. In addition, both quantitative and qualitative criteria must be able to be assessed.

In this regard, among the MCDM techniques, the Analytical Hierarchy Process (AHP) has been selected in this article. The AHP method was developed by Thomas L. Saaty in order to solve complex multi-criteria problems. Its hierarchical structure makes it possible to efficiently organize data on a problem, decomposing and analyzing them by parts, providing an objective and reliable result [24]. It stands out its flexibility with the use of quantitative or qualitative data, its ability to consider multiple criteria and structure them in a hierarchical way, the participation of experts and stakeholders in the decision making process, and the use of a relative comparison scale to analyze the importance of the criteria and preference among alternatives. This fact leads to guarantee the coherence and consistency of decisions in addition to obtain an overview of the problem that favors the understanding of all the criteria involved [12,13]. This method is the most widely used method for solving energy planning and operation problems [25–30].

The AHP method is based on:

- The definition of the participants and the problem.
- The structure of the hierarchical model: Identification of elements (criteria and sub-criteria).
- Prioritization of the elements of the hierarchical model.
- Binary comparisons between elements.
- Assessment of the elements by assigning "weights".
- Ranking of the alternatives according to the assigned weights.
- Synthesis.

In short, the AHP method is a decision model that allows data and information to be interpreted directly through judgments and measurements on a ratio scale within a hierarchical structure. This method is based on the direct interrelation of the decision maker with the analyst, so that the experience and knowledge of the former is as important as the values used in the process.

2.3. Proposed methodology

Fig. 1 shows the algorithm of the proposed decision-making methodology using a multi-criteria tool to prioritize cross-border electricity interconnection projects. Next, each of the steps that make up the developed methodology are explained.

Step 1. First, the cross-border electricity interconnection projects on which the multi-criteria technique is applied are selected. According to reference [31], information on planned transmission projects in Europe can be found.

Step 2. Next, indicators that directly affect electricity interconnection project selection should be chosen based on available data from the EU for the assessment of the costs and benefits of these projects [32]. However, this article proposes a reclassification to implement technical, economic, environmental and social criteria necessary for a complete energy planning. First, these four criteria are established to provide an overview of the problem, subsequently setting different sub-criteria within the four selected criteria.

Step 3. The indicators, as shown in the EU data [32], have their specific units and in order to have uniform results and to be able to compare projects later on, the values of these indicators must be standardized. Therefore, the previous data are then normalized according to the target country data to obtain uniform results in%. The values of the electricity situation of the country and year of study are assessed, including renewable electricity generation, electricity demand, and emissions of CO_2 and other pollutants, among others. In addition, the total cost of each project is calculated assuming a lifespan of 40 years [33]. As indicated in this report, according to European regulations, the lifespan of power transmission line projects is long and, in general, a value of 40 years is assumed.

Step 4. In this step, a matrix is constructed with normalized values to the total number of projects under analysis. There are two possible cases:

- The increase in the indicator has a positive impact: In this case, 100 % is assigned to the project with the highest value and the rest are calculated proportionally.
- The increase in the indicator has a negative impact: In this case, 100 % is assigned to the project with the lowest value and the rest are calculated proportionally.

The AHP method is applied based on this matrix. This paper has used the support software available for the application of this method [34].

Step 5. Several groups of decision makers must be considered to obtain a reliable and realistic assessment of projects because the experience of each decision maker will help to enrich the solution. The total set of decision-makers should be made up of professionals or specialists from different areas related to electricity infrastructure planning, socio-environmental impact of energy systems, planning and land management, among others. Questionnaires are used to carry out the consultations.

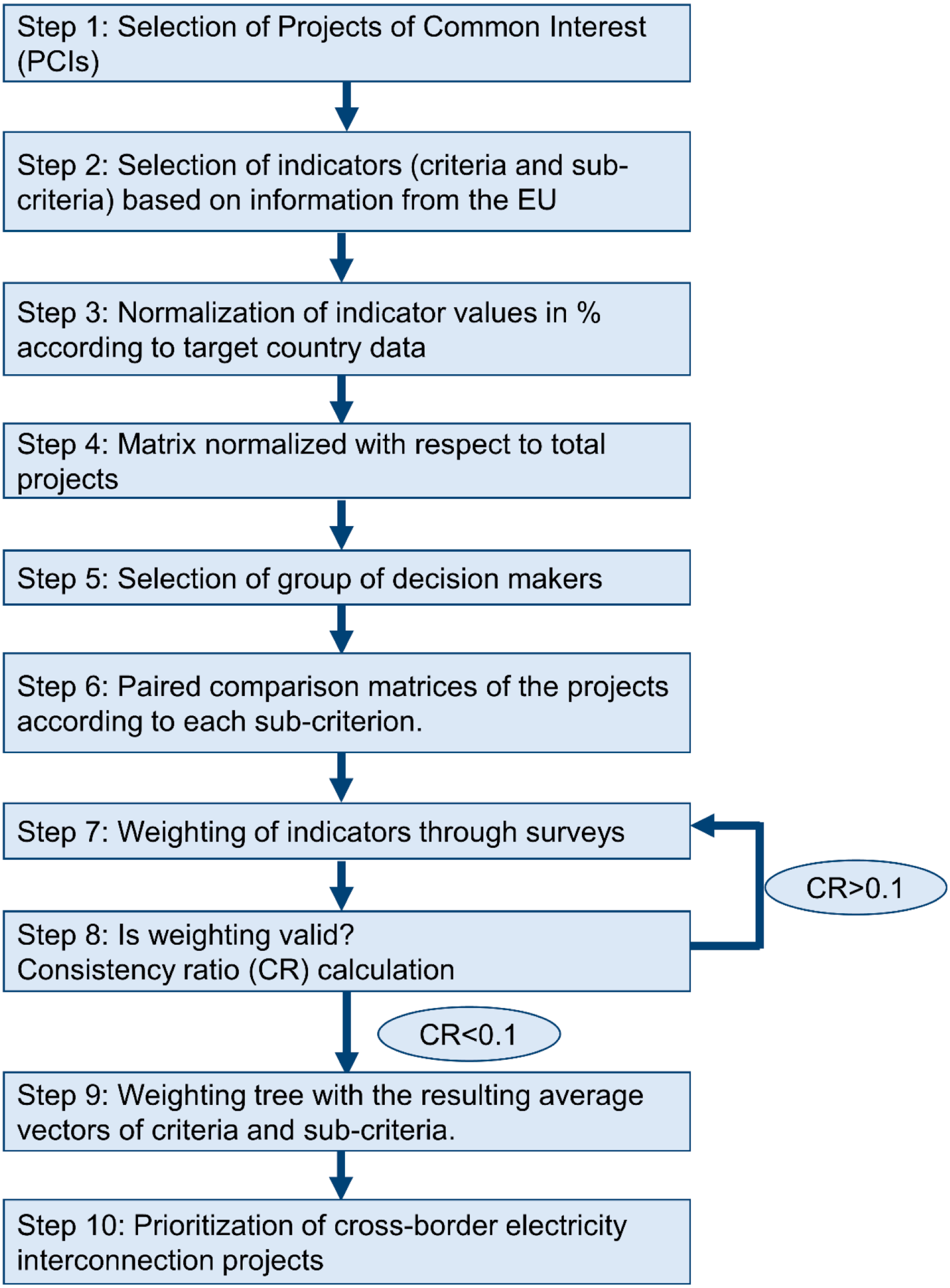

Fig. 1. Methodology proposed in this article.

Therefore, the following groups are proposed for the development of this work:

- Academics: university professors and researchers.
- Technicians: Network operators and experts in the electricity industry.
- Regulators: environmental management institutes and energy commissions.
- Associations: consumer associations and environmental groups.

Step 6. Next, the selected (social, technical, economic and environmental) criteria are compared, and this procedure is then repeated again to compare the sub-criteria. Therefore, in this case, a total of 5 pairwise comparison matrices are obtained (matrix of criteria and matrices for each group of sub-criteria within each criterion), and subsequently the average vector of each criterion and sub-criterion is calculated.

Step 7. In this step, the different indicators are weighted through surveys sent to groups of experts. Based on their preference, experts score the criteria using the Saaty scale (see Table 1). The opinions of different groups of decision makers may have different weights, so they must judge the order of importance of the groups of decision makers. The collective preference is determined using the geometric mean method because this method complies with the principle of reciprocity [35]. Although the geometric mean is less intuitive than the arithmetic mean, it is a measure that is less sensitive to extreme values than the arithmetic mean of a statistical sample. In addition, the geometric mean is suitable for calculating percentage variables or ratios. On the other hand, the reciprocity property of a comparison matrix refers to the relationship between the elements of the matrix. In AHP, if criterion *a* is preferred over criterion *b* with a certain value, then criterion *b* should be preferred over criterion *a* with its inverse value. Applying this principle of reciprocity ensures the consistency and reliability of the comparisons made in the AHP, which is essential to obtain accurate results in the decision-making process.

Step 8. The next step consists of calculating the consistency ratio to validate the judgments obtained in the surveys. According to AHP method [26], for the results to be considered adequate, the consistency ratio must be lower than 0.1. If this condition is not met, the decision makers must repeat their assessments until satisfying this constraint.

Step 9. Subsequently, with the weights resulting from the criteria and sub-criteria, a weighted tree is constructed with all the data obtained in the previous steps and the final weighting of each sub-criteria.

Step 10. Finally, the projects are prioritized by applying the final weights obtained in the previous step (step 9) to the normalized project matrix (step 4). The project with the highest value will provide the best benefits under the assessed criteria.

In short, the main steps to be considered in this methodology are the analysis of the information on costs and benefits published by the European Union to select cross-border electricity infrastructure projects [32]. From this information, the selection of criteria and sub-criteria is essential. A distinction must be made among technical, economic, social and environmental criteria, as these are the criteria to be taken into account in the planning of this type of project. Then, the standardization of these indicators according to the country of destination of these electrical infrastructures must be performed in order to obtain the matrix that will serve as a basis for the application of the AHP method. An important aspect is the proper identification of the decision groups, since they must be experts in each of the selected criteria to compensate the strengths and weaknesses between them. Finally, verification of the consistency of the results obtained is carried out.

3. Indicator selection

Electricity interconnection projects are decisive for the energy transition, so interconnection reinforcement is a priority in the development of the European electricity transmission network in the coming years. Cross-border interconnections have numerous technical and economic benefits in the interconnected countries:

- Increased integration and exchange of renewable energy
- Reduced dependence on imported fossil fuels and, therefore, decreased carbon dioxide emissions
- Improved electricity system security and reliability
- Decreased need for power plants to supply peak demand
- Increased number of possibilities of sharing regulation reserves
- Increased price competition between neighboring electric power systems

This section presents the indicators selected in this paper that directly affect the selection of one cross-border electricity interconnection project or another. First, four criteria have been established to obtain a global vision of the problem and then different sub-criteria within the four criteria mentioned above. As previously mentioned, the indicators used in MCDA to select transmission and storage projects are chosen based on the information obtained from the EU for the assessment of the costs and benefits of these projects [Anon., 32]. However, this article proposes a reclassification to implement technical, economic, environmental and social criteria necessary for obtaining a complete energy planning. Therefore, here, each indicator is associated with a sub-criterion, which in turn is grouped into social, economic, environmental and technical criteria. The indicators to be treated using the multicriteria project selection technique presented in Section 2 are identified and explained below.

The criteria selection of this paper is based on previous research [36–38]. These works point out the importance of incorporating economic, environmental, technical and social criteria to comprehensively study energy alternatives. Some of the criteria to be included are investment and operating costs, greenhouse gas emissions, impact on biodiversity, availability of energy resources, and public acceptance, among others. Thus, the criteria selected from the literature reviewed provide a robust and balanced framework for energy planning.

3.1. *Social criteria*

3.1.1. *Socioeconomic welfare (S1)*

Socioeconomic welfare is an indicator related to the reduction of congestion in power grids. By increasing the exchange capacity between two areas, generators in the lower-priced area can export energy to the higher-priced area. Therefore, this indicator is assessed as the reduction in variable generation costs in the transmission network provided by a project. This indicator is based on market studies and measured in euros/year.

3.1.2. *Residual social impact (S2)*

This indicator characterizes the impact of the project on the population based on assessments of preliminary studies. This indicator is expressed as the number of km that the electricity interconnection crosses in socially sensitive areas.

3.2. *Economic criteria*

3.2.1. *Investment costs (EC1)*

This indicator corresponds to investment costs related to the expenses in licenses, feasibility studies, design, land acquisition, execution, among others, required to start a project. The calculation of this indicator is based on public information from similar projects and is expressed as euros.

3.2.2. *Operation and maintenance costs (EC2)*

This indicator corresponds to operation costs that include both direct and indirect labor for infrastructure exploitation. Conversely,

Table 1
Saaty scale.

Value	Description
1	criterion *a* is equally preferable to criterion *b*
3	criterion *a* is slightly preferable to criterion *b*
5	criterion *a* is strongly preferable to criterion *b*
7	criterion *a* is very strongly preferable to criterion *b*
9	criterion *a* is extremely preferable to criterion *b*
2, 4, 6, 8	intermediates values

maintenance costs cover all expenses needed to ensure the lifespan of the equipment and systems. These costs are expressed as euros.

3.3. Environmental criteria

3.3.1. Variation in CO_2 emissions (EN1)

EN1 quantifies the change in the volume of CO_2 emissions in the electricity system resulting from the benefits of the project under analysis. This indicator measures the CO_2 emissions avoided due to the implementation of the project in tons of CO_2/year.

3.3.2. (Non-CO_2) emissions reduction (EN2)

This indicator represents the benefit associated with the reduction of emissions of air pollutants other than CO_2 (NOx, SOx, and non-methane volatile organic compounds (NMVOC)). This indicator is expressed as tons avoided/year.

EN2.1: NOx emissions reduction indicator
EN2.2: SOx emissions reduction indicator
EN2.3: NMVOC emissions reduction indicator

3.3.3. Residual environmental impact (EN3)

This indicator characterizes the impact of the project associated with nature and biodiversity and based on assessments of preliminary studies. This indicator is measured in the number of km that the interconnection crosses in sensitive environmental areas.

3.4. Technical criteria

3.4.1. Integration of renewable energy (T1)

This indicator represents the project's contribution to the integration of renewable energy sources, i.e., the system's capacity to enable the connection of these resources. This indicator is measured as the value of the avoided curtailment of renewable energy (MWh/year) because the project reduces or avoids the need to apply the mechanism of technical constraints due to distribution network overloads or voltage control and the replacement of renewables by conventional electricity generation.

3.4.2. Variation in distribution network losses (T2)

T2 measures the energy efficiency of a project. Generally, transmission projects arise from the need to transport electricity over long distances, which implies an increase in global system losses. This indicator is expressed as MWh/year and is based on network studies. These network studies are based on regional grid models. These models should include at least the relevant bidding countries/areas for the assessed project, typically the host countries, their neighbors, and countries where the project has a significant impact in terms of cross-border capacity or generation pattern. Then, the power line losses can be obtained by calculating the CA power flow [32].

3.4.3. Electricity supply security: expected energy not supplied (EENS) (T3)

EENS corresponds to the power cut to the electricity system due to outages resulting from incidents in the transmission network of the electricity system. The project for a new cross-border interconnection line may facilitate the adaptation of the electricity system by increasing the generation capacity when facing lost load and meet demand at any time. This indicator (T3) is calculated using Monte Carlo simulations with several climatic datasets and plant (and, if possible, network) disruption patterns. It is expressed as MWh reduced of EENS/year. When performing security of supply assessments, it is essential to model a large number of potential demand and generation availability scenarios. Simulations are performed over 510 years in each region analyzed (34 climate years, with variations in the availability of renewable resources such as hydro, wind and solar energy, and 15 forced outage patterns to model network availability). This number of simulations provides a wide range of demand and generation availability scenarios, which inherently include some high impact, low probability events. Therefore, it allows for a robust assessment of EENS indicator [32].

3.4.4. Electricity supply security: additional coverage margin (T4)

Additional coverage margin is the electricity generation capacity that would not be necessary to install after implementing the project under assessment while maintaining the same level of energy not supplied.

Transmission capacity increases the adequacy margin by enabling the use of surplus generation located elsewhere. T4 replaces the construction of additional electricity generation capacity in a specific area. This indicator is calculated through market simulations for each hour of the year, obtaining the level of electricity generation capacity required in the different areas with and without a project, measured in MWh.

3.4.5. Electricity supply security: system flexibility (T5)

This indicator measures the impact of the project on increasing the capacity of the electricity system to adapt to rapid and profound changes in net demand under high levels of renewable energy generation due to the intermittency and variability of these sources.

This indicator is measured using the value of the net demand corresponding to the difference between electricity demand and renewable energy generation [39]. Therefore, the T5 indicator is expressed as the quotient between the increase in network transfer capacity and remaining hourly ramp of net demand, measured in%.

The calculation process of this indicator is defined below (see Fig. 2):

- Hourly ramp of net demand (Ro), measured in MW
- Existing grid transfer capacity (GTC) without a new interconnection
- Remaining hourly ramp of net demand (Rr), calculated as the difference between Ro and GTC.
- Increased GTC, ΔGTC, with the new cross-border interconnection project
- Indicator, expressed as percentage of the quotient between ΔGTC and Rr.
    - If Rr is negative, the flexibility percentage will be 0 % because the existing transfer capacity is greater than the hourly ramp, and the new project will not improve this indicator at all.
    - If Rr is equal to ΔGTC, the flexibility percentage will be 100 %; therefore, the increased transfer capacity added by the new project will suffice to completely cover the ramp throughout the year.

3.4.6. Electricity supply security: system stability (T6)

This indicator qualitatively measures the impact of the project on the electricity supply stability (transient (T6.1), voltage (T6.2) and frequency (T6.3) stability), depending on the physical elements that the electricity interconnection incorporates into the system. Therefore, a value of 0 means that the project does not provide any improvement; +, provides a small improvement; and ++, provides a significant improvement.

In this paper, the values of these indicators, calculated by the system operators for each of the projects to be assessed [31], are normalized according to the target country. This allows the construction of a matrix of normalized values in% with the selected project portfolio.

In short, based on the assessment of costs and benefits of cross-border electricity infrastructure projects from a European perspective, the criteria and sub-criteria included in this article have been selected [32]. This source has been used to identify these indicators since this assessment constitutes a common and uniform basis for the evaluation of projects with respect to their value to European society.

4. Case study

4.1. Case study definition

The European Union is promoting new cross-border electricity

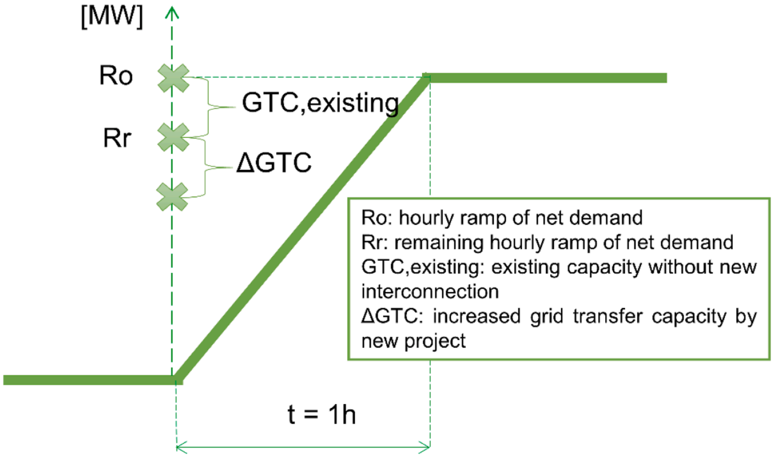

Fig. 2. Concept of electricity system flexibility.

interconnection projects for two key reasons:

- On the one hand, to guarantee that the internal electricity market in Europe favors the most economical energy exchange and strengthens electricity supply security, both through cooperation among member states and diversification of the construction of new electricity generation systems with renewable sources.
- On the other hand, to accelerate the energy transition, facilitating the exchange of electricity from renewable sources. The EU has prioritized interconnections between Spain and France to improve the cross-border interconnection ratio of Spain, which is still much lower than that of the other member countries. The goal is to solve the problem of the electrical isolation of Spain, which is considered an energy island due to its low capacity to exchange electricity with Europe. Increasing cross-border interconnections may improve the electricity supply security and continuity and the integration of renewable energy sources.

Therefore, to validate the proposed methodology, three Spanish electricity interconnection infrastructures proposed in EU PCIs have been chosen as a case study (see Fig. 3). Among the scenarios proposed by ENTSO-E [31], the one considered most realistic is the EUCO-30 scenario, since it is the most conservative and is supported by the political initiatives of the European Union member states. In addition, it is a medium-term scenario and is of greater interest for the projection of calculations. For these reasons, this article uses data from this scenario.

The existing power lines between Spain and France have a very high utilization, being saturated most of the hours of the year. Moreover, due to this saturation, a price differential between the Spanish electricity market and other European markets is very common. Consequently, strengthening interconnections is the highest priority to be undertaken in the development of the electricity transmission network for the coming years.

Table 2 summarizes the main characteristics of the three Spain-France interconnection projects. For more detailed information, see reference [31]. In particular, project 1 is already in the administrative authorization phase, whereas projects 2 and 3 remain in the phase of technical and environmental impact studies to define the best possible route and hence have a very low degree of maturation.

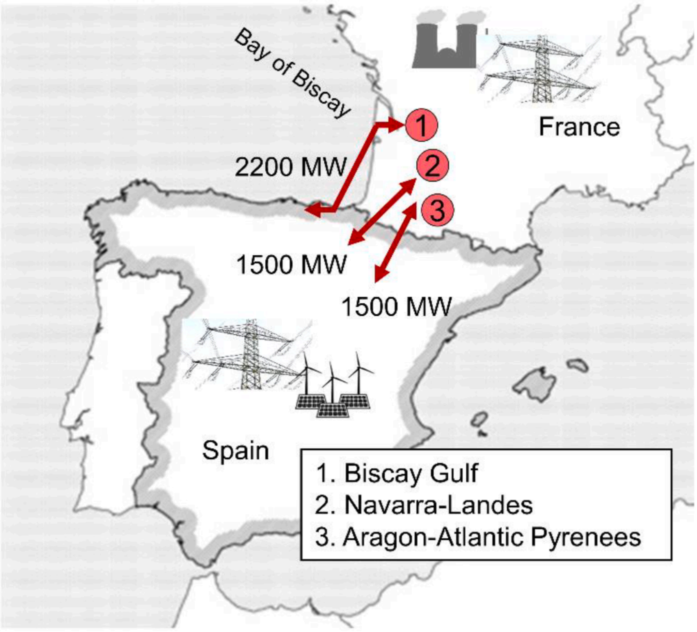

Fig. 3. Spain-France electricity interconnection projects of common interest.

Table 2
Characteristics of Spain-France interconnection projects.

Project	Type of elements	Total length (km)	Type of technology	Increase in capacity in Spain (MW)
1. Bay of Biscay	Submarine power cable	370	DC	2200
2. Navarra-Landes	Underground cable, overhead lines, substations	375	DC+AC	1500
3. Aragon-Atlantic Pyrenees	Underground cable, overhead lines, substations	340	DC+AC	1500

4.2. Results

The results from the step-by-step application of the methodology proposed in Section 2 are explained in this section.

Step 1. The three Spain-France interconnection infrastructure proposals of PCIs are selected to apply the methodology.
Step 2. Coherent energy planning requires implementing economic, technical, social and environmental criteria, as well as some sub-criteria linked to each decision-making criteria. These sub-criteria are based on EU data and aim to provide a common and uniform basis for analyzing projects regarding their value for European society [32].

Table 3 presents the values of the indicators for each of the projects under study.

Step 3. The indicators selected in step 2 are normalized to 2020 data of the Spanish electricity system (see Table 4) [40,41].

The total cost of each project, considering a lifespan of 40 years, is calculated using the following equation:

$$\text{Total cost of the project} = \text{Capital Expenses (CAPEX)} + 40\cdot\text{Operating Expenses (OPEX)}$$

Data from Table 3 are normalized according to the target country data (Table 4) to obtain uniform results in% (see Table 5), except for line km and total costs of each project which are maintained with their original units.

Step 4. From the matrix obtained in step 3, another matrix is constructed with values normalized to the total number of projects under assessment. Table 6 presents the normalized matrix. As previously mentioned in Section 2.2, to obtain this matrix, two possible cases are considered:

Table 3
Data of the indicators [32].

Indicator	Project 1	Project 2	Project 3
S1 (M€/year)	221	93	93
S2 (km)	0.269	2	12
EC1 (M€)	1750	1470	1170
EC2 (M€/year)	10.2	9.5	6.03
EN1 (T/year)	−1225,000	−523,000	−523,000
EN2.1 (kg/year)	−2247	−1458	−1458
EN2.2 (kg/year)	−1941	−1444	−1444
EN2.3 (kg/year)	−44,461	−24,208	−24,208
EN3 (km)	11	20	61
T1 (MWh/year)	7431,000	3628,000	3628,000
T2 (GWh/year)	2711	1750	1750
T2 (M€/year)	56	37	37
T3 (MWh/year)	7470	36.23	36.23
T4 (MWh)	316,490	150,970	139,050
T5 (%)	35	24	24
T6.1	++	++	++
T6.2	++	++	++
T6.3	+	+	+

Table 4
Data of the Spanish electricity system.

CO_2 emissions (kton)	36,130.85
NO_x emissions (kton)	702.7
SO_x emissions (kton)	126.9
NMVOC emissions (kton)	563.1
Electricity demand (GWh)	249,991
Renewable electricity generation (GWh)	110,566

Table 5
Data normalized to the target country data in%.

Indicator	Project 1	Project 2	Project 3
S1/Total cost	10.24	5.03	6.59
S2	–	–	–
EC1	–	–	–
EC2	–	–	–
EN1/CO_2 emissions	−3.39	−1.45	−1.45
EN2.1/NOx emissions	−0.00032	−0.00115	−0.00115
EN2.2/SOx emissions	−0.00153	−0.00114	−0.00114
EN2.3/NMVOC emissions	−0.0079	−0.0043	−0.0043
EN3	–	–	–
T1/Renewable electricity generation	6.72	3.28	3.28
T2/Total cost	3.06	2	2.62
T3/Electricity demand	0.002988	0.001449	0.001449
T4/Electricity demand	0.1266	0.0604	0.0556
T5	–	–	–
T6.1	–	–	–
T6.2	–	–	–
T6.3	–	–	–

- The increase in the indicator has a positive impact: 100 % is assigned to the project with the highest value and the rest are calculated proportionally.
- The increase in the indicator has a negative impact: 100 % is assigned to the project with the lowest value and the rest are calculated proportionally.

Regarding the economic indicators, project 1 has a higher investment cost since it mainly uses a submarine cable, which is very expensive and longer than the other infrastructures. Such a facility there requires great coordination between experts in electric power systems, structures, geologists and mariners. The route must be well analyzed to minimize environmental impact and maximize electrical protection.

Table 6
Matrix normalized to the total number of projects.

	Projects		
Indicators	1	2	3
S1	100 %	49.12 %	64.35 %
S2	100 %	55 %	18.03 %
EC1	66.86 %	79.59 %	100 %
EC2	59.12 %	63.47 %	100 %
EN1	100 %	42.77 %	42.77 %
EN2.1	27.83 %	100 %	100 %
EN2.2	100 %	74.50 %	74.50 %
EN2.3	100 %	54.43 %	54.43 %
EN3	100 %	13.45 %	2.24 %
T1	100 %	48.81 %	48.81 %
T2	65.34 %	100 %	76.33 %
T3	100 %	48.49 %	48.49 %
T4	100 %	47.71 %	43.92 %
T5	100 %	68.57 %	68.57 %
T6.1	++	++	++
T6.2	++	++	++
T6.3	+	+	+

From the environmental and social indicators, projects 2 and 3 have a greater environmental and social impact because these interconnections cross highly sensitive areas, such as the Pyrenees mountains, with great natural and heritage value. Furthermore, the economy of the populations living in this area depends to a large extent on sustainable and responsible tourism, based on its rich natural heritage and landscape. Therefore, project promoters must avoid any environmental impact as much as possible, as well as the evolution of the corresponding environmental impact.

Concerning the technical indicators, project 1 provides better results given its higher increase in interconnection capacity (2200 MW versus 1500 MW of the other two projects). This increased interconnection capacity makes it possible to expand renewable energy exports, to increase integration in the European market and to use the most economical power plants to meet the electricity demand at all times. In addition, project 1 strengthens the electricity supply security of both countries, by increasing their energy support, thus reducing the electricity generation capacity in reserve.

Step 5. Adequately applying the multi-criteria method requires defining the group of decision-makers. This group consists of specialists and professionals from different areas related to electricity infrastructure planning, environmental impact of energy systems, land planning and management, and cost and budget management, among others.

Steps 6 and 7. In these two steps of the methodology, through surveys, the groups of experts must select the most important criterion and sub-criterion by pairwise comparison, scoring the degree of preference from 1 to 9 using the Saaty scale. Additionally, the eigenvector that determines the final weight attributed by the decision-making groups to each criterion and sub-criterion is obtained from the software used [34].

In this study, all opinions of the decision-making groups are considered equally important. In addition, as previously mentioned, the weighted geometric mean is used to determine the collective preference.

It is important to take into account several groups of decision-makers since the experience of each of them will contribute to the enrichment of the solution. The strengths of some of them in specific fields will compensate for the weaknesses of other decision-makers in those fields. Four groups of decision-makers, each composed of four participants, have been included.

- Social sub-criteria: specialists in the development of electricity interconnection projects with profiles of university professors and researchers with expertise in this field of energy security have been considered.
- Technical sub-criteria: specialists in land-use planning and management, knowledgeable about technical restrictions, etc., have been considered. These have profiles of engineers dedicated to the electrical industry.
- Economic sub-criteria: specialists in cost and budget management have been included with profiles of engineer and legal advisor.
- Environmental sub-criteria: environmental consulting firms with experience in the management of projects that have an impact on the environment have been involved. These have profiles of biologists and engineers.

Table 7 presents the results from the criteria comparison surveys, following the methodology proposed in Section 2.

As shown above, the technical criterion is the most important criterion (35.50 %), closely followed by the environmental criterion (33.46 %). The main objective of these projects is to move towards a reliable, robust and flexible electricity system with a high penetration of renewable energy sources. In addition, the experts have also considered environmental criteria important because large electricity infrastructure projects have multiple effects on the landscape and the environment.

The same process is followed for each sub-criterion of three criteria.

For the social criterion, a 2 × 2 social sub-criteria matrix is obtained (see Table 8).

The indicator S1, corresponding to the increase in socioeconomic welfare, obtains a higher weight than S2 because reducing distribution network congestion is considered more important in this type of project than crossing socially sensitive areas. Implementing new interconnections reduces power generation constraints and increases market competition since energy exchanges become more efficient and less expensive.

Regarding the technical criterion, a 5 × 5 matrix of technical sub-criteria is obtained (see Table 9). The integration of renewables has a higher weighting (38.87 %) because electricity interconnection infrastructures maximize the volume of renewable energy production that a system can integrate under secure conditions since surpluses can be sent to other neighboring systems instead of being wasted. Furthermore, in the absence of renewable energy generation or in the presence of grid problems, interconnections make it possible to receive energy from other countries.

For the economic criterion, a 2 × 2 matrix of economic sub-criteria is obtained (see Table 10). The experts deem investment costs and operation and maintenance costs equally important.

In relation to the environmental criterion, a 5 × 5 matrix of environmental sub-criteria is obtained (see Table 11).

According to the decision-making groups, CO_2 emissions reduction is the most important indicator (EN1, 28.68 %), followed by environmental impact (EN3, 21.20 %). The projects under study will reduce these emissions by increasing the integration of renewable energy sources into the electricity system, in line with the EU goal of a climate-neutral system by 2050. The environmental impact is also considered essential. In this regard, a complete environmental study will allow to assess the magnitude of the impact of each project on the areas involved and to take measures to minimize the impact on the landscape, fauna and habitats of community interest.

Step 8. In this step, the consistency ratio is calculated to validate the judgments assessed in the surveys. To this end, first, the maximum eigenvalue, the consistency index and the random consistency index are calculated using formulas indicated in reference [26] (see results outlined in Table 12). The maximum eigenvalue is obtained using the matrix product of the pairwise comparison matrix of criteria and

Table 8
Weighting of the social sub-criteria.

	S1	S2	Weighted eigenvector
S1	1	1.19	54.32 %
S2	0.84	1	45.68 %

Table 7
Criteria weighting through surveys.

	Social	Technical	Environmental	Economic	Weighted eigenvector
Social	1	0.41	0.51	1.16	16.22 %
Technical	2.43	1	1	2.28	35.50 %
Environmental	1.97	1	1	2.24	33.46 %
Economic	0.86	0.44	0.45	1	14.82 %

Table 9
Weighting of the technical sub-criteria.

	T1	T2	T3	T4	T5	Weighted eigenvector
T1	1	3.2	2.43	2.43	2.43	38.87 %
T2	0.31	1	0.58	0.58	0.58	10.30 %
T3	0.41	1.73	1	1	1.41	18.05 %
T4	0.41	1.73	1	1	1.41	18.05 %
T5	0.41	1.73	0.71	0.71	1	14.73 %

Table 10
Weighting of the economic sub-criteria.

	EC1	EC2	Weighted eigenvector
EC1	1	1	50 %
EC2	1	1	50 %

Table 11
Weighting of the environmental sub-criteria.

	EN1	EN2.1	EN2.2	EN2.3	EN3	Weighted eigenvector
EN1	1	1.73	1.73	1.73	1.32	28.68 %
EN2.1	0.58	1	1	1	0.8	16.71 %
EN2.2	0.58	1	1	1	0.8	16.71 %
EN2.3	0.58	1	1	1	0.8	16.71 %
EN3	0.76	1.26	1.26	1.26	1	21.20 %

sub-criteria and the comparison eigenvector (outlined in the Tables of steps 6 and 7) and the corresponding sum of the elements of the matrix product, as indicated Eqs. (1)-(4). The consistency index depends on the maximum eigenvalue and the number of compared criteria, as shown Eq. (5). The random consistency index depends on the number of compared criteria, as indicated Eq. (6). Lastly, the consistency ratio is calculated as the quotient between the consistency index and the random index. As shown below, the consistency ratio is lower than 0.1 in all cases, which means that the obtained matrices are consistent and that the judgments made by the decision-making groups are valid.

$$A\cdot\overline{w} = \lambda_{max}\cdot\overline{w} \tag{1}$$

$$\sum_{j=1}^{n} a_{ij}\cdot\overline{w}_i = \lambda_{max}\cdot\overline{w}_i \tag{2}$$

$$\sum_{i=1}^{n} \overline{w}_i = 1 \tag{3}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}\cdot\overline{w}_i = \lambda_{max}\cdot\sum_{i=1}^{n}\overline{w}_i \tag{4}$$

$$Consistency\ index = \frac{\lambda_{max} - n_c}{n_c - 1} \tag{5}$$

$$Random\ consistency\ index = \frac{1.98\cdot(n_c - 2)}{n_c} \tag{6}$$

Where:

λ_{max}: maximum eigenvalue
A: pairwise comparison matrix
a_{ij}: elements of pairwise comparison matrix
$\overline{w}_i$: weighted eigenvector
n_c: number of criteria

Step 9. From the weights of the criteria and sub-criteria, a weighted tree is constructed, thus obtaining the final weighting of each sub-criterion (see Fig. 4).

Step 10. Finally, the weights obtained in the previous step are applied to the normalized matrix of projects (step 4), thereby prioritizing the projects (see Table 13).

After applying the multi-criteria method, the most beneficial project in the decision-making process is project 1 (0.8937), followed by project 3 (0.5815) and, lastly, project 2 (0.5648). Project 1 is technically better because this approach enables a greater integration and exchange of renewable energy while improving electricity supply security by helping to balance power generation and demand in any situation of renewable energy availability and supporting interconnected systems when facing electrical disturbances.

Project 1 also has the lowest environmental impact because the high-voltage direct current (HVDC) submarine power cable interconnection through the Bay of Biscay avoids the Pyrenees mountains, a region that is characterized by its considerable landscape relevance and cultural heritage. This justification is mainly based on the result from the indicator EN3. In addition, the route is parallel to the coast, thus avoiding fishing areas, ports, and areas of special importance for endangered fauna, as well as an unnecessary increase in the length of the power line. Additionally, this project integrates and exchanges a greater amount of renewable power generation (T1), which translates into a greater reduction of CO_2 emissions (EN1). However, the use of a long submarine power cable requires a higher investment and operational cost (EC1, EC2) than conventional options, such as airlines presents but is nevertheless preferred for minimizing the environmental impact.

Regarding the social indicators, project 1 further reduces the expected congestion at the border by increasing the energy exchange capacity (2200MW). In addition, the increased flow in both directions enables the use of less expensive energy at all times, providing a greater socio-economic benefit (S1) across Europe. Furthermore, the route avoids urban centers and highways at all times, taking advantage of forest roads and tracks. Simultaneously, the location of the power conversion station minimizes the visual and sound impact, ensuring a greater distance from population centers. For this reason, the S2 indicator of project 1 is better than that of the other two projects.

Project 1 is already in the administrative authorization phase, whereas the other two projects remain in the planning phase. Therefore, in the following years, the initial route could be modified to minimize the environmental impact and improve technical aspects.

In short, the methodology proposed in this article allows to analyze and prioritize several projects from social, technical, economic, and environmental points of view and to select the alternative that achieves the best balance of all criteria under consideration.

It is worth mentioning that previous works [28,42,43] also use the AHP method in decision making and demonstrate its robustness and

Table 12
Calculation of the consistency ratio.

	Maximum eigenvalue	Consistency index	Random consistency index	Number of alternatives	Consistency ratio
Comparison matrix of criteria	4.004	0.0033	0.99	4	0.0033
Comparison matrix of social sub-criteria	2.00	0	0	2	0
Comparison matrix of technical sub-criteria	5.028	0.007	1.188	5	0.0059
Comparison matrix of economic sub-criteria	2	0	0	2	0
Comparison matrix of environmental sub-criteria	5.001	0.00025	1.188	5	0.00021

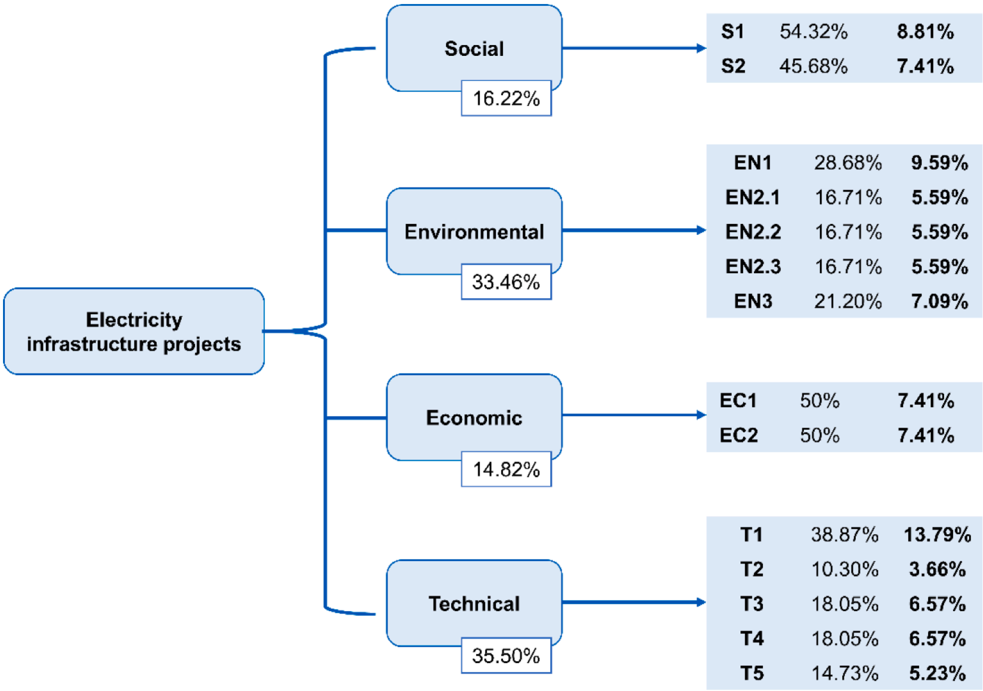

Fig. 4. Weighted tree.

Table 13
Prioritization of the projects.

	Projects		
Indicators	1	2	3
S1	0.0881	0.0433	0.0567
S2	0.0741	0.0099	0.0016
EC1	0.0495	0.0589	0.0741
EC2	0.0438	0.0470	0.0741
EN1	0.0959	0.0410	0.0410
EN2.1	0.0155	0.0559	0.0559
EN2.2	0.0559	0.0416	0.0416
EN2.3	0.0559	0.0304	0.0304
EN3	0.0709	0.0389	0.0127
T1	0.1379	0.0673	0.0673
T2	0.0238	0.0365	0.0278
T3	0.0641	0.0311	0.0311
T4	0.0641	0.0305	0.0281
T5	0.0523	0.0358	0.0358
AHP score	**0.8937**	**0.5648**	**0.5815**

validity for energy planning problems. Research [28] uses AHP technique for planning off-grid stand-alone power supply systems, standing out the possibility of combining quantitative and qualitative data for a proper assessment in such a complex problem with multiple objectives. The authors of [42] apply the method to modernize an existing grid with renewables integration. The authors of [43] also use this approach to study Jordan's electric power options from multiple viewpoints simultaneously to reach the optimal energy mix. The AHP method is a powerful tool for energy planning, providing a systematic and rational approach to analyze multiple criteria and alternatives, and facilitating balanced decisions in the energy sector.

4.3. Sensitivity analysis - criteria weighting

This section presents a sensitivity analysis to study the reliability of the results. Sensitivity analysis is a necessary complementary tool in decision-making process. In this way, analysts can observe how variation in the input data influences the effect of the output data. It is important to take account that if small variations in the inputs produce large changes in the outputs, decision-makers should assess the validity of the judgments made.

To carry out a sensitivity analysis of the AHP method, the weight assigned to each of the criteria is modified: technical, economic, environmental and social. Initially, the influence of each criterion is evaluated separately in order to determine the individual impact on the final decision. Subsequently, the combination of two criteria is analyzed, modifying their weights simultaneously to study interactions and the joint effect on the prioritization of alternatives. Next, the influence of three combined criteria is investigated, adjusting their weights coordinately. Finally, the base case including the four criteria is considered, assigning them the original weights obtained, in order to compare and contrast the results in each scenario with the initial configuration of the model.

It should be noted that this approach is essential, as it allows to identify the sensitivity of the AHP method to changes in the weighting of the criteria, providing a comprehensive study of its influence on decision making. This analysis makes it possible to assess the robustness and stability of the decisions derived from the AHP method, ensuring that decisions are not overly dependent on small variations in the weights of the criteria, which is crucial for the reliability and validity of the decision process.

Table 14 indicates the proposed scenarios in this paper with different weights of the criteria. As can be seen, each of the criteria has been modified separately, always considering that the sum is 100 %, in order to assess the effects that the changes have on decision-making. The study of a single criterion has also been included, although it is no longer a multi-criteria analysis, it is interesting to analyze the effects of conditioning decision-making to a single criterion.

Table 15 presents the results obtained for the proposed scenarios and graphically these can be seen in Fig. 5. It should be noted that project 1 would still be the best valued project, with the highest AHP score, since it is the project with the best technical performance, greatest social benefits and minimum environmental impact. However, considering only the economic criterion, project 3 would be the highest priority project. This is due to the fact that this project 3 has the lowest investment and maintenance costs, since this interconnection uses overhead cable with the shortest necessary length of the transmission line (340

Table 14
Scenarios proposed.

Scenarios	Technical criterion (%)	Environmental criterion (%)	Social criterion (%)	Economic criterion (%)
1	100	0	0	0
2	0	100	0	0
3	0	0	100	0
4	0	0	0	100
5	50	50	0	0
6	50	0	50	0
7	50	0	0	50
8	33.33	33.33	33.33	0
9	33.33	33.33	0	33.33
10	33.33	0	33.33	33.33
11	25	25	25	25
12	35.50	33.46	16.22	14.82

Table 15
Results obtained for each scenario.

Scenarios	Project 1	Project 2	Project 3
1	0.9643	0.5674	0.5361
2	0.8795	0.5337	0.5099
3	1	0.5181	0.4319
4	0.6299	0.7153	1
5	0.7763	0.5881	0.5293
6	0.9821	0.5427	0.4840
7	0.7971	0.6413	0.7681
8	0.8507	0.5647	0.4968
9	0.8926	0.5913	0.5454
10	0.8646	0.6001	0.6559
11	0.9201	0.5389	0.5254
12	0.8937	0.5648	0.5815

km).

Although the case study does not explicitly demonstrate the superiority of AHP over other methods, the inherent advantages of AHP in terms of structuring, expert participation, incorporation of quantitative and qualitative criteria, flexibility, and transparency justify its choice as a suitable and effective tool for energy planning. The AHP method has been widely used in energy planning in different parts of the world, where it has proven to be a reliable method for the assessment and selection of alternatives [44–46]. In addition, sensitivity analysis to understand how variations in the criteria weights affect the final results, expert diversity and consistency checks during pairwise comparisons allow to verify the validity of the AHP technique in this paper.

5. Discussion of security indicators

Electric power systems are key for the daily functioning of any country. These systems are complex and susceptible to failures and threats, which may cause serious outages, affecting services provided to society (economic activities, and public health, among others). For this reason, all countries aim to develop a reliable and secure system that guarantees electricity supply in any situation.

Resilience is an intrinsic property of a system defined as its ability to quickly absorb and/or restore from external disturbances by continuing to supply energy. The concept of resilience integrates four fundamental characteristics that reflect the level of resilience of electricity systems: capacity of resistance to the event, speed of restoration, preparedness for high-impact, unlikely future events and adaptability to a major contingency [47].

The three basic levels that determine the resilience of an electricity system are defined below.

- Reliability: is the capacity of the electricity system to continuously meet the demand with an acceptable level of quality and to maintain the exploitation indices under specific environmental and operational conditions during a determined period [48].
- Robustness: is the capacity of the electricity system to absorb the effects of an ongoing disruptive event. This property is essential since an attack may cause a component to fail, which, in turn, may affect other components as well. This phenomenon is termed a cascading failure [49].
- Restoration: is the ability of a component to restore its activity to its initial operating level once the disturbance has ended [49].

5.1. Discussion of reliability indicators

Reliability is the capacity of an electricity system to meet the electricity demand, comply with the operating restrictions of the system, and respond to changes in the system due to variations in demand or generation, and failures in power lines and equipment, among others.

The main index that evaluates the reliability of an electricity system is EENS (MWh/year). This indicator (T3) is related to the penetration of renewable energy sources into the electricity system. Because they are intermittent generation sources, there is a higher likelihood of loss of load and failure to supply power. Therefore, increasing renewable energy production increases the impact on this indicator. This indicator provides information on the number of outages and on their magnitude

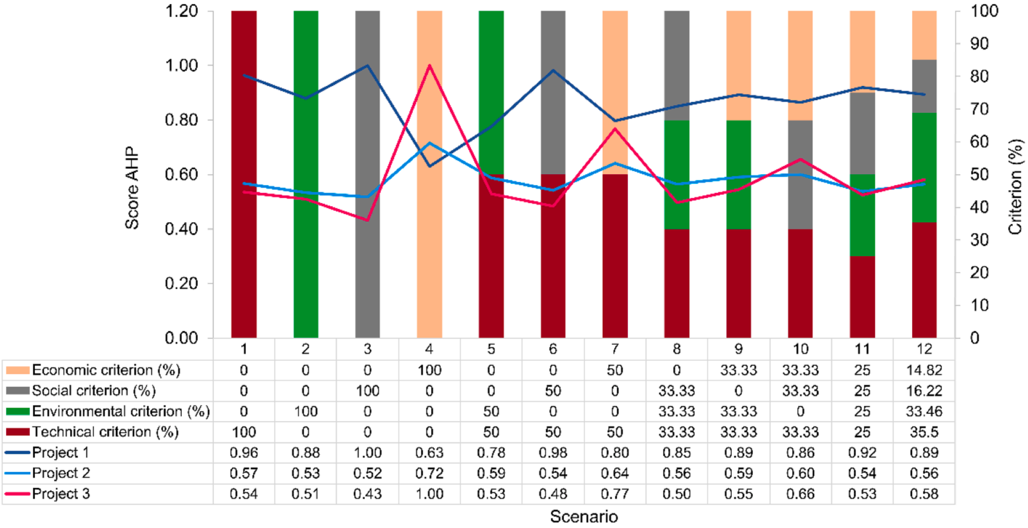

Fig. 5. Results for the proposed scenarios.

and reflects the improvement in the reliability of electric power systems since adding a new cross-border interconnection improves energy exchange between different areas in facing the risk of loss of load at peak hours [50,51].

The EENS indicator is measured using models which simulate the electricity dispatch for one year using probabilistic Monte Carlo techniques. This approach is used over analytical methods for its practicality given the complexity, non-linearity and involvement of many components in the electricity system. The process considers the effect of weather conditions on the likelihood of power line failures, the heuristic representation of generator instability, the redistribution of resources after a contingency, and the time required for system restoration, among others. Therefore, the value of this indicator is a realistic estimate and is used to assess the reliability of electricity systems.

The EENS results (indicator T3) indicate a double increase in project 1 when compared with the other two projects, which translates into a double improvement in the reliability of the current Spanish electricity system. This indicator provides useful information to study the behavior of the distribution network when facing contingencies and helps decision-making in planning improvements to existing electricity systems. The cross-border electricity interconnection proposed in project 1 increases the power transfer capacity between the countries (Spain-France) by 46 %, thus having a positive impact on the operating conditions of the Spanish system and further reducing the congestion of power lines. As such, the cross-border electricity interconnection increases reliability since interconnection lines improve energy exchange between different areas of the interconnected infrastructure.

5.2. *Discussion of robustness and restoration indicators*

Robustness is the internal capacity of the electricity system to continue to function under the effects of unforeseen failures. The outage of one transmission line may cause the overload of other lines, which increases the likelihood that other assets will fail and cause a failure of the entire system. This indicator is related to the effect of cascading failures.

Restoration is the capacity of the network to quickly reestablish itself after a high-impact external event or a failure of a system component and to restore the operating conditions of the electricity distribution network.

A parameter linked to the robustness and restoration of a system is the additional installed generation capacity to meet the expected demand in the event of maintenance, plant breakdowns, demand peaks due to extreme weather conditions or interruptions in the transmission line (T4). Cross-border interconnections make it possible to use the excess electricity generation capacity of an area to cover deficits in other areas of the system under these conditions. Therefore, this capacity will be smaller than the sum of the needs of the individual networks without interconnection [39,52], thereby reducing the need to build new power plants and facilitating the optimal management of available resources.

Another indicator associated with grid robustness and restoration is the system flexibility (T5), that is, the ability of the grid to adapt to changing, diverse and dynamic conditions, from the point of view of renewable energy sources, and to external factors which increase the vulnerability of the system. Flexibility is an important property of electric power systems with high renewable penetration for smoothing out system disturbances in extreme cases or expected deviations from renewable electricity generation and electricity demand, in addition to avoiding grid saturations or surges and problems with power supply quality.

Cross-border interconnections play a key role in achieving a robust and flexible power system by enabling backup functions between neighboring systems in the face of power failures or outages. The improvement in flexibility depends on the net transfer capacity; therefore, energy can only be imported/exported within the limits imposed by the fixed transfer capacities of power lines between different network areas. The integration of the electricity markets makes it possible to add a slack bus to maintain the maximum balance between what is injected into and exported from the grid and to moderate the energy flow problems of individual grid areas by taking advantage of the flexibility potential of other areas of the grid [53].

The indicators T4 and T5 enable operators of energy control centers to better analyze in real time the operation of the electricity system and its operational limits in the event of a series of simultaneous contingencies, and the available sources to balance and restore the system as quickly as possible.

Project 1 has the best value of the T4 indicator, which is related to the robustness of the electricity system. Cross-border electricity interconnection is the most significant instant backup for electricity supply security. Increasing the exchange capacity between different countries decreases the reserve margin necessary in a country to meet the demand in a short period in the face of power outages because reserve plants can be shared to enable a system to continuously operate in the event of a failure, thus reducing the need for investment in long-term generation.

The flexibility indicator (T5) is associated with the response capacity of the electricity system when facing expected or unforeseen variations, either in demand and/or generation. This value is essential to achieve a robust electricity system with high levels of renewable energy penetration since a small mismatch between demand and generation may lead to variation in system frequency and affect the operational reliability.

Project 1 has a greater interchangeability and, therefore, a higher capacity to share resources and optimize their use in case of imbalances, thus reducing the use of fossil fuels and foreign energy dependence. Furthermore, interconnections generally decrease production ramps in manageable power plants and help export/import between both countries, in case of energy excess or deficit, respectively.

In addition, these last indicators also show a direct relationship with improvements in the resilience of electric power systems because increasing cross-border interconnection provides more energy resources to restore the electricity supply when facing a major contingency, which may cause the loss of much of the electricity infrastructure after the event. Thus, project 1 may further reduce the time need to restore electricity service by increasing the transfer capacity between countries.

In short, achieving a secure, reliable and robust system requires preparing response plans for any event that may compromise the normal operation of the electricity system. By increasing cross-border interconnection, electricity supply security becomes an international rather than a national problem. Therefore, good coordination between countries, a robust network, and sufficient resources are essential to tackle critical problems. Increasing electricity interconnection capacity is the best compromise solution in the design of transmission network topologies based on reliability and robustness criteria.

6. Conclusions

The assessment of electricity interconnection projects within the framework of European electricity infrastructure planning is a complex task of analysis because there are multiple objectives, criteria and alternatives to consider. The goal of this paper is to propose a MCDA methodology for selecting and ranking cross-border electricity interconnection projects based on data available from the EU. This tool makes available at all times the maximum amount of information, synthesized and organized, so decision-makers are able to assess and select the most beneficial project, considering technical, economic, environmental and social criteria.

The main conclusions drawn from this article are as follows:

- Unlike the CBA method used in previous works for the assessment of interconnection projects, the proposed MCDA methodology in this paper makes it possible to assess the environmental and social impact and security of an electrical system, among other factors, for a complete and realistic analysis of electricity interconnection projects. Therefore, this tool provides a complete view of the real impact of cross-border electricity infrastructure projects, helping to prioritize projects according to technical, social, economic and environmental criteria.

- Selecting experts in all areas involved in planning electricity infrastructure projects for weighting different criteria and sub-criteria improves the project selection process. Thus, the proposed methodology is based on objective indicators and quantitative techniques, which will strengthen the defense of the best option.
- From the four general criteria studied, the technical criterion is considered the most important (35.50 %), followed closely by the environmental criterion (33.46 %). This is coherent because cross-border electricity interconnection projects are aimed at greater integration of renewable energy and improving the security of the electricity system while minimizing environmental impacts. Regarding the sub-criteria associated with the previous criteria, the integration of renewables (T1, 38.87 %) obtains the highest score because a greater electricity interconnection capacity allows exporting to the rest of Europe the surplus solar and wind energy produced in Spain and can avoid wasting it due to technical constraints of grid. In addition, the reduction of CO_2 emissions (EN1, 28.68 %) obtains the highest score within the environmental sub-criteria, as Europe must continue to reduce its emissions by promoting renewable energy.
- The methodology proposed in this article facilitates a better understanding of the behavior of interconnected power systems by analyzing and relating some technical indicators (T3, T4 and T5) to the reliability, robustness and restoration of power grids. These indicators improve the resilience of the system by increasing cross-border interconnection capacity, which increases the availability of energy resources to reduce the restoration time of electricity supply in the event of a major contingency that may result in the loss of much of the electricity infrastructure after the event.

In short, this article develops a structured and coherent tool based on multicriteria decision analysis to assess and prioritize a portfolio of cross-border electricity interconnection projects under technical, economic, environmental and social criteria. The proposed methodology makes it possible to obtain the real impact of projects implementation by providing a comprehensive view of all aspects involved in the assessment of these projects. Therefore, the application of this methodology can serve as a support tool in the process of selecting alternatives for electricity interconnection projects and help to better understand the behavior and limitations of transmission power grids.

CRediT authorship contribution statement

Natalia Naval: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jose M. Yusta:** Writing – original draft, Supervision, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jose M. Yusta reports financial support was provided by Spain Ministry of Science and Innovation.

Data availability

Data will be made available on request.

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