# Using multi-criteria decision analysis to support local energy policymaking

A case study concerning photovoltaics in Rajadell, Spain

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**Abstract**

Climate change, the depletion and volatility of fuel prices, and the energy dependence of Europe have driven the deployment of renewable energy sources. The role of local governments and citizens in the energy transition is key since a large part of the emissions are caused by urban environments. This study is focused on solar photovoltaic energy, considering the relevance that this technology has in attaining municipal climate goals. Multi-criteria decision analysis is suitable to deal with the multifaceted nature of sustainability and the complex process that decision-makers go through when planning local strategies that take into account economic, environmental, technical, and social criteria. With the support of an expert, an MCDA model based on the ELECTRE Tri-nC approach has been designed to classify multiple alternatives related to photovoltaic energy with the objective of reducing the emissions of municipalities, involving different types of installations, areas, sectors, and investors. The model is applied in the Spanish municipality of Rajadell, a rural village of 549 inhabitants located in the province of Barcelona. In 2022, the local council agreed to reduce the municipality's emissions by 55% by 2030 and to achieve climate neutrality by 2050. The results of the project demonstrate the relevance of photovoltaics in achieving these objectives. Specifically, it is believed that it can save up to 49.11% of annual emissions from the residential and services sectors. Following a sensitivity analysis, the model proved to be robust and can be used for further analyses in similar contexts.

**Keywords:** Multi-criteria decision analysis; ELECTRE Tri-nC; Local energy policymaking; Renewable energy; Photovoltaics.

## 1. Introduction

50 billion tonnes of greenhouse gas (GHG) emissions are annually released into the atmosphere on a global scale (Karakosta et al., 2013). In 2021, 83% of the energy consumed worldwide was derived from fossil fuels, which contributed to 73% of total global emissions. The rising concern related to climate change, its severe consequences, and the increasing

demand for energy have led to a significant increment in the use of renewable energy sources (RES). In May 2022, the EU presented the REPowerEU strategy to swiftly decrease dependence on fossil fuels and enhance the implementation of renewables.

In this context, local governments seek opportunities to assist their communities, especially considering the current energy crisis, and are promoting a variety of measures to meet climate goals. This project does not intend to discuss these measures but concentrates exclusively on the use of photovoltaics (PV) to contribute to cleaner and more energy-efficient cities. The approach to the decision-making process that municipalities must undertake to reach consensus on robust long-term solutions by considering economic, technical, environmental, and social criteria is indeed complex. Due to the intricate nature of these decisions, assisting them in selecting the most suitable strategy is an effort that requires support from optimization techniques such as multi-criteria decision analysis (MCDA). The purpose of this research is to design an MCDA model to evaluate and compare different photovoltaic projects with the objective of reducing the emissions of municipalities, considering different types of installations, areas, sectors, and investors. The model intends to be useful for determining which installations are most urgent to achieve the environmental targets, and it can also support local authorities when planning an energy strategy. This approach will be implemented in the municipality of Rajadell, Spain.

The structure of this paper is as follows: Section 2 is a literature review on renewable energies and the application of MCDA in this field, particularly PV. Section 3 describes the fundamental principles of PV and examines the regulatory framework within this technology in Spain. Section 4 presents the methodological framework. Section 5 applies the methodology to the Spanish municipality of Rajadell. Section 6 provides the results and discussion. Section 7 contains conclusions and future research.

## 2. Literature review

Renewable energy, as defined by the Office of Energy Efficiency and Renewable Energy, refers to the energy generated from continually replenishing natural sources such as the sun, wind, water, ocean tides, biomass, and geothermal resources. Hydropower, which uses water to power turbines, was the third largest contributor to the world's electrical supply in 2021. Hydropower plants have a high degree of dependability, great efficiency, and the ability to quickly adapt to load variations, which is essential for integrating increasing amounts of wind and solar power into the electrical grid. However, some plants are ageing and are in need of modernisation.

Wind power ranks second worldwide in installed renewable energy capacity and accounts for around 6% of energy production. The operation is comparable to that of hydropower, but in this instance, it uses the kinetic energy of air in motion. In 2021, 93% of the total built wind capacity was onshore, with the remaining 7% being offshore wind farms. Nonetheless, both types have significant potential for deployment.

Solar energy can be divided into two subcategories: photovoltaic technology and solar thermal. PV converts sunlight into electrical energy, while solar thermal technology uses solar energy for thermal purposes and power generation. Solar energy is the third largest renewable technology and has experienced the second greatest production growth of all renewable energies, with 179 TWh in 2021.

However, solar energy generates less than 4% of the world's power demand (Kannan & Vakeesan, 2016).

Other RES include bioenergy, geothermal, and marine. The European Commission defines "bioenergy" as renewable energy derived from biomass. The heating sector remains the largest consumer of bioenergy, while bioelectricity represents a minimal part of the power production capacity (Lehtveer & Fridahl, 2020). Geothermal energy can supply base-load power production as well as heating and cooling. Marine energies account for the smallest portion of renewable electricity, and the bulk of projects are still in demonstration phase (Zabihian & Fung, 2011).

Therefore, there is a wide variety of renewable energies, and a justification for the selection of exclusively incorporating PV systems in this work is needed. PV is considered a mature technology that is experiencing significant reductions in costs. Moreover, PV systems contribute to the creation of local employment, exhibit a wide range of applications, and enable individuals to embrace these systems. One distinguished advantage of PV lies in its capacity for self-consumption, as opposed to other energy sources that require extensive power plants.

Owing to the multidimensional character of sustainability targets, MCDA techniques have gained popularity in the decision-making process for sustainable energy and are often employed to examine one of the most crucial concerns for nations: energy policy formulation (Ren, 2021). Ranking alternative RES represents one of the most common research applications. For instance, Saraswat & Digalwar (2021) ranked different energy sources in India, using solar, wind, biomass, gas, thermal, and nuclear power as alternatives. Pereira & Pereira (2023) used Portugal as a case study to suggest a collaborative MCDA framework based on the Choquet multi-criteria preference aggregation model to rank different potential alternatives in different layers of the energy storage market.

Instead of evaluating technologies, Neves et al. (2018) intended to enhance municipal energy planning via the formulation of a feasible energy action plan by using an MCDA approach. The methodology was partially implemented in Odemira, Portugal.

Power plant selection has also been the subject of numerous research investigations. Shao et al. (2020) reviewed 85 studies that applied MCDA methods for renewable energy site selection.

Similarly, a significant part of solar photovoltaic energy with MCDA research focuses on finding suitable locations for solar farms. Sánchez-Lozano et al. (2014) used MCDA to identify suitable plots for installing PV farms in the municipality of Torre Pacheco, in the southeast of Spain. An additional application of decision-making in the PV sector is the comparison between different photovoltaic technologies, such as the work of Bouzid et al. (2021), who applied a multi-decision-maker approach to classify a set of photovoltaic panels for consumers.

As the EU seeks to lead the energy transition, it has proposed ambitious targets for the implementation of RES and the reduction of GHG emissions. The Commission's proposal aims to reduce GHG emissions by at least 55% by 2030 and to achieve climate neutrality by 2050. This implies that nations, above all municipalities, must adopt measures for achieving it.

Following a literature review on how MCDA has been used in photovoltaic technology, it was found that most of the studies analysed were focused on site selection and technology assessment. Nevertheless, the utilisation of MCDA methods in assessing and contrasting various photovoltaic installations for determining their degree of urgency for action in alignment with the environmental goals of municipalities remained unexplored. Based on the objectives of this study and its framework, the application of ELECTRE methods, specifically the ELECTRE Tri-nC approach, was determined to be the most appropriate strategy. Therefore, this research demonstrates the innovative aspect of the study as it explores the application of photovoltaic technology in municipal energy planning, an area that has not been previously investigated. Additionally, the use of ELECTRE Tri-nC for this purpose is novel and has not been employed in previous studies.

## 3. Background

Based on the photovoltaic effect, PV solar energy consists of the conversion of solar radiation into electricity. The conversion efficiency is determined as the proportion of incident light power transformed into electrical energy. Currently, the average efficiency of most solar panels is around 20% (Green et al., 2022). A standard power system is composed of the photovoltaic module array, the inverter, the power consumption, or load, and, if required, the charge controller and the battery bank (Sampaio & González, 2017). The performance of PV systems is dependent on their own components and their ability to capture solar energy. Therefore, the proper orientation and inclination of the PV modules can improve the energy efficiency and performance. There are other techniques that optimise the power output of PV systems, such as solar trackers or floating systems (El Hammoumi et al., 2022).

Spain's energy balance is still characterized by fossil fuels, notably in the transportation and industrial sectors. Natural gas is currently the major electricity source, accounting for about one-third of the generated electricity in 2022. Renewables are nowadays an increasingly major source of power production, accounting for 40% of national generation in 2022, including wind, solar, hydro, and bioenergy. Solar energy production increased by 24.5% compared to 2021.

In 2018, the Spanish government implemented the RD 15/2018 and RD 244/2019 policies, which had a notable positive impact on the renewable energy sector. The primary changes enacted to encourage the installation of PV systems were the removal of the sun tax, the elimination of power limits, and the surplus compensation that allowed the consumer to sell excess solar energy to the electricity grid. Energy self-consumption is fundamental for the deployment of renewable energies in urban environments. Consequently, it presents an opportunity for municipalities and provides them with effective means of contributing to the energy transition.

In addition to setting transparent and equitable regulations, policymakers have the responsibility of incentivising the uptake of PV systems via other mechanisms. This suggests the adoption of various measures, such as tax incentives, subsidies, and simplification of administrative procedures, to accelerate the deployment of renewable energies and thereby meet the climate targets. These policies must be conducted at all levels, including European, national, regional, and local (Colasante et al., 2022).

## 4. Methodology

The literature has divided MCDA problems into three categories: choice, ranking, and sorting. Since this project aims to classify different photovoltaic initiatives according to their urgency of implementation, it constitutes, in essence, a sorting problem.

Given the characteristics of the case study, the use of the ELECTRE family of outranking methods, more specifically the extension of ELECTRE Tri-nC, is considered appropriate for the following reasons: (i) The ELECTRE family of methods can deal with qualitative performance scales of criteria; (ii) ELECTRE methods can manage scale heterogeneity; (iii) ELECTRE methods allow consideration of indifference and preference thresholds, making it appropriate to consider imperfect data knowledge and arbitrariness.

Preferences in ELECTRE methods are modelled by using binary outranking relations, $S$, whose meaning is "at least as good as." In the ELECTRE Tri-nC model, alternatives are sorted based on their comparison to the reference actions that define the categories.

$A = \{a_1, a_2, \dots, a_i\}$ is the set of potential actions. The objective is to assign these actions to a set of entirely ordered categories denoted by $C = \{C_1, C_2, \dots, C_q\}$ with $q \geq 2$, with $C_1$ being the worst category and $C_q$ being the best one. $F = \{g_1, g_2, \dots, g_n\}$ with $n \geq 3$ is a coherent set of $n$ criteria, designed to evaluate any action considered for assignment. The performance of the action $a_i$ on the criteria $g_j$ is denoted by $g_j(a_i)$.

$w_j$ is the intrinsic weight and represents the importance coefficient of each criterion for all $g_j \in F$, such that $w_j > 0, j = 1, \dots, n$ and $\sum_{j=1}^{n} w_j = 1$.

Each criterion is considered a pseudo-criterion, meaning that two thresholds are associated with $g_j$: an indifference threshold, $q_j$, and a preference threshold, $p_j$, such that $p_j \geq q_j \geq 0$. The veto threshold $v_j$ allows for the possibility of $aSa'$ to be rejected completely if, for any one criterion $j$, $g_j(a') > g_j(a) + v_j$.

Finally, $B_h = \{b_h^r = 1, \dots, m_h\}$ denote a subset of reference actions that define category $C_h$, where $m_h \geq 1$ and $h = 1, \dots, q$.

$\lambda$ denotes the credibility level, that is the minimum degree of credibility judged necessary for validating an outranking statement when all the criteria from $F$ are considered. Typically, $\lambda$ takes values between [0.5, 1]. At this step, an action $a$ is compared to a reference action $B_h$ to attribute one category or an interval of categories considering the credibility level $\lambda$.

In this regard, the ELECTRE Tri-nC assignment procedure consists of two joint rules that must be applied, named the descending and ascending rule. Combining both criteria, the assignment procedures result in the selection of two alternative categories to which an action may be assigned. Consequently, ELECTRE Tri-nC methodologies provide the following as a potential action assignment: (i) one category, if the two selected categories are the same. (ii) two categories, when the two selected categories are consecutive. (iii) a range of categories delimited by the two selected categories when they are non-consecutive.

The implementation of ELECTRE methods in real-world decision problems requires software packages. The assignment of weights to the criterion using the DCM-SRF approach was executed using the DecSpace tool, and the implementation of the model was computed using the MCDA-ULaval software.

## 5. Case study

Rajadell, located in the province of Barcelona, Spain, has a population of 549 inhabitants and a surface area of 45.32 $km^2$. Its economic activity is mainly comprised of agricultural services and livestock. During 2016, each resident emitted 3.3 tonnes of $C0_2$ and consumed 11.19 MWh. In 2022, the local council agreed to reduce C0$_2$ emissions by 55% by 2030 and to achieve climate neutrality by 2050.

The energy transition must be carried out with the participation of public administration, citizens, and companies. Therefore, the purpose of this case study is to evaluate various photovoltaic installations that involve both private and public actors to determine which actions are more urgent. The model was co-constructed through the interaction between the analyst and an expert in the energy market. The alternatives evaluated are shown in Table 1.

**Table 1:** Alternatives proposed under assessment.

| | Alternatives proposed |
|---|---|
| $a_1$ | PV self-consumption in residences |
| $a_2$ | PV self-consumption in local buildings |
| $a_3$ | Solar street lighting |
| $a_4$ | Self-consumption at the sewage plant |
| $a_5$ | PV self-consumption in livestock farms |
| $a_6$ | Solar-powered water pumping system |
| $a_7$ | Local community solar farm |
| $a_8$ | Self-consumption in local businesses |
| $a_9$ | Solar-powered vehicle charging station |
| $a_{10}$ | Utility-scale solar farm |

The suggested alternatives are classified into a set of three predefined categories according to the level of urgency for implementation. $C_3$ refers to high urgency of implementation, $C_2$ medium urgency, and $C_1$ low urgency.

Environmental, economic, and social considerations are viewed as the three pillars that support the concept of sustainable development (Cinelli et al., 2014). Within the scope of this research, it was also believed to incorporate technical aspects. The most frequently used indicators in studies on the evaluation of energy projects and sustainability assessment were debated with the expert. The list with the selected indicators is presented in Table 2.

**Table 2:** Indicators selected for the case study.

| $g_j$ | Indicator | Units |
|---|---|---|
| $g_1$ | Equivalent annual annuity | € |
| $g_2$ | Payback period | Years |
| $g_3$ | Specific installation cost | €/$W_p$ |
| $g_4$ | Social acceptance | Three levels |
| $g_5$ | Citizen involvement | Four levels |
| $g_6$ | Environmental impact | Three levels |
| $g_7$ | Avoided $CO_2$ emissions | Tons of $CO_2$ |
| $g_8$ | Technical maturity | Two levels |
| $g_9$ | Administrative complexity | Three levels |
| $g_{10}$ | kWh/k$W_p$ ratio | kWh/k$W_p$ |

To assign weights to each of the criteria, the DCM-SFR method was applied. The procedure was performed during a meeting with the expert. The tool generated the normalised weights, which are displayed in Table 3.

**Table 3:** Normalised criteria weights obtained.

| Criterion | $w_j$ |
|---|---|
| $g_1$ | 8.06 |
| $g_2$ | 15.83 |
| $g_3$ | 10.65 |
| $g_4$ | 5.46 |
| $g_5$ | 1.58 |
| $g_6$ | 8.06 |
| $g_7$ | 10.65 |
| $g_8$ | 10.65 |
| $g_9$ | 14.53 |
| $g_{10}$ | 14.53 |

Following, the reference actions were defined. The expert determined two reference actions for each category. In addition, preference, indifference, and veto thresholds were established. These values can be observed in Table 4.

Table 4: Preference, indifference, and veto thresholds.

| | $q_j$ | $p_j$ | $v_j$ |
|---|---|---|---|
| $g_1$ | 1000 | 4500 | - |
| $g_2$ | 1 | 3 | - |
| $g_3$ | 0.5 | 1 | - |
| $g_4$ | 0 | 1 | 2 |
| $g_5$ | 0 | 2 | - |
| $g_6$ | 0 | 1 | - |
| $g_7$ | 5 | 100 | - |
| $g_8$ | 0 | 1 | - |
| $g_9$ | 0 | 1 | - |
| $g_{10}$ | 50 | 500 | - |

For the credibility level, a value of $\lambda = 0.7$ was determined. The model constructed was then implemented in the MCDA-ULaval software. The evaluation of each alternative for each criterion is shown in Table 5.

Table 5: Performance table.

| | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ | $g_7$ | $g_8$ | $g_9$ | $g_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $a_1$ | 33924.39 | 7.58 | 2.05 | L3 | L4 | L2 | 273.47 | L2 | L3 | 1312.19 |
| $a_2$ | 1296.00 | 8.26 | 1.88 | L3 | L2 | L3 | 15.60 | L2 | L3 | 1280.62 |
| $a_3$ | -25466.41 | 17.21 | 9.61 | L3 | L2 | L2 | 17.90 | L2 | L3 | 1531.39 |
| $a_4$ | 5873.06 | 5.48 | 1.73 | L3 | L1 | L3 | 12.47 | L2 | L3 | 1214.48 |
| $a_5$ | 7615.00 | 5.69 | 1.69 | L3 | L3 | L3 | 22.31 | L2 | L3 | 1310.30 |
| $a_6$ | 763.31 | 7.67 | 2.39 | L2 | L1 | L2 | 4.84 | L1 | L2 | 1983.58 |
| $a_7$ | 9199.48 | 6.66 | 2.05 | L2 | L3 | L1 | 37.15 | L1 | L1 | 1531.39 |
| $a_8$ | 8660.19 | 5.79 | 1.52 | L3 | L3 | L3 | 27.04 | L2 | L3 | 1260.75 |
| $a_9$ | -2407.17 | 7.62 | 3.54 | L2 | L2 | L2 | 8.73 | L1 | L2 | 1476.76 |
| $a_{10}$ | 2647.40 | 9.51 | 1.70 | L1 | L2 | L1 | 732.51 | L2 | L1 | 2040.14 |

## 6. Results and discussion

The ELECTRE Tri-nC technique classified each action into either a single category or an interval of categories, depending on the outcome of the ascending and descending rules. The analysis revealed that only one measure, $a_7$, was deemed to possess a sense of immediacy and was allocated to the category $C_3$, whereas a significant proportion of 40% of the actions proposed were assigned between $C_2$ and $C_3$. Three actions were assigned to $C_2$, corresponding to a medium implementation urgency. There was one alternative, $a_9$, placed between $C_2$ and $C_1$. Lastly, $a_3$ was identified as non-urgent and subsequently designated to $C_1$. For enhancing comprehension and facilitating understanding, the allocation of the alternatives can be seen graphically in Figure 1.

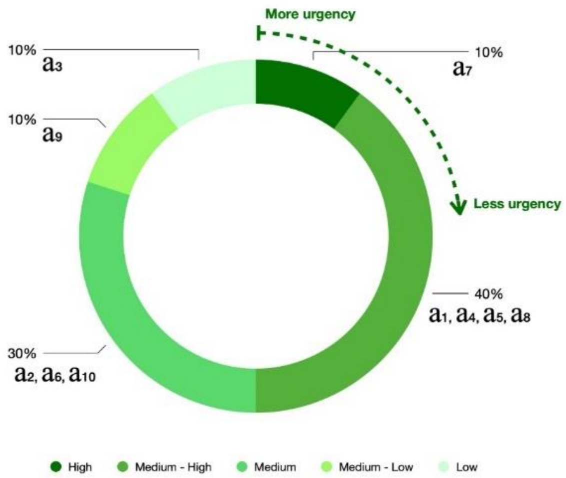


Figure 1: Classification of alternatives according to their urgency of implementation.

The only alternative that was classified as $C_3$ is $a_7$. The economic viability of this alternative is notable, as it demonstrates a payback period of less than seven years, and a significant financial impact. This could be attributed to the efficient distribution of power among participants, resulting in a higher percentage of self-consumption. However, the administrative complexity slows down the development of these proposals.

40% of the alternatives were categorised between $C_3$ and $C_2$, which are regarded as calls for medium-to-high urgency. Action $a_1$ implies the significant involvement of most of the population, so there is a great impact on the achievement of the environmental objectives. This measure can avoid over 200 tonnes of $CO_2$ annually. The actions $a_4$, $a_5$, and $a_8$, include the installation of solar panels for self-consumption on the water treatment plan, restaurants, rental houses, and some farms. These systems are very profitable as they are highly energy-consuming and have competitive installation costs.

Three actions, namely $a_2$, $a_6$, and $a_{10}$, were assigned to $C_2$. In contrast to other options, action $a_2$ has a reduced financial impact and a payback period that exceeds eight years. The $a_{10}$ proposal, which consists of building a utility-scale solar farm, has notable benefits but simultaneously implies certain drawbacks. It was determined with the expert that the criterion "social acceptance" possesses a veto threshold of 2. Consequently, alternatives that cause significant public disapproval cannot be deemed urgent based on this criterion. Initiative $a_6$ comprises not only the photovoltaic system but also the pumping control and regulation devices. Additionally, the structure of the PV array is composed of a single-axis tracking system, which increases the installation cost.

The $a_9$ is assigned to $C_1$ in the worst-case scenario and $C_2$ in the best-case scenario. This system remains in development and does not appear economically profitable, which would discourage private investment.

Alternative $a_3$ is the only one placed in the lowest category, mainly because its performance according to several criteria is not satisfactory.

Following the analysis of the results, a timeline proposition for the implementation of the projects was formulated.

Urgent measures should be implemented by 2026, whereas medium-high urgency actions are proposed to be implemented by 2028. Figure 2 shows the timeframe of the implementation proposal.

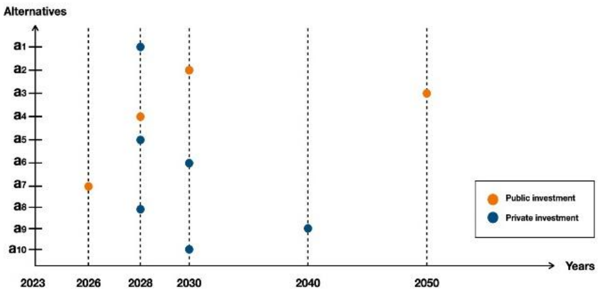


**Figure 2:** Timeframe of the implementation proposal.

Upon successful implementation of the actions until 2030, without considering the contribution from the photovoltaic power plant, the annual reduction in $CO_2$ emissions is expected to reach 392.98 tonnes. These proposals can reduce emissions in the residential and service sectors by 49%.

If the impact of the solar farm is taken into account, the estimated emissions savings are expected to reach 1125.39 tonnes. That amount is equivalent to 140.67% of emissions caused by the sectors mentioned above. Comparing these results with the environmental goals established by the municipality, it becomes evident how significantly photovoltaic energy contributes to the energy transition.

A sensitivity analysis was conducted to prove the robustness of the model. It was decided to run the model again to determine whether a ±0.05

variation in the credibility level affected the results. For a 0.05 decrease in the credibility level ($\lambda = 0.65$), there was a single variation in the upper range of $a_2$. For an increase of 0.05 ($\lambda = 0.75$), there were variations in two intervals, with $a_1$ converging on $C_3$ and $a_4$ converging on $C_2$.

In addition, three different scenarios related to the DCM-SFR procedure were analysed. First, referred to as "scenario one," in light of the inherent uncertainty associated with the placement of blank cards, it was established that no blank cards were inserted between levels. Second, two distinct scenarios were created to examine the impact of the ratio $z$, which influences the weight of each criterion. In scenario two, $z$ was 5, whereas in scenario three, $z$ was 15. The stability of the criterion weights was clear since changes in the number of blank cards and the ratio $z$ did not influence the category allocation.

## 7. Conclusions

The main objective of this dissertation was to assess various initiatives related to solar photovoltaic energy aimed at reducing emissions in municipalities.

From a methodological perspective, the categorisation of the model alternatives showed the majority were assigned to a range between $C_2$ and $C_3$. There was only one alternative assigned to the best category $C_3$ and the worst category $C_1$. These assignments demonstrate the relevance of photovoltaic technology in the current energy context and its multiple applications. However, there is still potential for improving the performance of photovoltaic systems by further reducing their installation costs, increasing the efficiency of the systems, and boosting the power output of the solar modules.

From a policymaking standpoint, the results of the model showed that 80% of the actions proposed should be implemented by 2030 to contribute to the fulfilment of the municipality's climate objectives. This requires not only the involvement of the local council but also the active participation of citizens and businesses associated with the economic activity of the municipality.

Furthermore, the key role of photovoltaic technology in the energy transition and, especially, in the reduction of urban emissions is validated. The implementation of some measures proposed in this work has the potential to directly reduce emissions from the residential and service sectors of the municipality by 49.11%. In addition, the town can contribute to national energy goals by adopting the implementation of a 1.5 MW solar farm. Combined with the aforementioned actions, it would result in a reduction of emissions equivalent to 61% of the municipality's total emissions, including those caused by transportation.

Overall, despite the fact that the model developed was evaluated in a Spanish municipality, and therefore, the context and regulations of this country were considered, it is believed that the model can also be useful in other contexts by adapting the analysis to each situation. Indeed, it would be valuable if other municipalities implemented the model to further validate it.

Moreover, there is a potential bias due to the fact that only the knowledge of an expert was involved. Considering the multidimensional character of the topic, it is recommended that further research includes the formation of a diverse focus group and the participation of policy decision-makers, as they will provide different viewpoints and perspectives.

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