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Using multi-criteria decision analysis to support local energy policymaking

A case study concerning photovoltaics in Rajadell, Spain

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“There is a driving force more powerful than steam, electricity and atomic energy: will.”

Albert Einstein

“If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.”

Nikola Tesla

Declaration

I declare that this document is an original work of my own authorship and that fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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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.

Resumo

As alterações climáticas, o esgotamento e a volatilidade dos preços dos combustíveis, e a dependência energética da Europa impulsionaram a implantação de fontes de energia renováveis. O papel dos governos locais e dos cidadãos na transição energética é fundamental, uma vez que uma grande parte das emissões é causada por ambientes urbanos. Este estudo centra-se na energia solar fotovoltaica, tendo em conta a importância que esta tecnologia tem para atingir os objectivos climáticos municipais. A análise de decisão multicritério é adequada para lidar com a natureza multifacetada da sustentabilidade e com o processo complexo pelo qual os decisores passam quando planeiam estratégias locais que têm em conta critérios económicos, ambientais, técnicos, e sociais. Com o apoio de um perito, foi concebido um modelo de MCDA baseado na abordagem ELECTRE Tri-nC para classificar múltiplas alternativas relacionadas com a energia fotovoltaica com o objetivo de reduzir as emissões dos municípios, envolvendo diferentes tipos de instalações, áreas, setores, e investidores. O modelo é aplicado no município espanhol de Rajadell, uma aldeia rural com 549 habitantes situada na província de Barcelona. Em 2022, o conselho local concordou em reduzir as emissões do município em 55% até 2030 e alcançar a neutralidade climática até 2050. Os resultados do projeto demonstram a relevância da energia fotovoltaica para alcançar estes objectivos. Especificamente, acredita-se que pode poupar até 49,11% das emissões anuais dos sectores residencial e dos serviços. Após uma análise de sensibilidade, o modelo revelou-se robusto e pode ser utilizado para outras análises em contextos semelhantes.

Palavras-chave: Análise de decisão multicritério; ELECTRE Tri-nC; Elaboração de políticas energéticas locais; Energias renováveis; Energia fotovoltaica.

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Acronyms

AC	Alternating Current
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CIT	Corporate Income Tax
CSP	Concentrated Solar Power
DC	Direct Current
DCM	Deck Cards Method
DM	Decision-maker
DSS	Decision Support System
EAA	Equivalent Annual Annuity
EERE	Energy Efficiency and Renewable Energy
ELECTRE	Elimination and Choice Translating Reality
ERDF	European Regional Development Fund
EU	European Union
GHG	Greenhouse Gas
GIS	Geographic Information Systems
ICAEN	Institut Català d'Energia
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
LED	Light Emitting Diode
MCDA	Multi-Criteria Decision Analysis or Multi-Criteria Decision Aiding
MCDM	Multi-Criteria Decision Making
NPV	Net Present Value
PPA	Power Purchase Agreement
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PV	Photovoltaics
PVGIS	Photovoltaic Geographical Information System
RD	Royal Decree
REBT	Reglamento Electrotécnico para Baja Tensión
RES	Renewable Energy Sources
SWARA	Step-Wise Weight Assessment Ratio Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UNEF	Unión Española Fotovoltaica
VAT	Value-added Tax
WPM	Weighted Product Model
WSM	Weighted Sum Method

Nomenclature

λ	Credibility index
a	Action
B	Reference action
C	Category
g	Criteria
p	Preference threshold
q	Indifference threshold
v	Veto threshold
w	Criterion's importance coefficient

1. Introduction

1.1 Problem statement

1.1.1 Context

Climate change involves long-term variations in temperatures and weather patterns primarily caused by the burning of fossil fuels that generate greenhouse gas (GHG) emissions that function like a blanket wrapped around the Earth, trapping the sun’s heat, and increasing temperatures (IPCC, 2023). Globally, approximately 50 billion tonnes of carbon dioxide equivalents of GHG are emitted each year (Karakosta et al., 2013), and they originate from a variety of sectors such as buildings, industry, transportation, agriculture, and energy. Consequently, it will require multiple strategies and innovation to decarbonize the entire economy.

The energy sector, including the power used in industry, buildings, and transportation, accounts for 73% of global emissions (Ritchie, 2020). Therefore, it is one of the main factors leading to GHG emissions and global warming. An analysis of the end use of energy in the EU in 2020 reveals three dominant categories: transport (28.4%), households (28%), and industry (26.1%) (Karakosta et al., 2013). Oil and petroleum products accounted for the biggest share (35%) in the structure of final energy consumption in 2020, followed by electricity (23.2%) and natural gas (21.9%)[1]. The primary energy consumed worldwide during 2021 came mostly from fossil fuels such as coal, gas, and oil, accounting for 83% of the total, while less than 13% was attributable to renewable sources[2]. The environmental concerns associated with conventional energy sources, their rapid depletion, and their high pricing require the exploration of alternative, clean, and sustainable energy sources. Within the existing framework, both renewable and nuclear energy sources are believed to be the most valuable solutions to decrease the environmental issues associated with fossil fuel-based energy production and partly provide solutions to global warming (Kim, 2021).

Renewable resources replace traditional fuels in three main applications: power generation, hot water production, and transportation. Focusing on electricity generation from renewable energy sources (RES), it is a potential option that provides multiple advantages, such as environmental profits by effectively producing limited amounts of GHG emissions, social benefits like creating employment locally, and a reduction of reliance on imported energy, notably relevant for European countries. Several nations have already included RES investments in their strategies for lowering dependency on gas and oil imports and the corresponding price volatility, as well as for cutting polluting emissions (Karakosta et al., 2013). However, electricity accounts for only one-fifth of worldwide energy consumption, so the contribution of renewables in the mobility and water heating and cooling sectors remains critical to the energy transition (International Energy Agency, 2022a).

1 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview

2 https://ourworldindata.org/grapher/energy-consumption-by-source-and-country

Most of the world's electricity in 2021 was generated via fossil fuels, while low-carbon sources only supplied 38% of the global electricity demand[3], and precisely, renewable energies accounted for 28%[4]. Certainly, it is a challenging matter, taking into consideration that renewable energy's share in electricity generation must increase to 65% by 2030, according to IRENA's 1.5ºC pathway (Renewable Energy Agency, 2022).

In May 2022, the EU presented its latest strategy, REPowerEU, to swiftly decrease dependence on Russian fossil fuels, accelerate the green transition, and enhance the implementation of renewables, increasing the headline 2030 target for renewables in the energy mix by 45 percent. Furthermore, the programme outlines an EU solar strategy, proposing doubling solar photovoltaic capacity by 2025 and mandating the installation of solar panels on newly built public and private buildings (European Commission, 2022). In Spain, the Integrated National Energy and Climate Plan (PNIEC) 2021-2030 defines the targets for the reduction of GHG emissions and the deployment of RES by 2030. The document specifies that renewable energies are expected to make up 42% of final energy demand and 74% of the electrical system. Concerning photovoltaic energy, it foresees 39 GW of installed capacity (MITECO, 2021). It is also relevant to mention the EU Covenant of Mayors for Climate and Energy, an initiative supported by the European Commission that unites thousands of local governments committed to achieving EU climate and energy goals. More than 2000 municipalities[5] in Spain have already pledged to reduce their GHG emissions by 55 percent by 2030, thereby improving their resilience and alleviating energy poverty.

1.1.2 Problem definition

Local administrations provide a range of structured services that are vital to the development of their communities. In the context of the energy sector, local governments are faced with opportunities to assist their communities, especially considering the current energy crisis. Because of the commitment of many municipal governments to reduce their emissions and create more sustainable and smarter cities, local authorities are promoting a variety of measures to meet these goals. Common actions include the installation of energy-efficient street lighting, the electrification or introduction of hydrogen in public transport, the enhancement of building thermal insulation, and the use of RES. This project does not intend to discuss these alternatives but concentrates exclusively on the use of photovoltaics to contribute to cleaner and more energy-efficient cities. The dissertation focuses on the Spanish energy and regulatory framework, primarily because photovoltaic energy has a significant impact on climate change mitigation in that country. Hence, many Spanish municipalities are implementing photovoltaic energy systems in their municipal buildings, whereas others have formed local solar energy communities or subsidised the installation of private photovoltaic (PV) systems. The approach to decision-making that municipalities need to carry out in order to agree on solid long-term solutions by considering economic, technical, environmental, and social criteria is indeed complex.

3 https://ourworldindata.org/low-carbon-electricity-by-country

4 https://ourworldindata.org/grapher/elec-fossil-nuclear-renewables

5 https://eu-mayors.ec.europa.eu/en/home

Due to the intricate nature of such 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).

This dissertation aims to develop an MCDA methodology to help municipalities plan the most suitable photovoltaic strategy to reduce their GHG emissions. For this purpose, different photovoltaic installations involving the investment of the local government, citizens and companies are compared. This approach will be implemented in the municipality of Rajadell, Spain.

Different methods based on MCDA have become increasingly prevalent in the energy field due to their capacity to manage complex decision processes in the presence of multiple and conflicting evaluation criteria, different stakeholder preferences, and many sources of ambiguity. Most studies have used these methodologies to evaluate renewable energy options (Saraswat & Digalwar, 2021) or to determine the optimal location for a power facility (Abdel-Basset et al., 2021), such as a photovoltaic farm (Shorabeh et al., 2019). Nevertheless, to the author's knowledge, MCDA has never been utilised in a project similar to this one, and, indeed, there is a knowledge gap to be filled by this work.

1.2 Motivation

Concerns about climate change, its dire consequences, and the rising demand for energy have resulted in a significant increase in the utilisation of RES, including photovoltaic energy. With governments across the globe establishing ambitious targets to produce renewable energy, the demand for photovoltaic technology is expected to increase further. The photovoltaic sector is a driver of economic growth and territorial development, plays a crucial role in the struggle against climate change, and promotes substantial benefits for rural communities and society. Thus, solar power is regarded as a prominent source of clean energy due to its numerous advantages, such as its minimal maintenance needs, absence of emissions, and long lifespan. As the technology that powers PV systems continues to develop, solar cells have become more efficient, thereby becoming more affordable and appropriate for widespread application. Apart from technological development and lower installation costs, the photovoltaic expansion has been driven by incentive policies to improve the appeal of renewable energies. Photovoltaics has enabled citizens to participate in this shift away from the traditional model, for instance, through self-consumption or by creating energy communities, thus decentralising the generation system. They are no longer mere consumers of energy from the grid; nowadays they can produce their own energy and consume it independently of the grid, store it, or feed it into the system.

According to the most recent UNEF report, "2021 was a historic year for the Spanish photovoltaic sector. Ground-mounted plants installed capacity reached 3.5 GW, a growth of 21% compared with 2020, and self-consumption had a record year, with capacity increasing to 1203 MW, more than 100% relative to 2020" (Unión Española Fotovoltaica (UNEF), 2022, p. 9).

Due to its privileged location and climate, Spain is especially favoured for photovoltaic energy production in comparison to the rest of Europe, as every square metre of its territory receives between 730 and 2400 kWh[6] of solar radiation per year, depending on its geographical location. In addition to these favourable conditions, public policies at all levels for fostering solar energy in Spain have been key to its success. This ranges from EU Next Generation Funds to national regulatory frameworks and regional incentives. In this project, the emphasis is on the role of municipalities since they have the greatest knowledge of the territory, the needs and interests of its residents, and the ultimate responsibility for making photovoltaic initiatives a reality. Due to the complexity and conflicting interests of these projects, a MCDA approach is necessary.

Overall, the motivation for this project lies in the author's interest in renewable energies, particularly photovoltaic energy, and his conviction that individuals and municipalities must be involved in energy planning and policymaking. In addition, the author is grateful for the opportunity to conduct a case study in his hometown of Rajadell, Spain.

1.3 Objectives

The purpose of this dissertation 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. This model is intended to be useful for determining which installations are most urgent to achieve the environmental targets, and it can also support local authorities when planning a local energy strategy. In addition, the following secondary objectives have been set for each section of the project:

Introduction:

(i) Identify and describe the problem at hand.

Literature review:

(ii) Obtain an overview of currently existing renewable energies and justify the choice of photovoltaics.

(iii) Analyse the existing scientific literature on the application of MCDA to the energy sector, and particularly to photovoltaic energy.

(iv) Identify the knowledge gap and how the study will fill it.

Background:

(v) Acquire a comprehensive understanding of the energy generation in Spain, the importance of the photovoltaics sector in the country, and its current framework.

(vi) Provide an overview of the fundamentals of photovoltaics.

Methodology:

(vii) Examine the MCDA methodology and its components, and select the most suitable MCDA for addressing the problem at hand.

6 https://globalsolaratlas.info/map

(viii) Become familiar with the selected model as well as its formulation, assumptions, and parameters.

Case Study:

(ix) Apply the proposed framework to the Spanish municipality of Rajadell.

Results and discussion:

(x) Discuss the results and critically analyse them.

(xi) Provide recommendations for policymakers according to the results obtained.

Conclusions:

(xii) Evaluate the fulfilment of the proposed objectives and personally assess the project.

1.4 Research methodology

In order to accomplish the objectives above-mentioned, a research methodology plan has been established. The present research strategy is a combination of quantitative and qualitative techniques. The quantitative aspect entails gathering and analysing numerical data to evaluate the performance of different photovoltaic systems based on a variety of criteria. The qualitative side involves speaking with experts to elicit their preferences. The methodology consists of the following sequential phases, although some information from earlier stages may be modified and expanded upon as the work progresses. The methodological process of the research is depicted in Figure 1.

1- Identification, definition, and characterization of the problem at hand.
2- Literature review and analysis of the current state of the art.
3- Model building.
4- Collection of data and model implementation.
5- Analysis and discussion of the results.

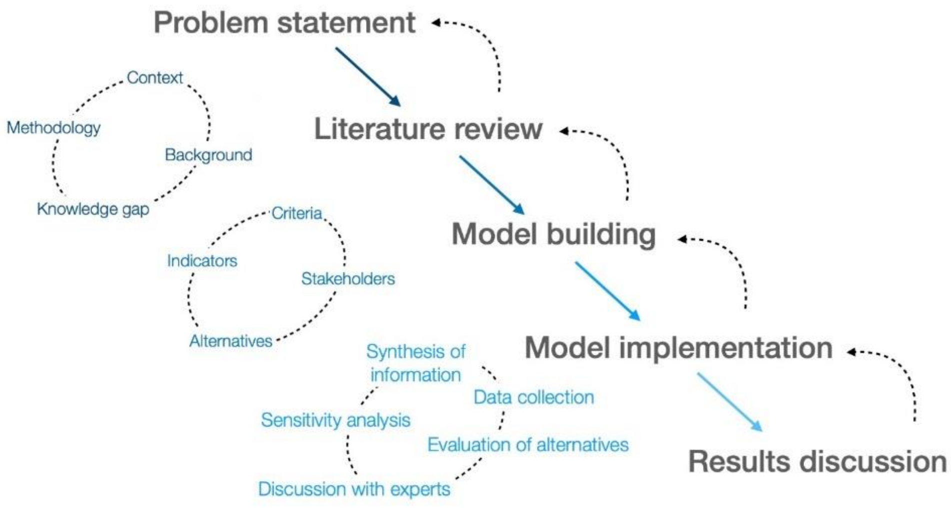

Figure 1: Research methodology.

Firstly, the context of the work is presented, followed by a description of the problem at hand. The second step consists of conducting a thorough survey of the current state of the art regarding renewable energies and, specifically, photovoltaic technology. In addition, a revision of the core concepts underlying MCDA and their application to the energy field is conducted. After that, an examination of the studies and methods that consider photovoltaic energy is performed. In the third step, the MCDA methodology is addressed, namely the methods used in the current work: ELECTRE Tri-nC and the DCM-SRF method. The model is then defined and constructed, although future improvements can always be incorporated as new information becomes available. The fourth step is the collection of data and the implementation of the whole model, following the meetings with the expert and the evaluation of the alternatives created for the municipality of Rajadell. The final step marks the final conjectures and conclusion of the project.

1.5 Structure

This document is comprised of a total of seven chapters, structured in chronological order according to the phases of the research methodology process. The first chapter introduces the project by describing its context, defining the problem, and outlining the proposed objectives. Additionally, the research methodology and procedures required to achieve these objectives are described. The second chapter is a literature review on renewable energies and the application of MCDA in this field, particularly photovoltaics. The previous choice of photovoltaic energy is justified, and a knowledge gap is identified. The third chapter details the fundamentals of photovoltaic technology and its current framework in Spain. In addition, it contextualises the energy sector in Spain and points out the importance of photovoltaic energy for the country. The fourth chapter focuses on the methodology employed to solve the defined problem and justifies the methodological choice. Chapter 5 addresses the application of this methodology to a case study. The penultimate chapter analyses and discusses the results obtained, while the concluding chapter presents the conclusions.

2. Literature review

2.1 Renewable energy

Renewable energy is obtained from continually replenishing natural processes, and it originates in its different forms mainly from the sun, wind, water, ocean tides, biomass, and geothermal resources. The Office of Energy Efficiency and Renewable Energy (EERE) defines renewable energy as energy produced from sources like the sun and wind that are naturally replenished and do not run out[7]. This section will provide a brief overview of each of these sources as well as their main characteristics.

2.1.1 Hydropower

In hydropower plants, water is channelled through a penstock, where it then pushes against and rotates the blades of a turbine to power a generator, which produces electricity. Typical hydroelectric facilities include run-of-the-river systems, in which the force of the river's current exerts pressure on a turbine, and storage systems, in which reservoirs gather and deliver water to turbines that are released as required to produce power. Additionally, pumped-storage hydropower plants pump water from a source to a storage reservoir at a higher elevation and release it to power hydro turbines below the reservoir[8]. The contribution of global hydropower production is greater than that of wind, solar photovoltaic, and other current forms of renewable energy combined. Behind coal and natural gas, hydropower was the third largest contributor to the world's electrical supply in 2021, generating over 4000 TWh of electricity[9] and accounting for more than 15% of the total. Hydropower generates most of the electricity in some developed countries, including Norway (91%), Switzerland (60%), and Canada (60%), as well as most of the electricity in 28 developing countries, such as Brazil (54%), Venezuela (64%), or Laos (71%)[10]. Compared to other methods of producing electrical power, hydropower offers several benefits. They include a high degree of dependability, proven technology, great efficiency, low operating costs, and the capacity to quickly adapt to load variations. The adaptability of hydropower is essential for integrating increasing amounts of wind and solar PV into electrical infrastructure. Indeed, there is currently no alternative technology that can compete with reservoir plants and pumped storage hydroelectric facilities in terms of their adaptability and storage capacities. Alongside batteries, pumped storage hydropower projects will remain a key source of electricity storage, and world pumped storage capacity is predicted to expand by 7% to 9 TWh by 2030 because of new developments. The disadvantages of hydropower include high initial costs of facilities, dependence on precipitation, changes in stream regimes, and displacement of people living in the reservoir area. In advanced economies, plants are ageing and need modernisation to ensure they can contribute to electricity security (Energy Agency, 2021).

7 https://www.energy.gov/eere/renewable-energy

8 Hydropower explained - U.S. Energy Information Administration (EIA)

9 https://ourworldindata.org/grapher/hydropower-consumption

10 https://ourworldindata.org/grapher/share-electricity-hydro

Research indicated that hydropower had the lowest GHG emissions (1.9 kg of $C0_2$ equivalent per MWh) during the power generation stage, despite the fact that it had the greatest land-use indicator (7.76 m^2 per MWh) and the highest water usage indicator, mostly as a result of water evaporation (Ali et al., 2023).

2.1.2 Wind power

Wind power ranks second worldwide behind hydropower in terms of RES installed capacity and represents, at around 6%, the fifth source of energy production. Furthermore, wind energy projects have the highest rate of expansion among all renewable power technologies, being the first RES for electricity generation in the EU in 2021 with 389 TWh produced. Such rapid development was possible due to an unprecedented increase in wind capacity additions, which reached 113 GW globally in 2020[11]. As early as 5000 B.C., humans were using wind energy to drive boats along the Nile. In China, primitive wind-powered water pumps were in use by 200 B.C. It was not until 1888, in Cleveland, that the first wind machine capable of generating electricity was constructed (Kaldellis & Zafirakis, 2011). In general, the operation is comparable to that of hydropower, but, in this instance, using the kinetic energy of air in motion. Contemporary wind turbines, via the rotor blades, convert kinetic energy into rotational energy, which is subsequently transferred through a shaft to the generator that produces electrical energy[12]. In 2021, 93% of the total 830 GW of built wind capacity was onshore, with the remaining 7% being offshore wind farms. Nonetheless, both onshore and offshore wind still have significant deployment and enhancement potential. In the case of onshore wind, innovation is focused on boosting technical productivity, whereas the maximum height of onshore wind turbines is often limited for environmental and public acceptability reasons. In contrast, there is no such constraint on turbine size in the offshore wind market; therefore research is concentrated on constructing larger turbines, which allow reductions in the overall cost of power generation. As a result, offshore reach is projected to grow substantially in the future (IEA, 2022d).

2.1.3 Solar

The sun is a limitless supply of free energy; therefore, if methods for its gathering and distribution were widely available, solar energy could hypothetically cover the energy requirements of the whole globe. These days, solar energy is applied for cooling and heating buildings, industrial heat generation, power generation, and other various applications. Solar energy may be further divided into two subcategories: photovoltaic technology and solar thermal. Photovoltaics uses semiconductors to directly convert sunlight into electrical energy. Solar thermal technology converts solar energy into thermal energy for industrial and residential purposes, including heating and cooling. This latter aspect is decisive since only three RES (i.e., biomass, geothermal, and solar) can provide adequate heat energy for power production (Kannan & Vakeesan, 2016).

11 https://ourworldindata.org/grapher/share-elec-by-source

12 Wind energy (irena.org)

In addition to PV technology, concentrating solar thermal power (CSP) is used to transform solar energy into electricity, even though 97% of the installed solar capacity is comprised of photovoltaic systems[13]. Certainly, there are several benefits as well as limitations involved with its usage.

The far more apparent shortcoming is that solar energy can only be captured during the day, but further downsides include relatively high initial installation costs, weak efficiency of solar panels (about 20%), and reduced battery lifespan. Despite these constraints, solar energy offers multiple profits. For instance, the GHG emissions related to solar power production (including manufacture, installation, operation, and maintenance) are minimal; the estimated range of $C0_2$ emissions per kilowatt-hour is between 0.03 and 0.09 kg, which represents an emission ratio of 1:9.5:18 compared to gas and coal, respectively. In addition, solar technology could increase employment prospects; according to the Solar Foundation, the solar sector employed around 208000 workers in the United States for manufacture, installation, and sales. Economically, the solar power market has several benefits, such as tax benefits, the elimination of electricity bills, enhanced property value, long-term durability, and low maintenance costs. (Kabir et al., 2018). Behind hydropower and wind, solar PV is the third largest renewable electricity technology and demonstrated the second greatest absolute production growth of all renewable technologies after wind in 2021, when PV output climbed by a record 179 TWh (up 22%), surpassing 1000 TWh. Throughout most of the globe, solar PV is becoming the most economical option for new power production, which is projected to spur investment in the coming years. Thus, photovoltaics is the dominant renewable technology in the private industry, with many companies investing in distributed solar PV installations on their own buildings and premises – accounting for nearly 30 percent of the total installed capacity in 2021 – and engaging in corporate power purchase agreements (PPAs) (IEA, 2022b). Many governments' policies, investments, and support for solar technology have contributed to providing a solid foundation for the commercialisation of this RES. Some nations, such as Spain and the Netherlands, are embracing solar energy as a significant component of their energy mix, with 11% and 14%, respectively. However, solar electricity generates less than 4% of the world's power demand[14].

2.1.4 Bioenergy

According to the European Commission, bioenergy is a RES derived from biomass, which is defined as biological sources such as agricultural or forestry leftovers, as well as biodegradable portions of industrial or municipal solid waste (Long et al., 2013). Bioenergy used for electricity may complement variable renewables and provide negative emissions when combined with carbon capture and storage technologies. So far, there are considerable questions over how much biomass can be delivered in a sustainable way to the energy system in Europe and globally (Lehtveer & Fridahl, 2020). Even excluding traditional biomass usage, bioenergy's contribution to final energy consumption across all sectors is five times higher than solar PV and wind combined, though the heating sector remains the largest source of bioenergy (IEA, 2022a).

13 https://ourworldindata.org/grapher/installed-global-renewable-energy-capacity-by-technology

14 https://ourworldindata.org/grapher/share-electricity-solar

Bioelectricity, on the other hand, represents a minimal part of the power-producing capacity, whereas solar and wind power provide significant and continuously growing shares. The global bioelectricity output during 2021 was around 666 TWh and purely represented 2.4% of the total energy production[15].

2.1.5 Geothermal

Geothermal energy can supply base-load power production as well as heating and cooling from high-temperature hydrothermal and hot rock resources that are commonly confined at the depths of the Earth as porous rocks, or reservoirs, and store thermal energy. Geothermal energy has garnered substantial interest as a renewable resource that does not emit significant $C0_2$ emissions during electricity generation (IEA, 2022b). Most of the geothermal installed capacity is in the United States (2.653 MW), Indonesia (2.343 MW), and Philippines (1.932 MW)[16], with this latest having a geothermal edge in many areas of the territory owing to the existence of subsurface reserves of hot fluids. In 2021, global geothermal electricity supply was almost 100 TWh (IEA, 2022b), and its production is notable in a few nations. For example, it contributes 10% of the total electricity generation in the Philippines and nearly 18% in New Zealand, where it is the second largest source of power (Ritchie et al., 2022).

2.1.6 Marine energy

With large, well-distributed resources, ocean energy has the potential to scale up over the long term. In fact, the oceans and seas possess a huge potential for energy generation, predicted at over 120000 TWh per year, sufficient to provide more than 400% of the present world consumption. However, ocean power accounts for the smallest portion of renewable electricity globally, and the bulk of projects are still in the demonstration phase mainly due to its high cost, with most projects being built in France, the United Kingdom, the United States, and Canada (IEA, 2022b; Zabihian & Fung, 2011). Marine energies can be categorised into five groups: tidal energy, wave energy, salinity gradient energy, ocean thermal energy, and ocean current energy. Currently, the first two are the most relevant. Tidal energy is created by the un and moon's gravitational influence, where the kinetic energy of the water is turned into the motion of a mechanical system, which subsequently powers a generator. One of the major benefits of this source over solar and wind is its predictability. Wave energy is a mix of potential energy due to its height and kinetic energy resulting from the movement of water particles. Wave energy converters may generate power from both forms (Zabihian & Fung, 2011).

2.2 Rationale for the selection of photovoltaic energy

As outlined in the introductory section, the essence of this study pertains to the matter of climate change and, particularly, the relevance of the energy sector in relation to this concern. Hence, the utilisation of renewable energies is suggested as an appropriate alternative for the decarbonization of this field.

15 https://ourworldindata.org/grapher/share-elec-by-source

16 https://ourworldindata.org/grapher/installed-geothermal-capacity

As explained previously, there is a wide variety of renewable energies, so it is valuable to provide a justification for the selection of exclusively incorporating photovoltaic systems in this project as well as indicate the distinctive traits that distinguish this technology from the others. In contrast to other forms of renewable energy, such as marine energy, photovoltaics is considered a mature technology that is experiencing significant expansion and notable reductions in costs. Over the past decade, there has been an 85% reduction in the cost of photovoltaic panels[17].

Additionally, it contributes to the creation of local employment. Photovoltaic energy exhibits a wide range of applications, enabling individuals, companies, and public entities to readily embrace such systems. One distinguished advantage of photovoltaics lies in its capacity for self-consumption, which sets it apart from other energy sources that necessitate the establishment of extensive power plants. Furthermore, solar energy is significant for Spain. The country possesses a high solar potential across its territory, in contrast to hydropower or wind power, which require locations with very specific conditions. In addition, the national government has prioritised the development of photovoltaics, leading to the implementation of regulations, subsidies, and tax incentives to support the spread of photovoltaic power. Finally, in comparison with solar thermal modules, photovoltaic panels for self-consumption produce electricity, which is in line with the energy focus of this project.

2.3 Multi-criteria decision analysis in the energy sector

Most policy decisions involve complex settings with conflicting priorities, which explains why MCDA has been regularly resorted to. MCDA is a strategy for alternative selection and prioritising when multiple criteria are considered, and it provides a variety of methodologies designed to assist decision-makers (DMs) in reaching better decisions. In addition, it also facilitates the comprehension of a multi-criteria situation, aids in interactive planning, and enables participants to methodically analyse and apply their value judgements. It promotes the solution's acceptability by permitting the incorporation of the preferences and interests of numerous stakeholders in an equitable and transparent manner (Neves et al., 2018). Owing to the multidimensional and complex 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). Energy policymaking problems involve selecting among energy alternatives, evaluating energy supply technologies, and energy planning. Multi-criteria decision-making (MCDM) methods are used as techniques for resolving energy decision-making issues since they analyse solutions from several opposing viewpoints (Kaya et al., 2019).

Before the 1970s, energy planning was completely governed by cost minimisation models subject to demand fulfilment and technological boundaries, mainly concerning power generation expansion planning or the choice of sites for fossil-fired generation plants. That energy crisis, essentially caused by the peaking of oil consumption and the imposition of embargoes by producing nations, meant that energy policies could not be evaluated anymore exclusively based on economic costs, but also on other assessment factors such as environmental implications and social impacts (Ehrgott et al., 2016).

17 https://ourworldindata.org/grapher/solar-pv-prices

These socio-environmental aspects highlight the importance of including the community in the decision-making processes for energy policy, with municipalities and local councils serving as the main gateways for democratising these systems. The European Commission suggests the use of MCDA for the purpose of selecting actions, and it is, in fact, the most often referenced practice for municipal energy planning and decision-making processes (Neves et al., 2018).

MCDM techniques have become popular for sustainable energy planning. Each of them has its own postulates and assumptions. Some of the most frequently used MCDA methods for energy-related topics are the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Elimination and Choice Translating Reality (ELECTRE), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Manirambona et al., 2022). These tools may be used in conjunction with fuzzy set theory to provide more realistic, sensitive, and precise outcomes for addressing the uncertainties inherent in human opinions. MCDM studies related to energy planning are mainly focused on evaluating technology alternatives, determining energy policy, energy investment, and power plant selection (Kaya et al., 2019). This section presents some recent studies on the subject.

Ranking alternative RES or sustainable technologies represents one of the most common research applications. For instance, Saraswat & Digalwar (2021) used fuzzy AHP to rank different energy sources in India, using solar, wind, biomass, gas, thermal, and nuclear power as alternatives. The Shannon entropy method was applied to determine the weights of decision criteria, including economic as payback period or investment cost, social as job creation, technical as efficiency or reliability, environmental as land requirement, and political as political acceptance. The result was compared with many well-known MCDM methodologies, such as TOPSIS or PROMETHEE-II. Another similar case is the work of Alizadeh et al. (2020), who established a model based on the ANP technique to assist fossil-fuel exporting countries to harness their RES effectively. Using Iran as a practical example, the research sought to rank various low-carbon energies and indicated that solar energy was most appropriate for the scenario analysed. Pereira & Pereira (2023) proposed a collaborative MCDA framework based on the Choquet multi-criteria preference aggregation model to rank different potential alternatives in several layers of the energy storage market, using Portugal as a case study, and involving the possibility for interactions between pairs of criteria, thereby overcoming the premise of criteria independence. The strategy was constructed in collaboration with policymakers and experts from each tier who served as performers in the decision-making procedure. 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 and executing it through the ELECTRE III outranking method. The methodology was partially implemented by the municipality of Odemira, Portugal. Power plant selection has also been the subject of numerous research investigations. This is the case of the analysis conducted by Zhao et al. (2022), which provided an MCDM technique combined with Geographic Information Systems (GIS) to resolve the complex nature of location prioritisation, based on the TOPSIS fuzzy-technique application. Shao et al. (2020) reviewed 85 studies that applied MCDM methods for renewable energy site selection and concluded that AHP is a common practice for weighting criteria, while GIS is a popular instrument for alternative rating.

The findings revealed that wind and solar energy account for more than 90 percent of the studies published. Abdel-Basset et al. (2021) proposed a multicriteria model that relied on PROMETHEE-II and AHP to accommodate multiple experts under imperfect information for the purpose of resolving the issue of determining the optimal location for an offshore wind power station.

2.4 Multi-criteria decision analysis applications to solar energy technologies

As stated previously, a significant part of solar photovoltaic energy and policymaking research focuses on finding suitable locations for power plants. Sánchez-Lozano et al. (2014) combined GIS with MCDA, specifically the ELECTRE-Tri method, to identify the best plots suitable for installing PV farms in the municipality of Torre Pacheco, in the southeast of Spain. Hoang Tuyet Nhi et al. (2022) put forward a fuzzy TOPSIS model for ranking potential locations for solar power plants. Rediske et al. (2020) used AHP methods for the weighting of the factors, gvSIG for processing the analysis of the areas, and TOPSIS for ranking the alternatives. Idris et al. (2022) concluded that the AHP approach has been the most extensively used technique for determining the ideal placement for photovoltaic farms. Furthermore, they reviewed the different methodologies applied to solar energy and analysed that existing studios were dominated by land-based and large-scale PV systems, and relatively few have addressed floating solar PV, for example Guo et al. (2021) created a location appraisal framework for floating photovoltaic power plants based on the fuzzy PROMETHEE method. 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) that applied a multi-decision-making approach to figure out the concern of classifying a set of available photovoltaic panels for consumers in Tunisia employing the VIKOR method to rank the PV modules, or the study of Hosseini Dehshiri & Firoozabadi (2023) that evaluated solar tracking systems that were tied to the grid. Fang et al. (2020) assessed five commercial PV technologies and facilitated sustainable technology selection and policy suggestions. In their paper, Azzouz et al. (2022) used the decision method PROMETHEE-II to select a photovoltaic electrical structure for remote locations. The purpose of Rani et al.’s (2020). study was to present an MCDM framework for handling solar panel selection problems in an ambiguous environment, utilising a method based on SWARA for determining the weighting of criteria, and VIKOR for sorting the alternatives. Less frequently, other researchers have analysed the sustainability and impact of PV projects and policies. The research of Boumaiza et al. (2022) employed a unique approach, named ABM-BN-SA, and sensitivity analysis to identify the relative influence of criteria, as well as a comparative analysis of AHP, TOPSIS, and ELECTRE II. The programme offered a decision support system for studying the optimal combination of solar energy regulations and incentives in Qatar. Reddy et al. (2019) evaluated and compared the sustainability of five solar power initiatives in India and China using the WSM, WPM, and TOPSIS methods. Mastrocinque et al. (2020) used the photovoltaic energy sector as a case study for a MCDM framework and assessed seven European countries to come up with sustainable investment decisions.

Table 1 summarises the studies that have been reviewed regarding the application of MCDA and solar energy. As can be noticed, the studies have relied primarily on the application of multiple MCDA methodologies to select the optimal location for a solar power plant or to evaluate and compare various technological aspects of photovoltaics. Sustainability and policy assessment have also been studied.

Table 1: Studies applying MCDA to photovoltaics.

Purpose	Study	
Site selection	(Sánchez-Lozano et al., 2016)	(Haurant et al., 2011)
	(Vafaeipour et al., 2014)	(Idris et al., 2022)
	(Hoang Tuyet Nhi et al., 2022)	(Sánchez-Lozano et al., 2014)
	(Sánchez-Lozano et al., 2013)	(Guo et al., 2021)
	(Uyan, 2013)	(Jun et al., 2014)
	(Rediske et al., 2020)	
Technology assessment	(Azzopardi et al., 2013)	(Bouzid et al., 2021)
	(Hosseini Dehshiri & Firoozabadi., 2023)	(Fang et al., 2020)
	(Socorro García-Cascales et al., 2012)	(Cavallaro, 2010)
	(Azzouz et al., 2022)	(Rani et al., 2020)
	(Thebault et al., 2022)	(Azzopardi et al., 2013)
Sustainability assessment	(Reddy et al., 2019)	(Mastrocinque et al., 2020)
Policy and investment assessment	(Mastrocinque et al., 2020)	(Cucchiella & D'Adamo, 2015)
	(Matulaitis et al., 2016)	(Aragonés-Beltrán et al., 2010)

2.5 Knowledge gap

As the EU seeks to lead the clean energy transition, it has proposed ambitious targets for the implementation of renewable energy technologies, such as photovoltaic, and the reduction of GHG emissions. The Commission's proposal is to reduce GHG emissions by at least 55% by 2030 and to achieve climate neutrality by 2050[18]. This implies that nations, and above all municipalities, have a great responsibility for achieving it. To ensure the accomplishment of their intended objectives, local governments need to strengthen their current governance frameworks.

MCDA methods have proven useful in assisting DMs with evaluating alternatives based on multiple criteria. However, the development of effective decision-making tools to categorise photovoltaic initiatives remains a continuing challenge. Following a review of literature related to the use of MCDA in the context of photovoltaic technology, it has been noted that most studies examined primarily focus on site selection for a PV power plant, and technology assessment, such as comparing PV modules.

18 https://climate.ec.europa.eu/index_en

Nevertheless, the utilisation of the MCDA technique in assessing and contrasting various photovoltaic installations for the purpose of determining their degree of urgency for action in alignment with the environmental goals of municipalities remains unexplored. In addition, this project compares initiatives with various public and private investors. In fact, photovoltaics is one of the technologies that allows municipalities, citizens, and enterprises to directly contribute to achieving environmental goals.

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

3.1 Solar photovoltaic technology

Based on the photovoltaic effect, photovoltaic solar energy consists of the conversion of solar radiation into electricity. This phenomenon was discovered in 1839 by the French physicist Alexandre Edmond Becquerel, who detected the emergence of voltage between the terminals of a semiconductor material exposed to light, essentially the photovoltaic effect. This effect arises in materials known as semiconductors, which present two energy bands. The valence band allows the presence of electrons, whereas there is no presence of them in the conduction band. When photons from sunlight provide enough energy to displace the outermost electron from the valence band to the conduction band, direct current (DC) electricity is generated (Sampaio & González, 2017). Therefore, 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).

The semiconductor is incorporated into a solar cell, which is the fundamental element and main component of PV systems. Silicon, the second most plentiful element on Earth, is the most widely used material for solar cells, with c-Si cells leading the market in 2021, accounting for 95% of total manufactured capacity, while cadmium telluride (CdTe) thin-film PV technology makes up the remaining (IEA, 2022c, p. 13). Figure 2 shows the different stages involved in the manufacture of a photovoltaic panel.

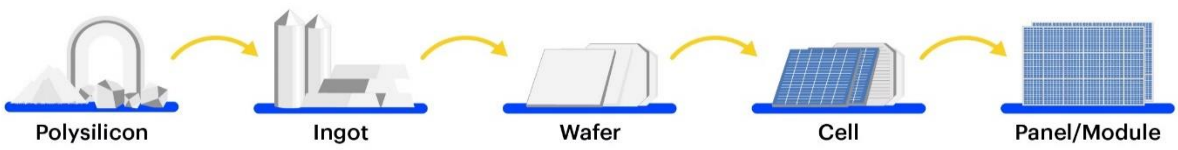

Figure 2: The main steps for the manufacture of a solar module[19].

80% of the total energy consumed to produce silicon solar PV modules is provided by electricity. This electricity-intensive process consumed 364 PJ in 2021 and accounted for over 0.2% of global industry energy expenditure. However, 62% of the electricity used was fuelled by coal, largely due to China's industrial concentration, which is still responsible for about 70% of production. Reducing the carbon intensity of production might thus be a major opportunity for the PV industry to reduce its carbon footprint by, for instance, employing renewable power for manufacturing processes. Nonetheless, solar panels displace significantly more emissions than they emit during module production; e.g., 1 GW of photovoltaic installed capacity may offset 1.5 million tonnes of carbon dioxide per year from coal-fired generation (IEA, 2022c, pp. 36–38).

19 https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary

While cell technologies are focused on the chemical and physical processes of converting sunlight into electricity at the single-cell level, system technologies are concerned with supplying the produced energy in a proper manner to be utilised on the consumption side (Shubbak, 2019, pp. 10–12). Simplistically, a standard power system, as shown in Figure 3, is composed mainly 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).

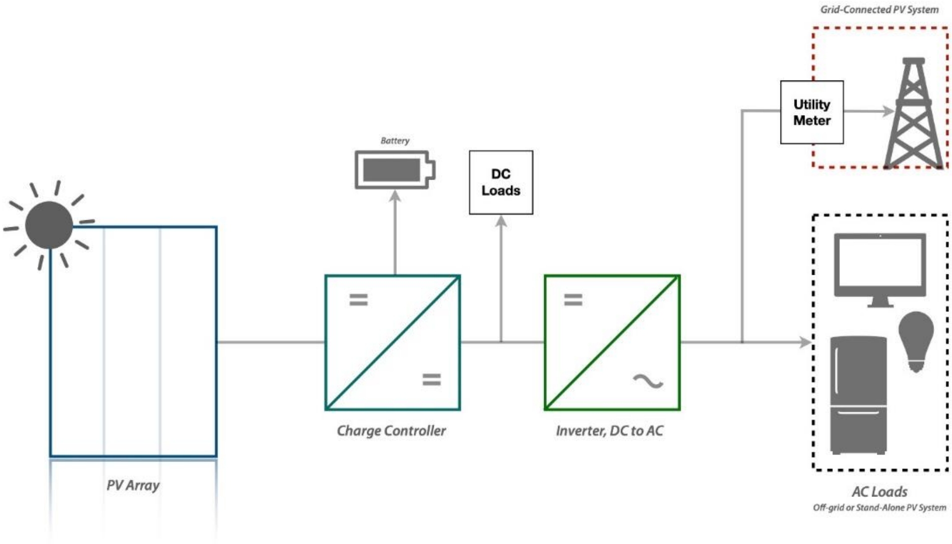

Figure 3: Elements of a common photovoltaic system.

The photovoltaic array consists of several solar panels, each made up of basic units called photovoltaic cells, connected in series and/or parallel to convert solar energy directly into electricity. The current power output of solar panels is around 400–500 W for commercial scale applications, while the largest advanced modules on the market offer up to almost 700 W under standard test conditions (IEA, 2022c, pp. 28–29).

The mounting structure of photovoltaic panels for both roof and ground mounting is a fundamental part of the photovoltaic system and directly impacts the installation process. It provides robustness and stability to the solar array and guarantees its structural integrity against adverse climate conditions, especially wind. The most commonly used materials are steel, which ensures a support with high durability and low maintenance; aluminium, due to its light density and anti-corrosion properties; and precast concrete blocks, which are suitable for installing panels on flat surfaces, thereby reducing cost and installation times. In free-standing structures, the modules are mounted on a rack with air flowing freely behind them. In roof-added or building-integrated systems, the modules are completely incorporated into the structure of a building's roof, with little air movement behind the modules (Azzouz et al., 2022).

The performance of photovoltaic systems is dependent on their own components and their ability to capture solar energy. Sunlight is not constant and varies according to time and latitude. Therefore, the proper orientation and inclination can improve the energy efficiency and performance of the system. The structure provides the installation with the desired inclination and orientation to maximize energy harvesting.

The optimal orientation for solar panels in Spain is towards the south, as this guarantees that the panels are irradiated for most of the day. When this is not feasible, other orientations as near as possible to the south are typically sought. The azimuth angle indicates the deviation of the plane from a south orientation. Additionally, the existence of shadows must be considered (Dhimish & Silvestre, 2019). There are other techniques that optimize the power output of PV systems, such as solar trackers or floating systems. Tracking systems combine solar panels with a mobile platform that lets the orientation and tilt of the modules be controlled at the same time. This makes sure that the panels are always perpendicular to the sun's rays. Research indicates that tracking systems might capture 20 to 50% more solar energy than PV placed at a constant angle. Floating technology decreases the temperature of PV panels by taking advantage of the natural cooling action of water and, consequently, increasing their efficiency. Its application in dam reservoirs can minimise water evaporation considerably (El Hammoumi et al., 2022). Figure 4 illustrates an example of a solar tracking system and a floating solar farm.

Figure 4: Solar farm with a module tracker system (left)[20] and Europe's largest floating solar park located in Portugal (right)[21].

As for the charge controller, it has the role of protecting batteries from overcharging or being fully discharged. It regulates the amperage and voltage that are delivered to the loads, and any excess power is delivered to the battery system (Shubbak, 2019). Batteries are used to store the excess power generated by the solar array for use at night or on days with low sunlight or cloudy conditions (Sampaio & González, 2017).

In the absence of a charge controller and batteries, all this energy is delivered to the inverter, which is responsible for transforming the DC into alternating current (AC) suitable for consumption. When production exceeds demand, the surplus energy is supplied to the grid, or, if this is not feasible, production is limited.

20 https://www.britannica.com/technology/solar-tracker

21 https://www.weforum.org/agenda/2022/05/portugal-europe-floating-solar-farm-renewable-energy/

3.2 The Spanish energy sector

The existing energy framework in Spain is based on the 2050 goals of climate neutrality, i.e., 100% renewable energy in the electricity mix and 97% in the overall energy mix. As such, it focuses on the vast deployment of RES, mainly solar and wind, the increase of energy efficiency, electrification, and green hydrogen. This is believed to have the potential to stimulate the economy, create employment opportunities, strengthen energy security, and boost competitiveness. Notwithstanding, Spain's entire energy balance is still characterized by fossil fuels, notably in the transportation and industrial sectors (IEA, 2021a, p. 11). The mobility industry is one of the most oil-dependent, with more than 90% of transportation driven by fossil fuels. Spanish industries consumed 18.7 Mtoe in 2020 and used mainly natural gas (43%), electricity (31%)[22]. In comparison, in the residential sector, electricity was the main energy source, accounting for 48% of the total supply[23]. Figure 5 shows Spain's energy consumption categorised by sector, as well as its primary sources and transformations, mainly into electricity. Electricity accounts for over a quarter of the country's total final energy consumption, and it is the second-largest energy source after oil (IEA, 2021a, p. 111). In addition, electricity demand is projected to increase across all sectors, substantially owing to the increasing electrification of multiple areas, such as buildings. It is therefore an elementary component to be taken into consideration when aiming to reduce greenhouse gas emissions.

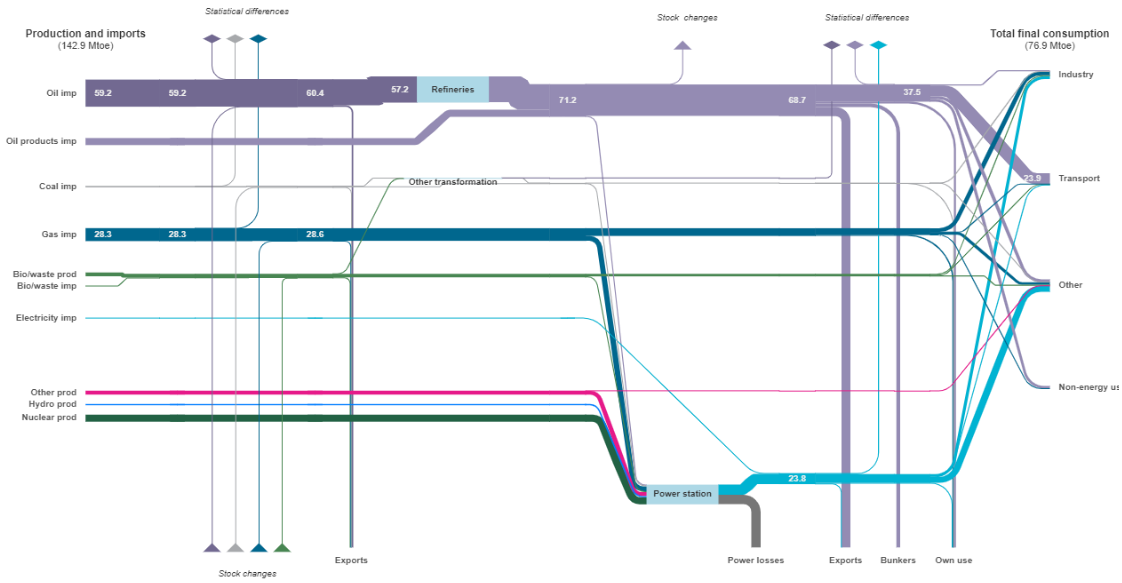

Figure 5: 2020 Sankey's diagram of Spain[24].

Figure 6 shows the evolution of electricity share by source in Spain. Natural gas is currently the major electricity source, accounting for about one-third of the generated electricity in 2022[25].

22 In 2020, energy consumption was slightly reduced due to the Covid-19 pandemic

23 https://www.iea.org/sankey/

24 https://www.iea.org/sankey/

25 https://ourworldindata.org/grapher/energy-consumption-by-source-and-country

The flexibility of natural gas power plants is applied to balance the fluctuation of electricity output from RES such as solar and wind and the coal phase-out, alongside the variable yearly power generation from hydro sources. Renewables are nowadays an increasingly major source of power production, accounting for 40% of national generation in 2022[26], including wind, solar, hydro, and bioenergy. In 2019, Spain counted 26 GW of wind capacity, 25 GW of gas-fired power plants, 13 GW of hydro, 11.2 GW of solar (8.9 GW of photovoltaic panels), 7.9 GW of coal-fired plants, and 7.1 GW of nuclear power. While Spain's achievement in increasing the proportion of renewables is noteworthy, the future trajectory of its power mix requires careful consideration to guarantee a smooth transition, primarily because some nuclear reactors are scheduled to shut down by the end of 2030. Nuclear, as a low-carbon energy source, generated 22% of electricity in 2022 and is currently the third electricity source (IEA, 2021a, p. 13). Renewable generation has decreased by 4.0% compared to the previous year, marked by a precipitous decline in hydro production, which has reached historic lows, although solar generation increased by 24.5% compared to 2021, generating 31988 GWh. In analogy, non-renewable generation rose by 15.3% in 2022 and CO_2 equivalent emissions from the national electricity mix increased by 23.8% from 2021, reaching 44.4 million equivalent tonnes, which was 60% below the 2007 emission levels. Spain's electricity exchange programmes with other countries closed 2022 with the highest export balance in history. A total of 28426 GWh were programmed for exports, which is 71.4% more than the previous year, and 8,585 GWh for imports, which is slightly less than half the value of 2021. In 2022, the average ultimate price of energy on the electricity market stood at 204.79 €/MWh, the highest price ever recorded for the second consecutive year. This is nearly twice the cost in 2021 and more than three times the price in 2018 and 2019 (Red Eléctrica, 2022, pp. 5–7).

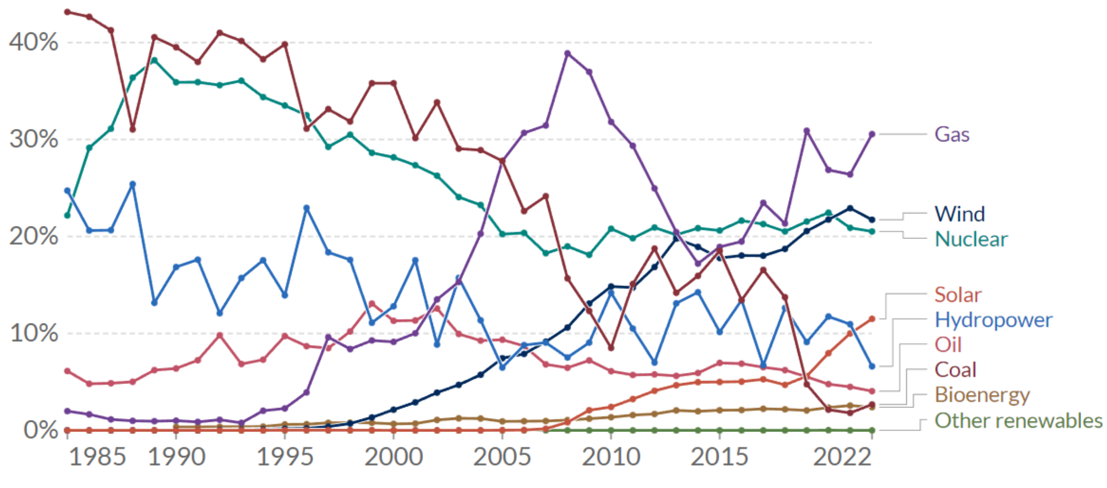

Figure 6: Share of electricity production by source, Spain[27]

During 2022, the country reached a percentage of installed power from RES of 59.2% of the total installed capacity. The generation park incorporated 5.9GW of renewable installed capacity, of which 4.5GW corresponded to solar photovoltaic technology, representing the highest increase in photovoltaic technology (Red Eléctrica, 2022, p. 5).

26 https://ourworldindata.org/grapher/share-elec-by-source

27 https://ourworldindata.org/grapher/share-elec-by-source

The geographical distribution of photovoltaic solar energy installations on the Spanish mainland is irregular, with three autonomous communities accounting for almost 70% of Spain's capacity [28]. Spain is among the countries with the optimal climatic conditions for the generation of solar energy, and its solar irradiance potential is significantly greater than that of Germany, the largest European producer. As well as the plentiful solar radiation, the deployment of solar photovoltaic power plants in Spain has been made feasible by the European Union and national policies promoting renewable energy.

3.3 Regulatory framework

The core solar energy regulations in Spain, with which all photovoltaic installations must comply, are the following:

- Royal Decree (RD) 1995/2000[29], for installations over 15 kV DC or 1 kV AC.
- Law 24/2013[30], which controls the electricity sector, regulates all types of activities aimed at the supply of electricity, including generation, transmission, distribution, recharging, and commercialisation.
- RD 842/2022[31], which ratifies the Low Voltage Electrotechnical Regulations (REBT)[32].

Depending on the PV system concerned, there are additional regulatory standards. A distinction may be made between a stand-alone system, a solar power plant for energy production and commercialisation, and a system intended for the self-use of energy.

A stand-alone system has no grid connection point. This means that they are unable to interact with the grid and must generate or store their own energy (Khaligh & Onar, 2010). For these systems, the ITC-BT-04 and ITC-BT-40 instructions of the REBT must be adopted.

PV power plants have the purpose of feeding energy into the electrical grid, so they are not designed for consumption but rather for production. For power capacities below 100 kW, the regulatory framework aligns closely with that of autonomous PV systems, with the inclusion of RD 1699/2011[33], which governs the grid connection of small power production facilities. In cases where the system exhibits an output exceeding 100 kW, the subsequent regulations are enforced:

- RD 413/2014[34], which regulates the activity of electricity production from renewable sources.
- RD 23/2020[35], which includes some energy measures.
- RD 1183/2020[36], which regulates the access and connection conditions.

Self-consumption of electrical energy is one of the fundamental pillars of the development of renewable energies, and its implementation is largely linked to urban environments. Consequently, self-consumption presents a development opportunity for municipalities and provides them with an effective means of contributing to the energy transition.

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28 https://www.sistemaelectrico-ree.es/informe-de-energias-renovables/sol/potencia-instalada/solar-fotovoltaica-solpotencia

29 https://www.boe.es/buscar/pdf/2000/BOE-A-2000-24019-consolidado.pdf

30 https://www.boe.es/boe/dias/2013/12/27/pdfs/BOE-A-2013-13645.pdf

31 https://www.boe.es/buscar/doc.php?id=BOE-A-2002-18099

32https://www.boe.es/biblioteca_juridica/codigos/codigo.php?id=326&modo=2&nota=0&tab=2

33 https://www.boe.es/boe/dias/2011/12/08/pdfs/BOE-A-2011-19242.pdf

34 https://www.boe.es/boe/dias/2014/06/10/pdfs/BOE-A-2014-6123.pdf

35 https://www.boe.es/buscar/pdf/2020/BOE-A-2020-6621-consolidado.pdf

36 https://www.boe.es/buscar/pdf/2020/BOE-A-2020-17278-consolidado.pdf

All electricity consumers, including citizens, businesses, and industries, can set up self-consumption systems to supply their consumption and can do so individually, if there is only one consumer associated with the installation, or collectively, if there are multiple consumers involved with the production facilities (IDAE, 2023a).

With the attainment of grid parity, denoting the stage at which the cost associated with producing PV power is equivalent to the cost of purchasing it from the grid, photovoltaic self-consumption will play a key role in facilitating the shift towards a low-carbon energy system. Spain, among the EU countries with the highest solar irradiation, has recently made the decision to eliminate one of the most restrictive self-consumption regulations (López Prol & Steininger, 2017). In 2018 and 2019, the Spanish government implemented two significant policies, namely RD 15/2018[37] and RD 244/2019[38], which had a notable impact on the energy sector. The primary changes enacted to encourage the installation of PV systems are the removal of the sun tax, the elimination of power limits, and the surplus compensation that allows the consumer to sell excess solar energy to the electricity grid. The surplus is sold back to the retailer, with the corresponding value being directly deducted from the monthly electricity bill. The compensation cannot surpass the total amount of the electricity bill. Shared PV systems are legally authorised, enabling communities of neighbours and associations to establish collective self-consumption photovoltaic systems (Dasí-Crespo et al., 2023). Thus, self-consumption is regulated by RD 15/2018 and RD 244/2019 of the Spanish government, which establishes administrative, technical, and economic conditions for self-consumption. These systems may or may not have surpluses and may or may not be eligible for financial compensation. Their authorisation process is straightforward and does not require environmental or operating authorisation.

The expansion of photovoltaic systems in southern Europe has been boosted by favourable sunshine levels as well as the implementation of supportive policies and legislation. 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). In Spain, public funds for renewable energy subsidies are typically managed by regional governments, which are responsible for developing the incentive programmes, which are further bolstered by financial assistance from the European Regional Development Fund (ERDF)[39]. As an example, the Catalan Energy Institute (ICAEN) provided a total of 114,988,848€[40] in subsidies to support the implementation of self-consumption systems. The national government, in addition to regulating the electricity sector, can provide income tax deductions. Local governments also have a crucial role in promoting the adoption of these systems and may facilitate their implementation through tax bonifications, such as property tax, tax on economic activities, or construction tax.

37 https://www.boe.es/boe/dias/2018/10/06/pdfs/BOE-A-2018-13593.pdf

38 https://www.boe.es/boe/dias/2019/04/06/pdfs/BOE-A-2019-5089.pdf

39 https://ec.europa.eu/regional_policy/funding/erdf_en

40 https://icaen.gencat.cat/ca/energia/ajuts/energies-renovables/

4. Methodology

4.1 Multi-criteria decision analysis

MCDA, also known as MCDM, is a structured approach used to assist decision-makers in making decisions in a transparent and systematic manner when multiple criteria must be considered simultaneously to choose, rank, or sort alternatives. This methodology has been utilised in a wide range of contexts, such as environmental management (Coban et al., 2018), healthcare (Pereira et al., 2020), energy (Cabeça et al., 2021; Henriques et al., 2022), business (Yalcin et al., 2022), and many others. Indeed, MCDA has been one of the fastest-growing areas of operational research over the past few decades, and it is essential for structuring and solving problems involving multiple criteria (Ishizaka, 2013). Ehrgott et al. (2016) established three categories of problems based on the desired outcome. The choice problematic (α) consists of assisting DMs in selecting a subset of actions that is as small as feasible, so that a single action can be selected. The ranking problem (γ) involves ordering all actions within a given set of actions from best to worst. The sorting problematic (β) consists of assigning each action to one of the pre-defined categories. Figure 7 is a graphical representation of these problems. In addition, Roy & Słowiński (2013) considered the description problematic (δ), which describes alternatives and their consequences in a formal and systematic manner or develops a cognitive procedure so that DMs can assess them.

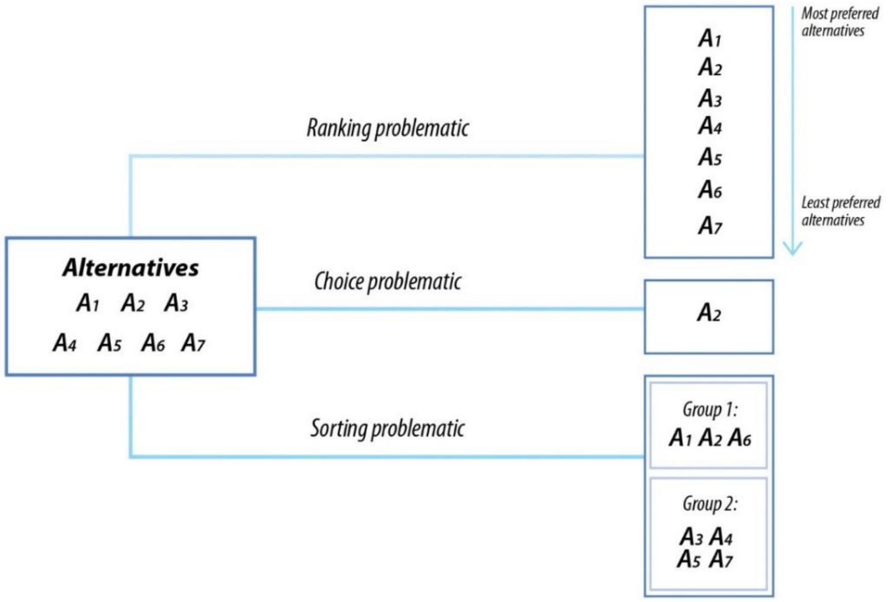

Figure 7: Classification of MCDA problems.

Throughout the years, a variety of models have been created to address these various situations. In the literature, MCDA methods are divided into the three categories listed below (A. A. Pereira & Pereira, 2023):

(i) **Outranking models:** Criteria are compared pairwise to identify the extent to which a preference for one over the other can be asserted. After aggregating the scores, the preference for one alternative over another is determined. In comparison to other methods, the outranking methods have the property of permitting alternatives to be incomparable.

(ii) **Value measurement models:** Using a numerical score, indicate the preference for each alternative. The technique is executed independently for each criterion, and then the partial preferences modelled by the multiple criteria are aggregated into a single function measuring the overall preferability of each alternative.

(iii) **Reference-level models:** A level of satisfaction is determined for each criterion. The model then searches out the alternative that accomplishes these levels most effectively.

Each method has unique characteristics regarding how criteria are evaluated, the numerical algorithm used, the level of uncertainty in the data set, how weights are estimated, and the model employed to describe the decision-makers' preferences. The user must select the optimal method for a given circumstance by weighting all the distinct technique characteristics, taking into consideration the limitations, peculiarities, and preconditions of each approach (Ishizaka, 2013). Figure 8 displays the classification of the main MCDA methods used according to the types of problems to which they can be applied.

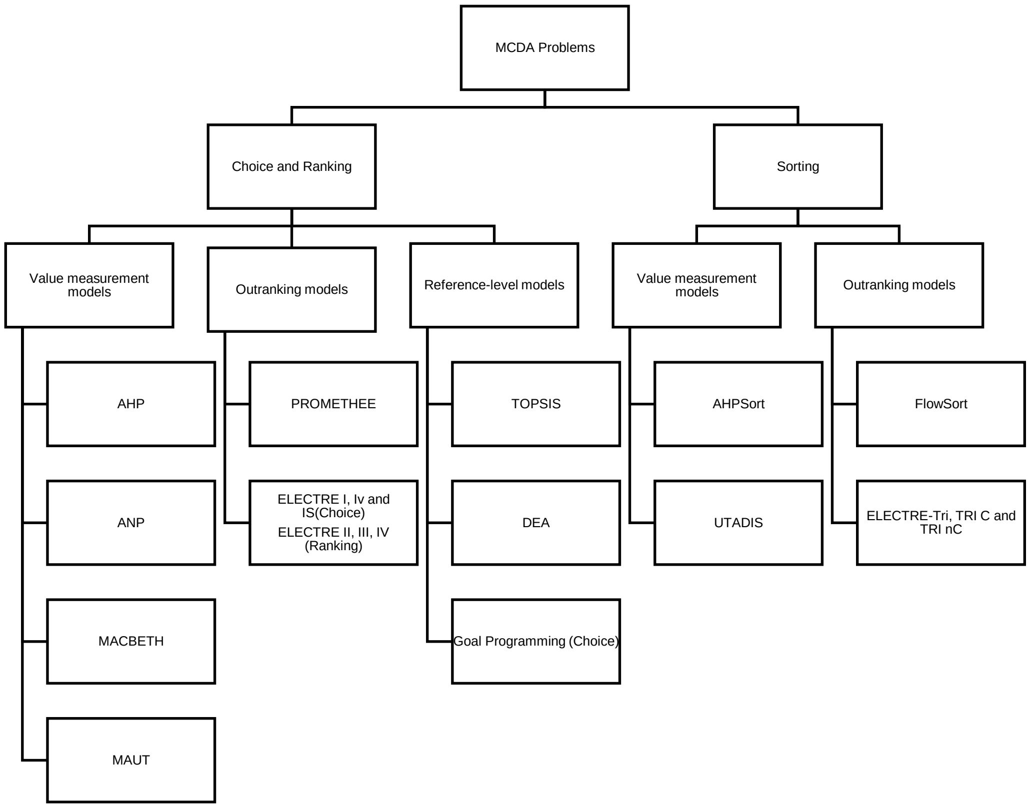

Figure 8: Classification of MCDA models (Ishizaka, 2013).

Due to space and time constraints, not all methodologies can be explained in depth in this dissertation. The selected technique will be described in detail, along with a justification for its selection.

4.2 Rationale for the selection of methodology

Figure 9 provides a concise overview of the four sequential stages that were undertaken in the selection of the methodology to be employed for the analysis of the problem defined. Below is the detailed reasoning behind each stage of the process.

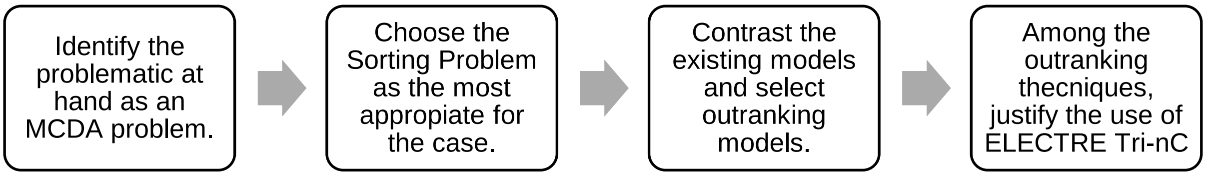

Figure 9: Methodology selection process.

The field of energy planning is well-suited for MCDA methods due to the presence of numerous conflicting criteria, multiple sources of uncertainty, diverse stakeholders' perspectives, subjective judgements, the involvement of multiple DMs, extended time frames, and capital-intensive investments (Løken, 2007). Moreover, the evaluation of sustainability can be regarded as a decision-making problem because it aims to improve decision-making in complex projects through the inclusion of both public and expert perspectives, and must integrate conflicting aspects of technical, economic, environmental, and social dimensions (Talukder & Hipel, 2021). Hence, the problem defined in this project is undoubtedly an MCDA problem.

As mentioned previously, the literature has divided the types of problems into three categories: choice, ranking, and sorting. This project aims to compare and evaluate different photovoltaic initiatives in the framework of a specific municipality, which can help municipalities prioritise actions or promote the implementation of some private installations. Naturally, each municipality has its own context and specific needs, so the priorities will vary from case to case. For that reason, the alternatives will be sorted into predefined groups, ranked according to their priority level for action. In essence, it constitutes a sorting problem. It would not make sense to address this study as a choice or ranking problem because the actions proposed can be implemented in parallel or may be complementary. In addition, sorting allows to discern the relative strengths and weaknesses of each alternative instead of merely assigning ranks or selecting a single option.

Among the models for solving sorting problems are value measurement and outranking models. Each approach has advantages, drawbacks, postulates, and hypotheses. Some researchers have opted to apply multiple methods to a single study, either in combination to make use of the strengths of both methods or in parallel to provide the DM with a broader decision-making foundation. (Manirambona et al., 2022). In this project, due to simplicity issues and time constraints, a single method will be applied, and its selection will be adequately justified.

In comparison to other multi-criteria evaluation methods, outranking methods enable incomparable alternatives. This feature is essential when comparing options that cannot be compared for some reason (Boumaiza et al., 2022). In contrast to value measurement models, outranking models evaluate all the alternatives equally and therefore do not permit performance compensation among criteria. In essence, a strong performance on one criterion cannot compensate for a decline in performance on another. Consequently, outranking models are seen as more appropriate for this work.

The two methodologies under consideration are Flowsort, which belongs to the PROMETHEE family of methods, and ELECTRE. ELECTRE methods, despite having several mathematical concepts that can be difficult for DMs to understand, are particularly relevant in situations where models incorporate a minimum of three criteria, alternatives are evaluated using an ordinal scale, there is heterogeneity related to the nature of the scales with the criteria, and it is possible to consider indifference and preference thresholds (Cabeça et al., 2021). Given the characteristics of the case study, the use of the ELECTRE family of outranking methods, more specifically the extension of ELECTRE Tri-nC was considered appropriate for the following reasons (Mateo, 2012):

(i) The ELECTRE family of methods can deal with qualitative performance scales of criteria, enabling verbal or numerical performances to be considered without the need for re-coding.

(ii) ELECTRE methods can manage scale heterogeneity. Each procedure can be executed with the original performances of the actions on the criteria preserved, without the need to convert the original scales into abstract ones with an arbitrarily imposed range, for example, by employing a normalisation technique or assessing the corresponding evaluations using a utility or value function.

(iii) ELECTRE methods allow consideration of indifference and preference thresholds when modelling imperfect knowledge of data, making it appropriate to consider imperfect data knowledge and arbitrariness associated with the construction of the family of criteria. Small preference differences should not be viewed as significant.

(iv) ELECTRE Tri-nC method also allows for studying the interaction between criteria; however, this will not be addressed in this work.

4.3 The ELECTRE family of methods

Since their conception, ELECTRE (ELimination Et Choix Traduisant la REalité) methods have been extensively employed for MCDA in numerous real-world decision problems (Ehrgott et al., 2016). The origins of ELECTRE methods go back to 1965 at the European consulting firm SEMA, when ELECTRE I was proposed by Bernard Roy. The method has since evolved to an “unofficial” version, ELECTRE IV, which incorporates the concept of a veto threshold. An additional version known as ELECTRE IS was used to represent situations with imprecise data. That is the current variant of the choice problematic ELECTRE methods. In the late 1960s, ELECTRE II was introduced as a solution to the problem of ranking actions from best to worst.

A few years later, ELECTRE III, a new approach to ranking, was developed. These methods primarily introduced the use of pseudo-criteria and fuzzy binary outranking relations. ELECTRE IV is the only strategy that does not employ relative coefficients of criteria importance. In the late 1970s, the trichotomy procedure was proposed as a new method for classifying actions into predefined and ordered categories. After several years, ELECTRE A was implemented. ELECTRE Tri, one of the latest sorting techniques, was inspired by these earlier endeavours (Ehrgott et al., 2016; Govindan & Jepsen, 2016). Recently, Almeida-Dias et al., (2010) proposed ELECTRE Tri-C, a novel sorting approach that does not require designating a boundary between consecutive categories since they are defined by reference actions as opposed to boundary actions as in previous methods. ELECTRE Tri-NC possesses significant advantages over ELECTRE TRI-C. For instance, there is no limit on the number of reference actions in each category, whereas in ELECTRE Tri-C the DM is required to create a unique reference action for each category. In addition, when employing ELECTRE Tri-NC, it is permitted to merge two consecutive categories by retaining the union of the characteristic reference actions of the two merged categories and to split a category by creating two new consecutive categories via an ordered partition of the reference actions (Dias & Mousseau, 2018).

Preferences in ELECTRE methods are modelled by using binary outranking relations, S, whose meaning is “at least as good as”. Considering two actions a and b, four situations may occur (J. R. Figueira et al., 2013):

(i) $\text{aSb and not bSa} \rightarrow \text{a is preferred to b}$

(ii) $\text{bSa and not aSb} \rightarrow \text{b is preferred to a}$

(iii) $\text{aSb and bSa} \rightarrow \text{a is indifferent to b}$

(iv) $\text{Not aSb and not bSa} \rightarrow \text{a is incomparable to b}$

Preference corresponds to a circumstance in which there are clear and positive arguments in favour of one action over the other. Figueira et al. (2013) also distinguish between strict and weak preferences. Indifference corresponds to a situation where there is an equivalence between the two actions. Incomparability refers to the absence of justifications for any other relationships.

The formation of an outranking relationship relies on two fundamental concepts: These two conditions must be fulfilled for the assertion aSb to be valid (Ehrgott et al., 2016):

1. Concordance: For the validation of an outranking aSb, a sufficient majority of criteria need to endorse this assertion.
2. Non-discordance: When the concordance condition holds, none of the minority criteria should contradict the assertion aSb too strongly.

Each technique consists of two main procedures: aggregation and exploitation. In the multiple criteria aggregation phase, concordance and non-discordance concepts are used to compare alternatives pairwise based on their performance on the criteria. In methods dealing with problematic α and γ, the alternatives are contrasted to themselves. In problematic β methods, the alternatives under consideration are compared to a set of reference alternatives. These pairwise comparisons of alternatives result in the formation of outranking relations (preference, indifference, and incomparability).

The second phase consists of an exploitation procedure particular to the ELECTRE approach that exploits the previously constructed outranking relation and yields results based on the nature of the problem (choosing, ranking, or sorting) (Govindan & Jepsen, 2016).

In ELECTRE methods, the relative importance of criteria is determined by two discrete sets of parameters: relative importance coefficients and veto thresholds. The ELECTRE importance coefficient refers to the inherent "weight" or voting power of each criterion. Veto thresholds express the power assigned to a given criterion to be against the assertion "a outranks b" when the difference between $g(b)$ and $g(a)$ performance exceeds this threshold. To account for the imprecise nature of action evaluation and the arbitrariness of constructing a family of criteria, ELECTRE methods employ discriminating (indifference and preference) thresholds. This results in the development of pseudo-criteria models for each criterion (Ehrgott et al., 2016).

4.3.1 The ELECTRE Tri-nC method

In the ELECTRE Tri-nC model, alternatives are sorted based on their comparison to the reference actions that define the categories. Since they are not contrasting the alternatives under consideration against each other, altering, removing, or adding an alternative has no effect on the results regarding the other alternatives.

4.3.1.1 Problem statement

The sorting problem is based on several assumptions (Almeida-Dias et al., 2012):

(i) Total ordering: A set of categories to which alternatives are assigned must be completely ordered, from the worst to the best, without ties.

(ii) Equally processed: The definition of a category is predicated on the fact that it must be conceived a priori to receive actions that will be processed similarly.

(iii) Category characterisation: Each category is characterised by reference actions.

$A = \{a_1, a_2, \dots, a_i\}$ denotes the set of potential actions, which may be completely known a priori or may appear gradually during the decision-analysis procedure. The objective is to assign these actions to a set of entirely ordered categories (with C_1 being the worst category and C_q being the best one), denoted by $C = \{C_1, C_2, \dots, C_q\}\ with\ q \geq 2$. To ensure that all actions are equally processed, categories must be established a priori $(\text{J. R. Figueira et al.}, 2013)$.

$F = \{g_1, g_2, \dots, g_n\}\ with\ n \geq 3$ is a coherent set of n criteria, designed to evaluate any action considered for assignment to a particular category. A quantitative or qualitative scale of varying levels of performance must be defined. Additionally, a preference direction must be selected, either minimise (the lower the level, the better) or maximise (the greater the level, the better). 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 $\sum_{j=1}^{n} w_j = 1$ $(\text{J. R. Figueira et al.}, 2013)$.

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 $p_j \geq q_j \geq 0$.

These thresholds can be constant values or also be defined as variables, and are introduced in order to take into account the imprecise character of the data (uncertainty, imprecision, and ill-determination) resulting from the computation of the performances $g_j(a), \forall a \in A$, as well as the arbitrariness that an analyst often faces when building each criterion from F. The preference threshold (p_j) is the smallest difference in performance that, when exceeded, is considered significant enough to indicate a strict preference in favour of the action with the greatest performance, according to criterion g_j. The indifference threshold (q_j) is the most significant performance difference determined compatible with an indifference situation between two actions with differing performances (Almeida-Dias et al., 2012). Based on their values, three different preferences relations are defined in Table 2:

Table 2: Preference relations.

Indifference relation	$\boldsymbol{g_j(a) - g_j(a') \leq q_j}$	$\boldsymbol{a}$ is indifferent to $\boldsymbol{a'}$	$\boldsymbol{a\ I_j a'}$
Weak preference	$q_j < g_j(a) - g_j(a') \leq p_j$	a is weakly preferred to a'	$a\ Q_j a'$
Strict preference	$g_j(a) - g_j(a') > p_j$	a is strictly preferred to a'	$a\ P_j a'$

The objective is to generate a credibility matrix that evaluates the validity of the claim that '' a is at least as good as a'. A credibility index will be used for this purpose: $\sigma(a, a')$ designate the credibility index, which represents the credibility of the outranking a over a'. Accordingly, when all the criteria from F are considered, a may be judged to be at least as good as a'

$$\sigma(a, a') = c(a, a') \prod_{j=1}^{n} T_j(a, a')$$

The credibility of the assertion '' action a outranks action a' '' is based on two fundamental concepts in the construction of outranking relations in ELECTRE methods: Concordance and Non-Discordance. On the one hand, the concept of concordance is represented by the global concordance index $c(a, a')$, that can be calculated as follows:

$$c(a, a') = \sum_{j \in C(aPa')} Wj \quad + \sum_{j \in C(aQa')} Wj \quad + \sum_{j \in C(aIa')} Wj \quad + \sum_{j \in C(a'Qa)} W_j \varphi_j$$

The strength of the concordant coalition is determined by the criteria that strictly support the assertion aSa' (a outranks a'), this means that each criterion contributing to aPa', aQa', and aIa' is considered with its overall weight. A criterion that leads to $a'Qa$ should not be disregarded entirely in terms of its contribution to the assertion aSa', since this weak preference situation, '' action a' is weakly preferred to a '' , represents a hesitation between aIa' and aPa'. Thus, the criterion is represented by a fraction, φ_j, that indicates how much g_j favours the outranking of a over a':

$$\varphi_j = \frac{p_j - (g_j(a') - g_j(a))}{p_j - q_j} \in [0,1[$$

The higher, the more g_j is in favour of the considered outranking.

On the other hand, the term $\prod_{j=1}^{n} T_j(a, a')$ integrates the concept of non-discordance.

The non-discordance principle requires that within the minority of criteria that do not support the assertion, none of them is strongly against the assertion. Indeed, that there is no discrepancy associated with the assertion aSa'. For each criterion, the value of this term is estimated as such, where $d_j(a,a')$ refers to the discordance index :

$$T_j(a,a') = \begin{cases} \dfrac{1-d_j(a,a')}{1-c_j(a,a')}, & if\ d_j(a,a') > c_j(a,a') \\ 1, & otherwise \end{cases}$$

For each pair of actions $(a,a') \in A$, there is a concordance and discordance measure. When the concordance index, $c_j(a,a')$, on the criterion j is strictly greater than the discordance index, $d_j(a,a')$, the credibility remains equal to the comprehensive concordance index. If there are no discordant criteria, the credibility of the outranking relation, $\sigma(a,a')$, is equivalent to the comprehensive concordance index, $c(a,a')$, and $\prod_{j=1}^{n} T_j(a,a') = 1$.

However, when the comprehensive concordance index is strictly lower than the discordance index on the discordant criterion, the credibility index becomes lower than the comprehensive concordance index due to the opposition effect on this criterion.

To calculate discordance $d_j(a,a')$, a veto threshold is defined, such that $v_j \geq p_j \geq 0$. The veto threshold, v_j allows for the possibility of aSa' to be rejected completely if, for any one criterion j, $g_j(a') > g_j(a) + v_j$. For each criterion, a discordance matrix is generated. In contrast to concordance, there is no aggregation of criteria; one discordant criterion is sufficient to reject outranking. Calculating the discordance index is as follows:

$$d_j(a,a') = \begin{cases} 1, & if\ g_j(a') - g_j(a) > v_j \\ \dfrac{g_j(a) - g_j(a') + p_j}{p_j - v_j}, & if\ p_j < g_j(a') - g_j(a) < v_j \\ 0, & if\ g_j(a') - g_j(a) < p_j \end{cases}$$

If $g_j(a') - g_j(a)$ is greater than the veto threshold v_j, then g_j is definitively in discordance with the outranking of a over a', so that $d_j(a,a')$ attains its maximum value, which is 1. If $g_j(a') - g_j(a)$ is greater than the preference threshold p_j, but smaller than the veto threshold v_j, then g_j is in partial discord with the outranking of a over a'. Alternatively, if $g_j(a') - g_j(a)$ is lower than the preference threshold p_j, then g_j is not in discordance with the outranking of a over a', and $d_j(a,a')$ reaches its minimum value, which is 0.

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 $h = 1, \dots, q$. Notice that C_1 is the worst category and C_q is the best one, with $q \geq 2$. Let $B \cup \{B_0, B_{q+1}\}$ denote the set of $(q+2)$ subsets of reference actions, such that $B = \{B_1, B_2, \dots, B_q\}$.

The two particular subsets of reference actions, denoted $B_0 = \{b_0^1\}$ and $B_{q+1} = \{b_{q+1}^1\}$, contain two reference actions defined as follows: $g_j(b_0^1)$ is the worst possible performance on criterion g_j, and $g_j(b_{q+1}^1)$ is the best possible performance on the same criterion g_j, for all $g_j \in F$, such that $g_j(b_0^1) < g_j(a) < g_j(b_{q+1}^1)$ for any action a.

4.3.1.2 Assignment procedure

Prior to assigning the alternatives to categories, the credibility index λ has to be defined. λ 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, λ takes values between [0.5, 1]. When comparing an action a to a subset of reference actions B_h, this credibility level enables the definition of the following four λ-binary relations:

(a) λ-outranking: $\{a\}S^{\lambda}B_h \leftrightarrow \sigma(\{a\}, B_h) \geq \lambda$

(b) λ-preference: $\{a\}P^{\lambda}B_h \leftrightarrow \sigma(\{a\}, B_h) \geq \lambda$ and $\sigma(B_h, \{a\}) < \lambda$

(c) λ-indifference:$\{a\}I^{\lambda}B_h \leftrightarrow \sigma(\{a\}, B_h) \geq \lambda$ and $\sigma(B_h, \{a\}) \geq \lambda$

(d) λ-incomparability: $\{a\}R^{\lambda}B_h \leftrightarrow \sigma(\{a\}, B_h) < \lambda$ and $\sigma(B_h, \{a\}) < \lambda$

Each characteristic reference action from B_{h+1} must be forced to dominate each characteristic reference action from B_h in order to construct the characteristic reference actions. 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 λ. In this regard, the ELECTRE Tri-nC assignment procedure consists of two joint rules that must be applied jointly, called the descending rule and the ascending rule. Both rules include the selecting function presented below, which allows the assignment of an action to one of two successive categories. Table 3 and Table 4 contain the formulation of the assignment rules.

$$\rho(\{a\}, B_h) = min\{\sigma(\{a\}, B_h), \sigma(B_h, \{a\})\}$$

Combining the ascending and descending 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.

Table 3: Ascending rule.

Ascending rule	Increase $\boldsymbol{h}$ of $\boldsymbol{B_h}$ from zero until the first value, $\boldsymbol{k}$, such that $\boldsymbol{\sigma(B_k, \{a\}) \geq \lambda}$
(I)	For $k = 1$, select C_1 as a possible category to assign action a
(II)	For $0 < k < (q+1)$, if $\rho(\{\boldsymbol{a}\}, B_k) > \rho(\{\boldsymbol{a}\}, B_{k-1}) >$, select C_k as a possible category to assign a, otherwise select C_{k-1}
(III)	For $k = (q+1)$, select C_q as a possible category to assign a

Table 4: Descending rule.

Descending rule	Decrease $\boldsymbol{h}$ of $\boldsymbol{B_h}$ from $(\boldsymbol{q}+\boldsymbol{1})$ until the first value, $\boldsymbol{t}$, such that $\boldsymbol{\sigma(\{a\}, B_t) \geq \lambda}$
(I)	For $t = q$, select C_q as a possible category to assign action a
(II)	For $0 < t < q$, if $\rho(\{\boldsymbol{a}\}, B_t) > \rho(\{\boldsymbol{a}\}, B_{t+1}) >$, then select C_t as a possible category to assign a; otherwise select C_{t+1}
(III)	For $t = 0$, select C_1 as a possible category to assign a

4.3.2 Criteria weighting method: the DCM-SRF

Once the various criteria have been identified, the DMs must indicate the subjective importance they assign to each criterion relative to the others. In the context of decision aiding, determining the weights of the criteria is a challenging but crucial task. The selected weighting technique is the revised Simos' procedure, also known as the "playing cards" approach, which was created particularly for the ELECTRE methods. The method has been successfully implemented in a variety of real-world settings and has proved to be a reliable procedure, especially useful because it allows DMs who are unfamiliar with MCDA to easily express their opinion. The methodology involves an interactive exercise between the DM and the analyst and can be divided into two phases: the first phase involves the gathering of information, and the second phase consists of the computations that result in the assignment of a score to each criterion (J. Figueira & Roy, 2002).

Initially, the user is provided with a deck of cards bearing the names of each criterion and, if necessary, supplementary information. A "playing card" represents each criterion. Therefore, there are n cards, where n is the number of criteria of a family F.The DM is then required to rank the criteria in ascending order based on their importance, from least to most relevant. If two or more cards have the same importance, they must be arranged adjacent to one another. Consequently, we obtain a comprehensive pre-order for all criteria. Within this pre-order, there are r ranks, each consisting of a single card or card subset (Siskos & Tsotsolas, 2015).

After ordering the criteria according to their order of relevance, the DMs are provided with a set of white cards for assessing the magnitude of the differences between the various criteria. Each white card denotes a distinction in significance between consecutive cards. The difference in weight between two consecutive cards (or subsets) will henceforth be referred to as u. One white card represents a difference equal to two u. Two white cards represent a threefold disparity, etc. The DM is asked to insert white cards between those criteria whose relevance gap is greater: equally relevant criteria will stand alongside one another, subsets with a minor relevance difference will not be separated by a white card, and subsets with a substantial relevance difference will be separated by one or more white cards. Finally, the DMs are asked to indicate how many times the first criterion in the ranking is more valuable than the last. Let z represent the value of this ratio (Siskos & Tsotsolas, 2015).

The outcomes of this interaction with the DM may be utilised to determine the non-normalized and normalized weights of criteria. The algorithm must assign a numerical value to the weights of each criterion $\mathrm{g_i}$ for $\mathrm{i} = 1, \dots, \mathrm{n}$ and is fully described in J. Figueira & Roy (2002):

The non-normalized weights $\mathrm{k}(1), \dots, \mathrm{k}(\mathrm{r}), \dots, \mathrm{k}(\bar{\mathrm{n}})$ associated with each subset relate to its rank. The number of white cards between ranks r and $\mathrm{r}+1$ is denoted by e'_{r}

$$\begin{cases} e_r = e'_r + 1\,, \qquad \forall r = 1, \dots, \bar{\bar{n}} - 1, \\ e = \sum_{r=1}^{\bar{\bar{n}}-1} e_r, \\ u = \dfrac{z-1}{e} \end{cases}$$

With $e_0 = 0$, we obtain $k(r) = 1 + u(e_0 + \dots + e_{r-1})$. If there are multiple criteria *ex aequo* in the rank r, then they must have the same weight $k(r)$.

The computation for the normalized weights k_i is as follows: If g_i is a criterion of rank r, and k'_i is the weight of this criterion in its non-normalized expression $k'_i = k(r)$, then:

$$\begin{cases} K' = \sum_{i=1}^{n} k'_i\,, \\ k_i^* = \dfrac{100}{K'} k'_i. \end{cases}$$

k_i^* is the normalized weight of criterion g_i and it is frequently represented as k''_i , with the only difference being that the latter is a rounded number with w digits following the decimal point. The final weights k_j must satisfy the condition $\sum_{j=1}^{n} k_j = 1$.

By using the technique of rounding, we obtain:

$$\begin{cases} K'' = \sum_{i=1}^{n} k''_i \leq 100, \\ \epsilon = 100 - K'' \leq 10^{-w} \times n. \end{cases}$$

4.3.3 Software implementation

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 will be executed using the DecSpace tool[41], a Decision Support System (DSS) that has been developed by José Rui de Matos Figueira. It functions as a web-based service and offers users the ability to create, edit, and share projects in the form of workflows. The platform is designed to be user-friendly and intuitive.

The MCDA-ULaval[42] software has been used to implement the model and obtain the results. MCDA-ULaval is a free and open-source desktop programme that was created by Université Laval. This software package is focused on the methodologies from the ELECTRE family.

41 https://cegist.tecnico.ulisboa.pt/~cegist.daemon/software

42 https://mcda.fsa.ulaval.ca/

5. Case study

5.1 Overview

Rajadell is situated in the eastern area of the Bages region, in the province of Barcelona, Spain. The municipality consists of various urban centres and many dispersed farmhouses. The economic base of the municipality is comprised of agricultural activities and livestock. It has recently evolved into a summer resort community with second residences. In 2022, it had a population of 549 inhabitants[43] and a surface area of 45.32 km^2, which corresponds to a population density of approximately 12 people per km^2, significantly lower than the Spanish average of 92 people per square kilometre. The population is distributed in the following population centres: *Rajadell Centre* (293), *Can Servitge* (116), *Monistrolet* (52), *Les Casetes* (47), and *L'estació* (41). Figure 10 shows the extension of the municipality and the location of its urban centres.

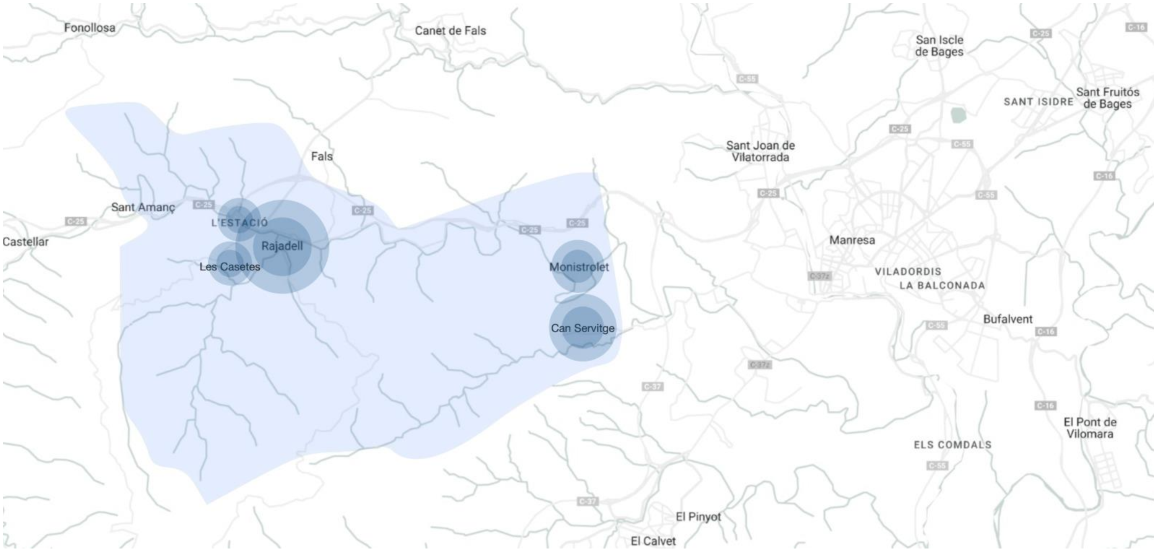

Figure 10: Map of Rajadell with its respective population centres[44].

According to official data[45], there are 259 homes, 85% of which are primary residences, and 62% have a low energy rating. Most of them are over 45 years old and larger than 100m^2. Each house is inhabited by an average of 2.39 people. During 2016, it was estimated that each resident of Rajadell emitted 3.34 tonnes of CO_2 and consumed 11.19 MWh, which implied a total energy consumption of almost 6000 MWh and equivalent emissions of around 1800 tonnes. Compared to 2005, emissions per capita slightly decreased while energy consumption increased.

43 Available at https://www.rajadell.cat/

44 Own elaboration with information extracted from the Spanish cadastre: https://www.sedecatastro.gob.es/

45 https://media.diba.cat/diba/indicadors-habitatge/plots/plots/08178.pdf

As energy demand is expected to increase in the coming years, it is necessary to use RES and improve system efficiency to reduce emissions. As can be seen in Figure 11, citizens mostly use energy for transport and domestic purposes.

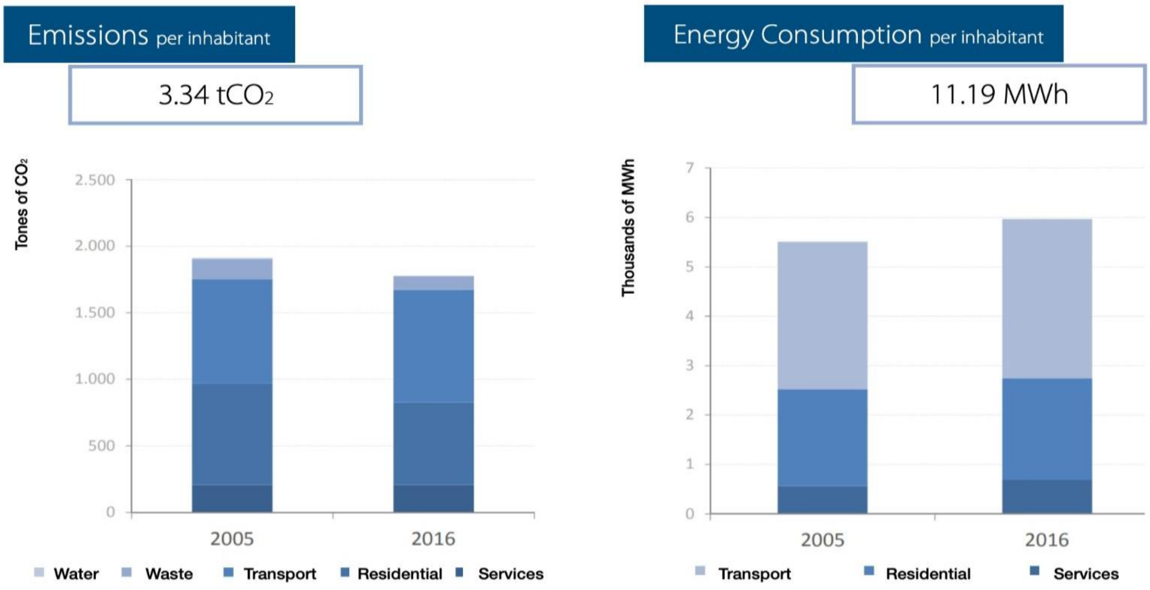

Figure 11: Emissions and energy consumption of Rajadell, classified by sector[46].

On July 29, 2022, the city council agreed to join the *Covenant of Mayors for Climate and Energy*, promoted by the European Commission[47]. The pact consists of a commitment by European cities and towns to achieve the EU's CO_2 emissions reduction objectives through energy efficiency actions and initiatives related to RES. The local council is committed to implementing effective policies to reduce pollution resulting from global warming. It has pledged to reduce CO_2 emissions on its territory by 55% by 2030 and to achieve climate neutrality by 2050. The electricity consumed in the municipality is supplied by the electricity grid, and the only local power generation is by means of photovoltaic self-consumption installations. Currently, there are 20 PV systems registered with a total power of 0.14 MW[48]. The area has great potential for solar energy. The annual global irradiation in Rajadell is approximately 1600 kWh per m^2 for horizontally mounted modules and 1900 kWh per m^2 if the modules are affixed at the optimal angle. Figure 12 shows the global irradiance in Spain, and the location of the village is indicated by a black dot.

46 https://www.diba.cat/documents/102577937/241062712/DADES_RAJADELL_30_40_V.pdf/8e9371f8-8f8f-46f0-829c-96334f886221

47 https://www.seu-e.cat/ca/web/rajadell/govern-obert-i-transparencia/accio-de-govern-i-normativa/accio-de-govern-i-grups-politics/actes-de-ple

48 https://icaen.gencat.cat/es/energia/autoconsum/Observatori-de-lautoconsum-a-catalunya

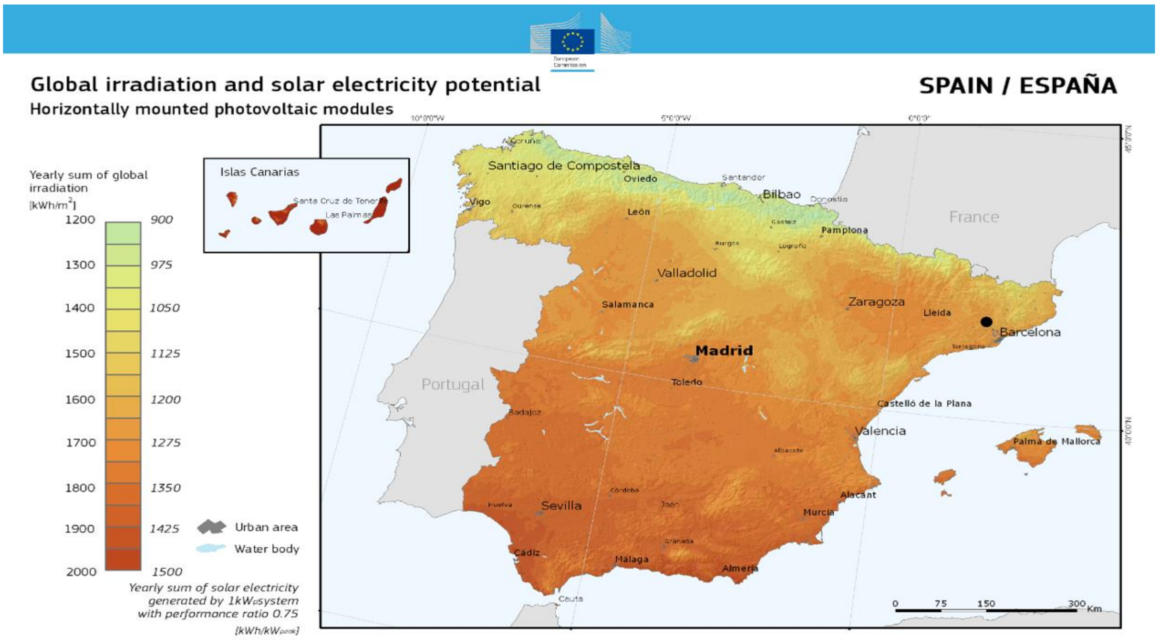

Figure 12: Global irradiation for horizontally mounted photovoltaic modules[49].

As well as solar resources, the region has considerable wind potential, and in 2021, two wind farms were intended to be constructed in the territory. However, these plans were ultimately rejected because of objections from the residents and municipal authorities[50].

The energy transition must be carried out with the participation of the public administration, citizens, and companies. For that reason, the purpose of this case study is to evaluate various photovoltaic installations that involve both private and public actors in order to determine which actions are most urgent according to the established criteria. The steps needed to study the case and evaluate the model are as follows:

1- Identification of the stakeholders involved.
2- Definition of the categories.
3- Selection of criteria and weighting.
4- Generation of potential actions and evaluation of them in light of the established criteria.
5- Determination of reference actions for each category and parameters such as thresholds and credibility level.
6- Execution of the results using the selected software.
7- Critical analysis and discussion of the results.

The creation of the model, the proposal and evaluation of alternatives, and the selection of the criteria have been performed individually. These have been discussed and validated with an expert in the photovoltaic sector. The weights of the criterion have been determined in an interactive meeting with the expert, and the values of the thresholds and other parameters have also been validated in conjunction with him.

49 https://re.jrc.ec.europa.eu/pvg_download/map_index.html

50 https://www.ccma.cat/324/tomben-els-projectes-de-dos-parcs-eolics-al-bages-per-lelevat-impacte-paisatgistic/noticia-amp/3084870/

5.2 Identification of the local stakeholders

The successful implementation of local energy planning strategies, deployed as a set of measures to improve energy efficiency and boost renewable energy generation to reduce CO_2 emissions, is dependent on the satisfaction of the stakeholders involved in the implementation processes. Actors and their behaviour are fundamentally important in public policymaking, as they are the ones who contribute to decisions. An actor with an interest in the decision-making process is referred to as a stakeholder, as opposed to an actor with the ability to decide – a decision-maker -, an actor with regulatory or ownership powers over the decision-making process – a player, and an actor with the knowledge to assist other actors in making decisions – an expert (M. A. Pereira et al., 2021).

This stage proceeds with the identification of the main local stakeholders in the context of the local energy plan definition. Specifically, those whose interests are affected by the issue, whose actions influence the issue, who possess information, resources, and expertise necessary for strategy formulation and implementation and whose participation is needed for the successful implementation of the plan. Their roles and levels of influence, as well as their concerns and values, must be evaluated (Lück & Nyga, 2017). It is essential that some of the identified stakeholders participate in the planning phase. The involvement entails a heavier workload, but it is fruitful. When feasible, it should be done from the very beginning of the decision-making process so that all stakeholders can actively participate and contribute to the decision process (Soltani et al., 2015). Regarding municipal energy planning issues, examples of significant stakeholders are the mayor, residents, businesses, industries, local technicians, and neighbouring municipalities. In most cities they will be similar, although specific stakeholders will be involved on a case-by-case basis (Gustafsson et al., 2015). In this case, the stakeholders have been identified and listed in Table 5:

Table 5: List of stakeholders.

Stakeholder	Influence and interests
Local administration of Rajadell	Local governments must be the leading example for the municipality, as they have the resources, expertise, and legislative and purchasing authority to evaluate potential actions and afterwards implement them. As policymakers, they are essential as they can enable and provide incentives to encourage PV adoption.
Equipment suppliers, engineers, and installers operating in the region	They provide all the necessary equipment, technology, and installation services. They help with system design, installation, and maintenance, guaranteeing the successful implementation of photovoltaic initiatives in the town.
Rajadell residents and homeowners	Residents have an active role because they can implement photovoltaic systems in their own residences, thereby becoming both direct consumers and producers of the energy they generate.

Local businesses, rural touristic establishments, restaurants, and farms	Local private companies can find several direct and indirect benefits for themselves by implementing PV systems, such as reducing energy costs, improving their environmental footprint, or taking advantage of available incentives.
Local farmers and landowners	PV systems can help farmers reduce their energy costs, provide agricultural benefits, and increase the economic return on their land.
Electricity distributor and energy marketers	The energy providers will get involved in grid integration, evaluating the impact of PV systems on the existing infrastructure, and ensuring the reliability and efficiency of energy distribution.

5.3 Categories

The suggested alternatives are classified into an appropriate set of three predefined categories according to the level of urgency for implementation. Alternatives assigned to C_3 can be considered highly important to the achievement of the goals of the municipality and require immediate implementation. Category C_2 includes actions that contribute to the overall renewable energy objectives without immediate urgency, so they can be implemented in the medium term. For example, they may require careful evaluation and planning. Finally, C_1 is characterized by actions that do not require immediate action and can be implemented over the long term. Nevertheless, they can be regarded as part of a comprehensive renewable energy plan. Table 6 contains each category with its description and meaning.

Table 6: Categories selected for the model, their description, and meaning.

Category	Description	Meaning
$\boldsymbol{C_1}$	Low urgency of action	To be implemented by 2050
$\boldsymbol{C_2}$	Medium urgency of action	To be implemented by 2030
$\boldsymbol{C_3}$	High urgency of action	To be implemented within 3 years

5.4 Criteria selection

Sustainable development entails meeting the requirements of the present without compromising the ability of future generations to meet their own needs. 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 has been believed to incorporate technical aspects involved in the implementation of photovoltaic projects.

After the literature review, the most frequently used indicators in the evaluation of energy projects were debated with the expert, taking into consideration the accessibility and accuracy of the data for the sample and the period under consideration. Figure 13 shows many of the criteria discussed.

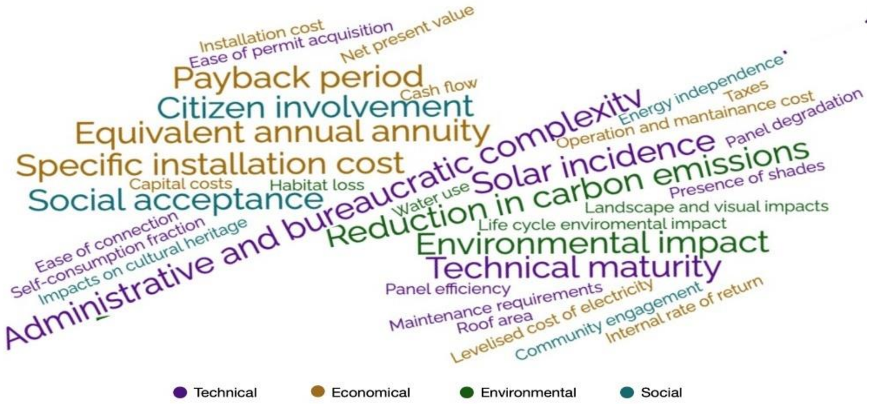

Figure 13: Different criteria used in MCDA research applied to photovoltaics (Bandaru et al., 2021).

Table 7 presents the selected criteria and their respective dimensions. Each criterion is characterized by its indicator, scale, and direction of preference. The preference direction indicates how preferences emerge along the scale. If the objective is to maximise, the preference increases as performance improves; if the target is to minimise, the preference grows as performance diminishes. Several studies have widely used certain metrics, such as the Equivalent Annual Annuity (EAA), the payback period, the avoidance of $C0_2$ emissions, or the environmental impact (Singh et al., 2019). Other criteria have been adapted in some form for this project, such as social acceptance, installation cost, citizen involvement, technical maturity, or administrative and bureaucratic complexity. Eventually, the solar incidence has been included based on the experience in the photovoltaic market sector.

Table 7: Criteria tree.

Notation	Dimension	Criterion	Direction	Indicator	Measure [units]
g_1	Economical	Financial impact	Maximise	EAA	Cardinal [€]
g_2	Economical	Recovery of the initial investment	Minimise	Payback period	Cardinal [years]
g_3	Economical	Installation cost	Minimise	Specific installation cost	Cardinal [€ / W_p]
g_4	Social	Social acceptance	Maximise	Level of social acceptance	Ordinal
g_5	Social	Citizen involvement	Maximise	Level of citizen involvement	Ordinal
g_6	Environmental	Environmental impact	Minimise	Level of local environmental impact	Ordinal

g_7	Environmental	Avoided emissions	Maximise	Annual avoidance of CO_2 equivalent emissions	Cardinal [tonnes of $CO_{2_{eq}}$]
g_8	Technical	Technical Maturity	Maximise	Level of System Development	Ordinal
g_9	Technical	Administrative and bureaucratic complexity	Minimise	Level of administrative and bureaucratic complexity	Ordinal
g_{10}	Technical	Solar Incidence	Maximise	kWh/kW$_p$ ratio	Cardinal [kWh/kW$_p$]

For better comprehension, a description of the selected criteria is provided below.

5.4.1 Description of the criteria

5.4.1.1 Financial impact

Various financial indicators, such as the Net Present Value (NPV) and the Levelized Cost of Energy (LCOE), can be evaluated. In the case of photovoltaic systems, the LCOE is more suitable for the industry or for macroscales (Thebault et al., 2020). NPV is frequently used to compare investments. However, when the durations of the investments differ, the EAA is a more appropriate metric for comparison (Neves et al., 2018). EAA is an indicator for determining the financial efficiency of a project, and it can be viewed as the constant-value cash flow generated by an action over its lifespan if it were an annuity. The criterion should be maximized. The calculation is as follows:

$$EAA = \frac{NPV * r}{1 - (1 + r)^{-n}}$$

based on the calculation of the NPV of the action, as follows:

$$NPV = -\sum_{i=0}^{n} \frac{investment_i}{(1 + r)^i} + \sum_{i=1}^{n} \frac{FS_i}{(1 + r)^i}$$

where:

$investment_i$ is the investment made in year i [€]

FS_i are the financial savings due to the action's implementation, in year i [€]

r is the discount rate [%]

n is the lifespan of the action [years]

5.4.1.2 Recovery of the initial investment

The estimated number of years required to recover the initial investment is an effective measure of investment risk. The payback period will be utilised since it is the most comprehensive and user-friendly method that indicates economic feasibility. The criterion must be minimized.

The payback period (P) is generally calculated by dividing the initial investment (C_i) by the annual financial gain (C_a) (Kiran, 2022).

$$P = \frac{C_i}{C_a}$$

5.4.1.3 Installation cost

Installation cost is the most commonly used economic criteria to evaluate energy systems (Soltani et al., 2015). The initial investment (C_i) itself indicates the economic dimension of the proposed installation. It is an essential indicator in this instance, as the customer's ability to afford the cost is crucial to deciding whether to execute the project. To compare projects of differing dimensions and power capacities, the specific installation cost will be used as an indicator (Henriques et al., 2016).

$$€/W_p = \frac{C_i}{P_p}$$

Where P_p is the installed solar power of the PV system in W_p.

5.4.1.4 Social acceptance

The long-term success of photovoltaic systems relies on public support and perception. Assessing social acceptance as a criterion allows stakeholders' needs, preferences, and concerns to be taken into account, ensuring their participation in decision-making processes and the successful deployment of photovoltaic installations (Strazzera & Statzu, 2017). This makes it possible to choose photovoltaic systems that are not only technically feasible but also socially accepted. It will be measured using the qualitative scale given in Table 8:

Table 8: Levels of social acceptance.

Level 1	Strong objection.
Level 2	Slight dissatisfaction by the population.
Level 3	Great acceptance by the population.

5.4.1.5 Citizen involvement

Social progress in the local regions through the introduction of an energy initiative is one of the most important factors in determining the quality of life (Soltani et al., 2015). The success of photovoltaic energy depends to a large extent on self-consumption and on people's own participation in adopting this type of system. As a result, integrating the community in the adoption of PV installations in their cities is critical since it generates a sense of ownership and shared responsibility, supporting sustainable and harmonious growth. For this purpose, Table 9 represents the qualitative scale that has been established to measure the degree of citizen involvement:

Table 9: Levels of citizen involvement.

Level 1	There is no active citizen participation.
Level 2	Some residents may benefit either directly or indirectly.

Level 3	Some members of the population are involved in the process.
Level 4	Most of the population is involved in the process.

5.4.1.6 Local environmental impact

For assessing the environmental impact of an energy project, the impact of the installation on land use and its visual impact can be evaluated (Mathew & Mariappan, 2014). This criterion should be mitigated as much as possible. To ascertain this, three stages have been established to assess the impact of each alternative. They are reflected in Table 10.

Table 10: Levels of local environmental impact.

Level 1	Great land use, need for large additional infrastructure or great visual impact.
Level 2	Some visual impact or land use.
Level 3	Little environmental and visual impact.

5.4.1.7 Avoided CO_2 emissions

The reduction of emissions is one of the objectives that the town council has set itself for the coming years. Therefore, this criterion must be maximised and will be measured by calculating the annual avoidance of CO2 equivalent emissions in tonnes of CO_2, excluding emissions from land use (Henriques & Antunes, 2012). It is associated with a continuous numerical scale.

5.4.1.8 Technical maturity

Technical maturity is a criterion for assessing the technology applied to energy systems. Measuring the degree of technological maturity indicates how widespread the technology is at both the national and international levels (Soltani et al., 2015). In this instance, since all the alternatives to be analysed utilise photovoltaic energy, the deployment level of the specific system under study will be evaluated. Table 11 shows the two levels of the scale.

Table 11: Levels of technical maturity.

Level 1	System in the start-up or development phase.
Level 2	Widely used technology and system.

5.4.1.9 Administrative and bureaucratic complexity

Permits and licensing can be a lengthy process requiring approvals from local, regional, and central administrations. Depending on the characteristics of the project, it may require a land lease agreement, site access licence, environmental certificate, or grid connection contract (Bandaru et al., 2021). In certain instances, administrative and legal procedures impede the implementation of a project.

In contrast, administrative simplification facilitates the growth of a particular system or technology. Consequently, the real feasibility of implementing an alternative depends on this criterion. In this case, the scale is divided into three levels, as defined in Table 12.

Table 12: Levels of administrative and bureaucratic complexity.

Level 1	Complex legal, technical, and administrative procedures.
Level 2	Existence of certain complicated bureaucratic or legal formalities.
Level 3	Simple bureaucratic formalities and rapid legalisation of the installation.

5.4.1.10 Solar incidence

For all proposed installations, the photovoltaic elements, such as solar modules and the inverter, shall be considered to have the same efficiency and performance. In addition, the geographical location is basically the same (the municipality of Rajadell), so the amount of solar irradiation remains identical in all cases. The major distinction between one alternative and another in terms of energy performance is the amount of solar energy that the system can capture, which is dependent on the orientation, inclination, existence of a solar-tracking system, the presence of shadows, and the mounting position (roof-added or free-standing). For this reason, the kWh/kW_p ratio is the indicator employed. This ratio reflects the amount of energy that a photovoltaic system can deliver per kW of installed capacity, based on the aforementioned factors. It will be estimated with the assistance of the PVGIS tool of the European Commission[51]. It corresponds to a continuous numerical scale.

5.4.2 Criteria weighting

To assign weights to each of the criteria, the Deck Cards Method (DCM), using the revised " Deck of cards " procedure (DCM-SRF method), has been applied. The procedure was performed during a meeting with the expert. This meeting commenced with an explanation of the procedure and allocation process. The expert appeared to have no difficulty comprehending the procedure or completing the respective tasks. He was completely familiar with the criteria because they were decided in a previous meeting.

In the first phase, the expert was asked to rank the ten criteria by ranking the ten cards containing the name of a criterion from the least important to the most important. Afterwards, he was tasked with evaluating the difference in importance between each two ranks by inserting white cards between them. Six white cards were used in total. The final question that was posed to him was, "How many times is the most important criterion more important than the least important criterion?" (M. A. Pereira & Marques, 2022). Let z represent the value of this ratio; it was assigned a value of 10. The ranking of the criteria, the number and position of the blank cards, and the ratio z were believed to be suitable by the expert. The results of this stage are shown in Table 13.

51 https://re.jrc.ec.europa.eu/pvg_tools/en/

Table 13: Input for the DCM-SRF procedure - criteria ranking and ratio z -.

Ranking	Criterion / Blank card(s)
Most important	Payback period (g_2)
	0
Intermediate level 1	Administrative and bureaucratic complexity (g_9) kWh / kWp ratio (g_{10})
	2
Intermediate level 2	Investment cost (g_3) Avoidance of emissions (g_7) Technical maturity (g_8)
	1
Intermediate level 3	Financial impact (g_1) Environmental impact (g_6)
	1
Intermediate level 4	Social acceptance (g_4)
	2
Least important	Citizen involvement (g_5)
Ratio z	**10**

After this interactive stage, the calculations were handled using the DecSpace platform[52]. For this, a DecSpace SRF project was constructed and executed, using the ranking of the criteria, the blank cards added, and the ratio z. Then, the tool generated the normalised weights, which are displayed in Table 14.

Table 14: Normalised criteria weights obtained with the SRF procedure.

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

5.5 Generation and evaluation of actions

A set of actions that can contribute to the achievement of the objectives is selected for further analysis and evaluation. For the generation of potential actions, workshops, brainstorming, and roundtables may be utilised. It is also useful to explore the experience and best practices of other municipalities as a model or source of inspiration. However, the specific conditions of different territories can vary significantly. Depending on the characteristics of each region, possible alternatives may be the same or distinct. For example, a large capital city differs substantially from a village, and a southern city does not have the same needs as a northern city located in the mountains.

For this reason, the municipality of Rajadell and its main characteristics have been studied.

52 http://app.decspacedev.sysresearch.org/#/

The proposed actions are intended to cover the sectors that emit the most emissions in the municipality and in which some type of photovoltaic installation is proposed to reduce these emissions and, simultaneously, increase the production of renewable energy. These include, among others, the residential sector, agriculture, tourism, and private road transport. A great deal of attention ought to be devoted to the public sector since the local authority is expected to serve as a role model and therefore must undertake exceptional measures regarding its own buildings and facilities. The actions may pertain to either public or private investment, or a combination of both. Additionally, they can consider both private and public sites. Each action proposed is duly justified, and all the installations have been dimensioned as close to reality as feasible. Table 15 lists the specifications taken into consideration:

Table 15: Specifications for evaluating the alternatives.

Concept	Value
Electricity tariff (IEA, 2021b)	256.21 €/MWh for residential and public applications 211.74 €/MWh for business and private companies
Photovoltaic module[53]	Power: 415 W_p Degradation: 0.55 % System loss: 14%
Inflation[54]	1.5 %
Carbon intensity of electricity[55]	259 g CO2/kWh
Discount rate (Mitscher & Rüther, 2012)	10%
CIT rate in Spain[56]	25%
Surplus compensation	0.1 €/kWh (Batlle Castelbon, 2022)

Some other assumptions for the assessment of the alternatives are:

- The solar module corresponds to the JA Solar brand, and it is considered to be the same for all the alternatives, with a few justified exceptions. In all instances, the efficiency and degradation of the photovoltaic components are equally estimated.
- The inflation rate assumed is from 2019 in the EU, prior to the conflict in Ukraine and the COVID-19 pandemic.
- No electrical storage system is proposed to be installed; only in the third alternative would there be batteries due to the proposal to use sunlight energy during the night.
- All proposed installations are grid-connected, and they are designed to sell the surplus energy.
- For the calculation of the annual CO_2 emissions, the value is approximated by considering the energy produced by the system and the carbon intensity coefficient.
- In each scenario, the annual maintenance cost and the replacement cost of certain components, such as the inverter, are estimated.

All calculations are detailed in the annexes as well as the financial analysis.

53 https://www.jasolar.com/uploadfile/2023/0309/20230309022526341.pdf

54 https://www.imf.org/external/datamapper/PCPIPCH@WEO/EURO/EU

55 https://canviclimatic.gencat.cat/es/actua/factors_demissio_associats_a_lenergia/index.html

56 https://sede.agenciatributaria.gob.es/Sede/impuesto-sobre-sociedades/que-base-imponible-se-determina-sociedades/tipo-impositivo.html

5.5.1 Installation of PV modules for self-consumption in single-family houses

In 2019, the Rajadell city council approved a municipal ordinance promoting photovoltaic energy self-consumption installations[57]. To incentivize this type of installation, the municipality offers a tax rebate on the annual property tax paid by the proprietors. The bonus is fifty percent of the total amount and is applicable for five consecutive years. Moreover, the construction tax is reduced by 95%. Next Generation funds for this type of installation are currently exhausted and therefore will not be considered[58].

In the present scenario, the solar panels will be installed on the roofs of the homes due to urban planning and aesthetic considerations. As more than 95% of the residences[59] in the municipality are single-family, it makes sense for the proposed installations to be for individual self-consumption. In a large city like Barcelona, where the majority of the population resides in owners' communities, most of the installations will be of a collective nature, also known as an energy community. Due to the increased costs associated with an electrical storage system and its low economic profitability, its use in self-consumption installations will not be considered. Furthermore, they are not necessary because the installations are connected to the electrical grid and the surpluses generated by the solar system are compensated in accordance with Spanish legislation. The investor in this case is the citizen himself, who assumes the cost of the installation with his private capital.

According to official data, there are 259 family residences in the town[60], of which 20 already have a self-consumption photovoltaic installation, with a total installed power of 140 kW[61]. Taking into consideration the technical difficulty of implementing self-consumption systems on some homes, for example due to ancient roofs, the presence of excessive shadows, or improper orientation, it is proposed to install solar panels on 80% of the homes, or 207 houses. Considering an average of 10 panels installed per household, which is 4.15 kW_p[62] per home, this would result in a total installed power of 859.05 kWp.

An average price for residential installations has been set at 2.05 €/Wp for this project, VAT included (Arcos-Vargas et al., 2018), which implies an average cost per installation of 8507.5€ and a total cost of 1761052.5 €. Due to the consumption curve of a residential user, the usual percentage of self-consumption is around 40-60%.

This implies that approximately half of the energy produced is injected into the grid and economically compensated by the energy company at an intermediate price of 0.1 €/kWh (Batlle Castelbon, 2022). As can be noted in Figure 14, typical residential consumption is partially shifted away from peak solar production hours.

57 https://bop.diba.cat/anuncis/antic/022019017830

58 https://icaen.gencat.cat/ca/energia/ajuts/energies-renovables/ajuts-renovables-2022/

59 https://www.idescat.cat/emex/?id=081786

60 https://www.idescat.cat/emex/?id=081786

61 https://icaen.gencat.cat/es/energia/autoconsum/Observatori-de-lautoconsum-a-catalunya/evolucio-de-lautoconsum/

62 https://icaen.gencat.cat/es/energia/autoconsum/Observatori-de-lautoconsum-a-catalunya/evolucio-de-lautoconsum/

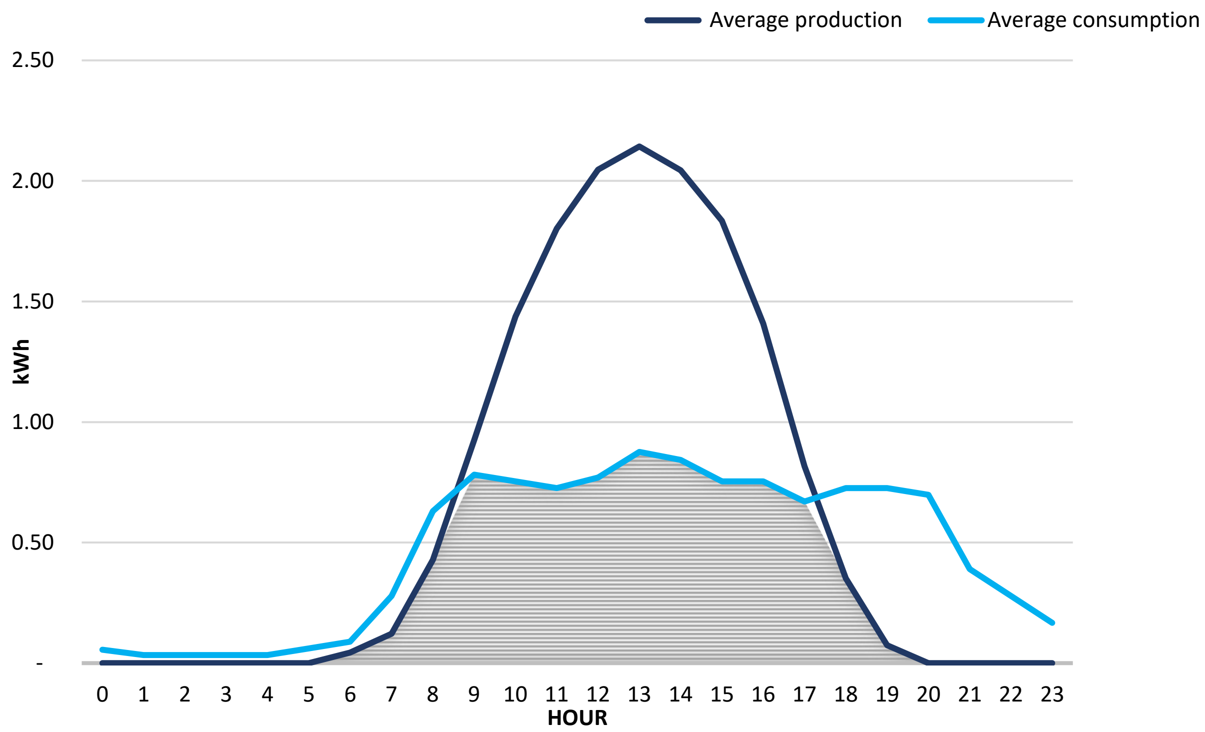

Figure 14: Consumption and production curves.

Based on official sources, the domestic electricity consumption in Rajadell was 4069 kW_h[63] per household in 2020, slightly higher than the Spanish average (3487 kW_h[64]). The estimated slope is 15º. Since some houses will suffer from the existence of certain shadows, the system's losses will be 16%. Most residences have been oriented as much towards the south as possible. From a visual inspection using Google Maps, the estimated azimuthal angles of the houses are reflected in Table 16:

Table 16: Azimuth angle of houses and kWh/kW_p ratio.

Orientation (Azimuth)	Percentage of houses	kW*h* / kW_p
South (0º)	20%	1352.98
Southeast (-35º)	30%	1317.40
Southwest (35º)	30%	1327.48
East-southeast (-70º)	10%	1233.26
West-southwest (70º)	10%	1248.07

The solar incidence, calculated as the arithmetic mean of the above values, is 1312.19 kWh/kW_p. For the economic assessment, the only subsidy considered is the IBI bonification, considering a value of the annual tax quota of 400€ per home[65].

63 https://analisi.transparenciacatalunya.cat/

64https://www.idae.es/uploads/documentos/documentos_Documentacion_Basica_Residencial_Unido_c93da537.pdf

65 https://www.naciodigital.cat/manresa/noticia/93069/mapes-creus-pagues-molt-ibi-aixo-es-costa-impost-cada-municipi

5.5.2 Installation of PV modules for self-consumption in municipal buildings

Premises owned by the municipality include the town hall, the medical centre, the cultural centre, the building that houses the train station and the tourist office, and a building that houses the school, the library, and the sports field. Figure 15 depicts the locations of the mentioned premises.

Figure 15: Location of municipal buildings.

The electricity consumption data has been provided directly by the local council, and it is presumed that energy prices are the same as for residential consumers; nevertheless, the investor in this instance is the town council. The hourly energy consumption of these buildings is primarily determined by the presence of occupants and employees. Consequently, consumption is highest in the morning and on working days. In the case of the tourist office and the cultural centre, their timetables may differ, and weekend usage is also frequent. The percentage of self-consumed energy has been estimated considering the solar production obtained in PVGIS and the hourly consumption curve presented in Figure 16.

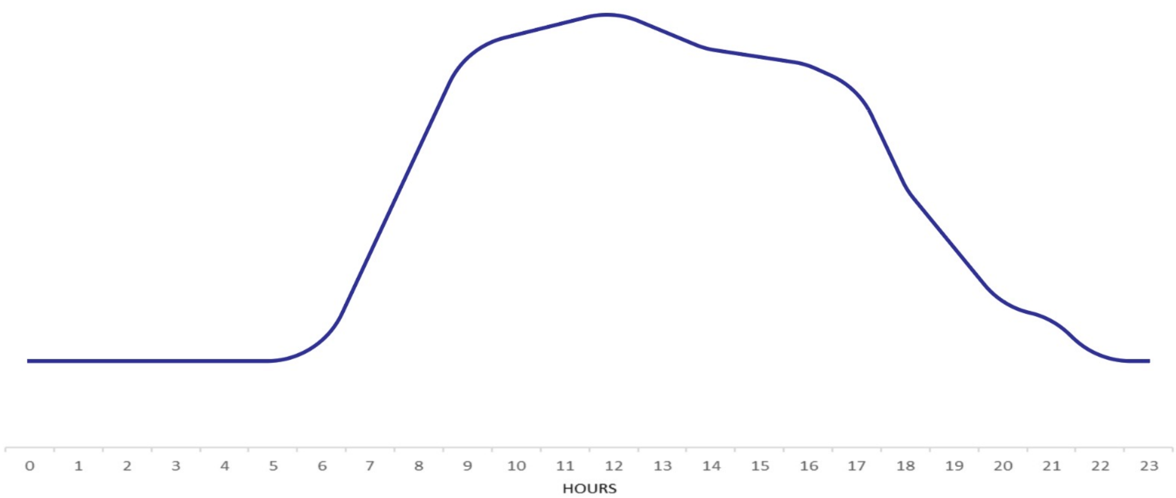

Figure 16: Hourly consumption curve for municipal buildings.

For calculating the dimensions of the installations, they have been considered to occupy the maximum available roof area. In certain cases, to avoid oversizing the system, it has been determined that a minimum of 40% self-consumed energy is required. Thus, the distribution of the solar panels on the respective municipal buildings is as shown in Figure 17:

Figure 17: PV panel distribution on the municipal building roofs.

The electricity not consumed is fed into the grid and compensated economically. The cost of the installation (VAT included) has been estimated according to the table of public prices for municipalities offered by the regional government[66]. Table 17 is a summary of the proposed installations for this alternative.

66 https://www.acm.cat/compres/productes/plaques-fotovoltaiques/lots-5-al-12-subministrament-equips-generacio-energia-solar

Table 17: Proposed municipal installations.

Building	Power (kW_p)	Cost (€)	kWh /kW_p ratio
Town hall	6.225	12325	1213.81
Medical centre	4.980	9860	1214.54
Train station and tourist office	6.640	13147	1304.92
School, library, and sports field	21.580	38628	1316.65
Cultural centre	10.790	20393	1262.63
Total	50.215	94354	1280.62[67]

5.5.3 Solar street lighting

Public lighting represents one of the largest energy bills for municipalities. In Europe, it is estimated that cities and towns spend an average of 40% of their municipal budgets on the electricity expenses associated with illuminating their streets and public buildings. Moreover, energy consumption for public lighting is increasing by approximately 2.6% per year. LED technology has radically altered both energy consumption and associated costs, reducing the installed power for the same illumination levels by an average of 60 – 80%. LED technology has stood out from other illumination devices due to its electronic nature, high energy efficiency, and extended lifespan. Priority, therefore, belongs to the replacement of light points in outdoor lighting spaces with LED technology, as well as the improvement of the directional quality of the luminaire and the implementation of systems for regulating the luminous flux, thereby achieving its variation throughout the night based on the needs of citizens and reducing energy consumption and light pollution (IDAE, 2023b).

In this project, the use of solar street lighting is proposed. These lighting systems are independent from the grid infrastructure and collect energy from the sun during the day and store it in a battery system. At night, this battery is responsible for distributing the stored energy and illuminating LED displays. As a result of its energy efficiency, maintenance, and light depreciation, a solar street lighting system is an enhanced alternative to conventional street lighting systems (Orejón-Sanchez & Gago-Calderón, 2018).

The proposal involves the renovation of municipal street lighting on rural roads, parking lots, and areas close to population centres. It does not contemplate the renovation of streetlights in urban areas because they have already been replaced by smart LED lighting. It is therefore proposed to renovate fifty percent of the existing lighting, equivalent to 310 luminaires. The investor is the local public entity. According to recent public prices, the price of a solar luminaire is stipulated at 1309.83€ incl. VAT[68]. This includes the photovoltaic system, the LED, and the installation. The system consists of a 50-watt luminaire, a storage and control system, and a 150W photovoltaic panel. Each luminaire has its own photovoltaic panel and is independent of other lights. An example of a luminaire can be seen in Figure 18.

67 Weighted average

68 https://www.acm.cat/compres/productes/enllumenat-public-led/lot-22-i-23-subministrament-installacio-manteniment-llumeneres-led/lot-territorial-7-bages-bergueda-solsones

The calculations have been computed using official street lighting consumption data, and the economic savings have been determined using an average of the local lighting costs of the last four years[69]. The mounting allows the solar module to be optimally aligned and tilted. Therefore, a fully south orientation and an inclination of 35° are considered, which means a ratio of 1531.39 kWh/kW_p. It is estimated that certain components, such as batteries, will need to be replaced after 10 years.

Figure 18: Solar street lighting in a French village[70].

5.5.4 Installation of PV modules for self-consumption on the sewage treatment plant

On May 6, 2022, a wastewater treatment plant, owned by the Catalan Water Agency, was installed in the municipality. The investment for this installation will therefore be covered by this public agency. The plant processes the wastewater from the municipality of Rajadell and some neighbouring localities, with a total capacity of 258 m^3 per day, equivalent to 1503 inhabitants[71]. The plant is divided into three divisions: the water line, the sludge line, and other facilities.

According to the IDAE, a small water treatment plant like this one consumes approximately 50 kWh per resident per year[72]. Therefore, it has been presumed that the plant has a total annual consumption of 75 MWh. The only viable space for solar panels is on the roofs of buildings. For aesthetic reasons, they shall be placed following their orientation and inclination, as depicted in Figure 19.

69 https://www.seu-e.cat/ca/web/rajadell/govern-obert-i-transparencia/gestio-economica/pressupost/pressupost/despeses-per-programa

70 https://www.fonroche-lighting.com/es/eur

71https://aca.gencat.cat/web/.content/20_Aigua/02_infraestructures/05_estacions_depuradores_daigues_residuals/Fitxes_EDAR/DRJD_Fitxa_Web_EDAR.pdf

72 https://www.idae.es/ca/tecnologies/eficiencia-energetica/serveis/proveiment-i-depuracio-daigua

Figure 19: PV panel distribution on the sewage treatment plant roof.

There is space for 102 panels of 415 W_p each, for a total installed power of 42.33 kW_p, distributed as detailed in Table 18:

Table 18: Sizing of the water treatment plant PV system.

Roof orientation	Azimuth	Number of panels	kWh/kW_p
Southeast	-26º	27	1343.63
Northwest	154º	27	1080.70
Southwest	65º	24	1285.21
Northeast	-115º	24	1148.94

The unit production ratios have been obtained using the PVGIS tool, considering a slope of 12º and system losses of 14%. The weighted average of production is 1214.48 kW_h / kW_p, which implies an annual electricity generation of 51408 kW_h, approximately 70% of the total energy consumption of the plant. It is assumed that 100% of the photovoltaic energy will be self-consumed, so the economic benefit of the installation will be due to the electricity savings from the grid. The installation costs will be comparable to those of a recent photovoltaic installation at a sewage treatment plant owned by the same corporation and located in the same region[73].

5.5.5 Installation of PV modules for self-consumption in livestock farms

Dairy farming is a key economic activity for the municipality and includes production, reproduction, and leisure farms, the latter for equines. Animal breeding comprises several species, such as bovine, caprine, equine, avian, ovine, porcine, cuniculture, apiculture, and heliciculture[74].

73 https://contractaciopublica.cat/ca/detall-publicacio/c58cf12b-de87-f3d8-192e-757a97b91ade/78838261

74 https://agricultura.gencat.cat/ca/serveis/registres-oficials/ramaderia-sanitat-animal/registre-explotacions-ramaderes/visor-interactiu-rer/

For this study, only the most relevant farms, avian and porcine fattening farms, will be considered. There are about 3007 head of breeding swine and 100852 places for poultry, equivalent to 282386 kg. According to a study conducted by the Catalan Energy Institute (ICAEN)[75], the annual energy consumption per head in the swine industry is 49 kWh. The majority of farms use fuel as their primary source of energy, accounting for 82% of total energy use, whereas electricity represents only 20%. It is estimated that each pig annually consumes 7.8 kWh of electrical energy. Regarding poultry farms, the electrical consumption is valued at 0.0921 kWh per kg (Oviedo-Rondón, 2019).

Energy needs to maintain the heating system are usually based on biomass and fossil fuels. The greatest demand for electrical energy on a farm is primarily for forced ventilation and lighting, as animals require controlled conditions of temperature, light, and humidity throughout the year for their optimal growth (Upton & Murphy, 2010). The peak consumption hours on a farm occur during the middle of the day, particularly during the summer months when temperatures are at their maximum. It is precisely during those hours of the day and months of the year that solar panels can produce the greatest amount of electricity. It should be considered adding a battery storage system when the connection to the grid is unreliable and power is required in the event of a grid outage, since it could affect the health of the animals. However, if the grid connection is stable, as in this case, the optimal strategy would be to sell the surplus energy due to the high cost of batteries for industrial installations. In addition, farms are typically situated in locations that are favourable for receiving sunlight, without shadows, and with persistent exposure to the sun. In turn, they generally have large gable roofs, which facilitate the installation of many photovoltaic modules that also serve as an additional layer of exterior insulation. The implementation of solar panels on farms, in addition to offering an important means of savings, is an added value that gives a competitive advantage for the company in terms of marketing, as it will acquire a reputation as a business committed to the environment and renewable energies.

Due to the characteristics of consumption and production, a self-consumption rate of 95% has been established. After a visual examination using Google Maps, an average azimuth angle of 29º is determined. The slope is assumed to be 8º (Bahón Silverio, 2019), which is typical for agricultural roofs. In total, there are six local farms on which solar panels would be installed and be eligible for the tax property subsidy.

5.5.6 Installation of a solar-powered water pumping system for irrigation

Agricultural activity is one of the major drivers of climate change and one of its primary victims, as well as suffering from an increasing drought that threatens its survival. Global warming's consequences are becoming obvious worldwide, but some water-scarce regions present higher vulnerability. Spain is considered one of the most exposed nations to climate change within the European Union and is likely to be highly vulnerable given its unbalanced balance between water resource availability and demand (Vargas-Armelin & Pindado, 2014). This spring 2023, for instance, more than 80% of the region's cereal harvest was lost due to drought and corresponding water restrictions that prohibited irrigation[76].

75 https://ruralcat.gencat.cat/migracio_resources/651123_informe_conclusions_ramader2007.pdf

76 https://www.naciodigital.cat/manresa/noticia/109244/perdues-mes-80-collita-cereal-catalunya-central-culpa-sequera

Water has traditionally been the primary factor limiting agricultural production, especially where precipitation falls short of crop demand. Pulling water from groundwater or surface drainage and applying the necessary pressure for irrigation is a significant energy expense and an increasing cost to agriculture. Therefore, the structure of irrigation systems is particularly sensitive to energy costs, and the continuous increases and volatility of energy prices in recent years have become a significant barrier to the sustainability of agricultural incomes. The connection between energy and water has sparked global interest in this topic, with the goal of reducing consumption of conventional energy sources, particularly for irrigation applications (Langarita et al., 2017).

The use of PV technology to power water pumps is an emerging technology that can be applied on a larger scale and offers an environmentally friendly alternative compared to conventional water pumps powered by diesel or fossil fuel electricity. There are numerous benefits to installing solar-powered water pumping systems, particularly where grid connection is not available and solar energy is abundant. Furthermore, there is a natural correlation between water demand and solar power availability. This system permits the local production of completely renewable, emission-free energy, allowing farmers to take advantage of competitive and long-term stable energy prices during the irrigation season and profit from the sale of surplus electricity during the rest of the year. However, these systems require a high initial investment (Sontake & Kalamkar, 2016). Occasionally, solar panels coexist with crops on the same surface, increasing the economic value of farms by more than 30% by improving the productivity and efficacy of the land. Certain crops benefit from shade because it reduces their temperature and prevents excessive evaporation[77]. Figure 20 is an example of it, commonly known as agrivoltaics.

Figure 20: Example of agrivoltaics[78].

The photovoltaic irrigation system consists of the PV generator, including the modules and the support structure, the frequency inverter, and a control system. The frequency inverter is used to solve the problems of rapid fluctuations in solar radiation, such as those caused by passing clouds, that can be detrimental to the stability and reliability of the equipment. The system is integrated with the generally existing irrigation infrastructure, such as motor pumps, pipelines, sprinklers, etc.

77 https://www.iberdrola.com/innovacion/energia-agrovoltaica

78 https://autosolar.es/energia-solar/agrofotovoltaica-combinando-fotosintesis-y-fotovoltaica

The most common application of these devices is to drive water from a main source, such as a canal or aquifer, to a high reservoir, which is utilized afterwards to distribute pressurized water to irrigators[79]. In the particular case of Rajadell, there are 866 hectares of agricultural land (nearly 20 percent of the total area of the town), of which 633 hectares are used for the cultivation of cereal products[80]. It is proposed to implement a solar-powered water pumping system on one of the lands in the municipality that utilises water deposits and automatic irrigation for vineyards and olive trees. In fact, it is one of the few farms that uses automatic irrigation, as most of the fields in the town are rainfed. The aerial view of this location is projected in Figure 21.

Figure 21: Aerial view of the project location.

Aside from rainwater collection, the farm is authorised to collect water from three water wells that feed three storage tanks with a total capacity of 10700 cubic meters that manage the irrigation activity. Between April and September, it requires 1800 m^3 of water per hectare, which equates to 10800 m^3 of water annually, comparable to the water reserve. Nowadays, agricultural operations are supplied by the public electricity grid[81]. The investment in this project consists of the photovoltaic installation and the irrigation control system. The solar system will be located on the ground and comprise a mobile structure with a horizontal axis that enables the panels to be perpendicular to the sun throughout the day. This structure is essential for achieving optimum efficiency and preventing abrupt changes in the pumping system[82]. However, this results in a 22% increase in the investment cost compared to a fixed structure (Naval & Yusta, 2022). In this instance, the additional equipment for pumping consists of installing a 3-kilowatt variable-frequency drive for each pump. This component enables the smoothing of fluctuations in PV production, thereby preventing pump failures and element damage[83]. The economic benefits of these systems include electricity bill savings and the sale of surplus energy.

79 https://maslowaten.eu/

80 https://analisi.transparenciacatalunya.cat/Medi-Rural-Pesca/Mapa-de-cultius-de-Catalunya-amb-origen-DUN/e7kw-9ebb

81 https://web.manresa.cat/media/docs/arxius/doc_contingut_10235.pdf

82 https://www.solartech.cn/product/system-products.html

83 https://search.abb.com/library/Download.aspx?DocumentID=3AXD50000733149&LanguageCode=es&DocumentPartId=&Action=Launch

In this case, as it is a 13.695 kW installation, the surplus electricity during the non-irrigation months is not deemed to be sold but rather used for other purposes. In addition, it is considered that there will be cost savings due to the fact that the electrical power from the grid that currently feeds the system will not be needed[84]. The maintenance cost is the result of the added maintenance of the panels, the solar structure, and the control and regulation system (García Andino H, 2021).

5.5.7 Implementation of a local community solar farm

Energy communities are collective projects in which individuals and other local entities, such as businesses or municipalities, collaborate to administer their own energy and benefit collectively from the same generation facilities. They intend to promote distributed renewable generation and local development, allowing individuals to directly participate in the electricity market while creating environmental and social benefits. Local communities may consist of public actors, businesses, and citizens[85]. In this example, it is supposed to comprise the municipal buildings and any interested citizens. Compared to solar roof systems, getting involved in a community solar farm can be a beneficial option if the roof is unsuitable or the owner is opposed to having solar panels installed on the property's roof. Even if the roof is suitable for solar, it may be worthwhile to participate in a community solar project if the costs are low and the contract terms are favourable. As community solar initiatives become more prevalent and contract terms become more consumer-friendly, solar farm alternatives will increasingly compete with rooftop solar. This project will be funded through a public initiative, and a portion of the power will be reserved for inhabitants who wish to participate, contributing a part of the cost. For this reason, a flat area of land owned by the municipality and near the town centre has been selected, as the utmost distance for a consumer to join the energy community, according to current legislation, is 2 kilometres[86]. Therefore, this local community would include the municipal buildings and some residents of the neighbourhoods of *L'estació*, *Les Castes,* and *Rajadell Centre*. Figure 22 displays the proposed location of the PV installation and a 2-kilometre radius around it. Citizens living within this maximum distance could join the local energy community.

84 https://comparadorluz.com/companias/endesa/potencia-contratada

85 https://comunitatsenergetiques.com/comunitats-energetiques/#ajuntament

86 https://www.idae.es/ayudas-y-financiacion/comunidades-energeticas

Figure 22: Location of the installation and area of concern for the energy community.

The photovoltaic system will have a peak power of 100 kW_p, so that 50% of the installation and, consequently, the energy generated, will belong to the municipal buildings listed in a_2. The remaining 50 kW_p would then be distributed among the neighbours who wished to join in. The self-consumption of the municipal entities is approximately 50%, as in a_2, but the self-consumption for the residential participants is considered to be 90%, exceeding that in a_1, because the peak power of each installation would be lower and therefore the energy produced would be significantly lower. Overall, self-consumption stands at 70%.

5.5.8 Installation of PV modules for self-consumption in restaurants and rental houses

Tourism and restaurants in the municipality are one of the economic drivers of the region and also require a high demand for electricity. Specifically, there are three restaurants in the municipality. One of them already has solar panels on the entire roof, so it is proposed to install photovoltaic modules in the other two restaurants[87]. Concerning rural tourism, there are currently three rural houses with a total capacity of 24 people[88]. For the calculations, it is assumed a self-consumption rate of 85% and an annual IBI cost of 550€. The proposed systems are listed in Table 19.

87 https://bagesturisme.cat/es/municipi/rajadell/

88 https://www.idescat.cat/emex/?id=081786&lang=es

Table 19: Proposed PV systems for restaurants and rental houses.

	Modules	kW_p	kWh/kW_p
Restaurant 1	77	31.955	1230.78
Restaurant 2	59	24.485	1209.64
Rental house 1	22	9.130	1214.74
Rural house 2	26	10.790	1353.96
Rural house 3	29	12.035	1395.63
Total	213	88.395	1260.75[89]

Figure 23 and 24 show the distribution of the solar modules on the roofs of the different businesses.

Figure 23: PV panel distribution for the restaurants.

Figure 24: PV panel distribution for the rental houses.

89 Weighted average

5.5.9 Installation of a solar-powered electric vehicle charging station

As previously noted, more than half of the energy used by Rajadell residents is consumed by transport. The automotive sector is characterised by an elevated use of energy, especially fossil fuels, and has a significant impact on the environment. Hence, promoting electric vehicles emerges as a pathway for furthering its sustainability, with a focus on the implementation of charging stations, which are currently scarce (Martínez-Lao et al., 2017). In the APP *Electromaps,* it is possible to locate up to 12149 charging stations in Spain, mainly concentrated in the large capitals[90]. However, there is currently no publicly accessible recharging network with the required capacity to enable mass adoption of electric mobility. In this area, photovoltaics can play a significant role, for instance, through photovoltaic power charging facilities. Photovoltaic charging stations offer numerous benefits since they utilise renewable energy for charging and provide vehicles with shaded parking. In addition, this type of electric vehicle charging station offers a high-power charging solution in areas where grid access is weaker than usual, such as rural areas far from large cities or communication routes, where investments of this kind are typically made. Considering this, the photovoltaic station appears as a complementary solution to continue constructing an electric vehicle charging infrastructure that democratises the implementation of this technology. At the end of June 2022, more than half a hundred photovoltaic stations were operational in Spain, so it is a market that has not yet expanded (En et al., 2020). Figure 25 is an example of a solar-powered electric vehicle charging system.

Figure 25: Example of a solar-powered electric vehicle charging station[91].

In this scenario, it is proposed to install pergolas with photovoltaic panels and electric chargers in one of the municipal car parks. The location chosen is one of the busiest areas in the town due to the presence of three restaurants, the pharmacy, and the railway station, and there is a nearby rest area close to the highway. In Figure 26, it can be appreciated the location of the recharging station and the nearest places of interest.

90 https://www.electromaps.com/es/puntos-carga/espana

91 https://www.amb.cat/web/ecologia/sostenibilitat/transicio-energetica/projectes/detall/-/projecteobert/fotolineres-laborals-metropolitanes/5844260/11818

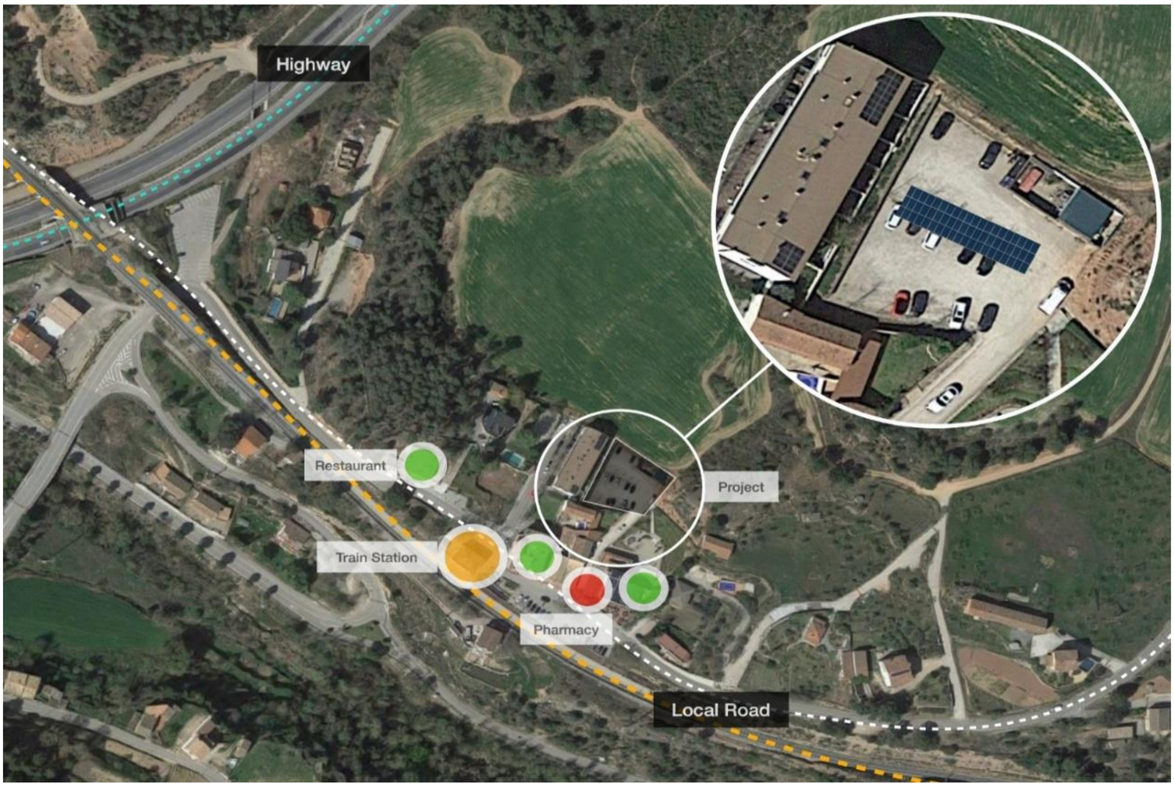

Figure 26: Location of the recharging station and its surrounding facilities.

The proposed installation is similar to that of the dissertation carried out by Galvarro Cano (2020) and is illustrated in Figure 27: a metal structure that comprises 23.4 kW_p of installed photovoltaic power with an inclination of 20º (consequently, the kWh/kW_p ratio is 1476.76), responsible for obtaining and transforming the energy, and several charging points. The total estimated cost without VAT is 82800€ (44000€ for recharging installation, 5000€ for electrical connection, 30950€ for photovoltaic installation, and 2850€ for other concepts).

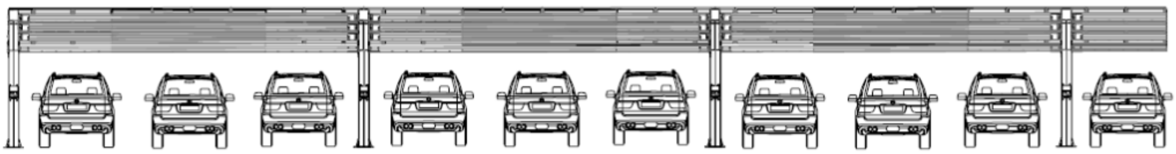

Figure 27: Example of the proposed system. Galvarro Cano (2020)

During daylight hours, the photovoltaic station generates sufficient energy for charging the electric vehicle as well as surplus energy for the distribution network. Due to the intermittency of consumption, it is considered that only 45% of the energy generated would be directly used to cover the consumption of the station. This demonstrates that for the photovoltaic installation to be economically profitable, it must be regarded as a grid-connected installation with surpluses. The remaining electricity demand will be supplied directly from the grid.

According to Galvarro Cano (2020), the average selling price is estimated to be 0.35€ per kW_h. It has been considered to have an average vehicle load of 40 kWh and an initial demand of 7 recharges per day, with an annual demand increase of 3%. The installation is eligible for government subsidies under the MOVES programme[92], specifically for the implementation of charging infrastructure for electric vehicles, accounting for 40% of the recharging installation cost.

5.5.10 Installation of a utility-scale solar farm

A photovoltaic power station is an extensive solar array that converts sunlight into energy that is then transmitted to the power infrastructure. A utility-scale solar farm is a large solar farm owned by a utility company whose electricity is either sold to wholesale utility buyers' customers via a power purchase agreement (PPA) or owned directly by an electric utility company (B. Kim et al., 2020). This proposal assumes that the electricity will be sold to the grid at an average price of 0.128 €/kWh[93]. The location for the installation was chosen to ensure that it would be as close as feasible to an electrical substation and that it did not affect land currently under cultivation. In addition, it is located quite far away from urban centres. It is close to the population centre of *Can Servitge*, but the neighbours will not be directly visually affected because the park is on the other side of the hill. The suggested location is indicated in Figure 28. The PV installation proposed, as an appropriate large-scale photovoltaic farm, is south-facing, easily accessible, not ubicated in environmentally protected areas, and located on flat terrain. The land area utilised is 11.25 hectares, which is comparable to a solar farm located in a nearby municipality. To maximise the efficiency of the system, a double solar tracking system will be used. It is estimated that for the land occupied, about 1.5 MW could be installed (Ortiz et al., 2017).

Figure 28: Location of the solar farm and distance to the electrical substation.

92 https://www.idae.es/ayudas-y-financiacion/para-movilidad-y-vehiculos/programa-moves-iii

93 https://www.omie.es/es

The weighted average total installed cost for utility-scale systems in Spain in 2021 was 0.851 € / Wp (Renewable Energy Agency, 2022a, p. 87). In the case of a dual tracking system, the investment costs increase by double, compared to a fixed structure (Naval & Yusta, 2022). The annual maintenance and operating costs for a system of these characteristics are approximately 0.03875 € per Wp (KIC InnoEnergy, 2015, p. 20). The land rental price has been estimated at 1500€ per hectare per year[94].

5.6 Parameters

5.6.1 Reference actions

In most cases, the DM and the analyst develop the reference actions. In this instance, the expert and the analyst have determined that each category should be represented by two reference actions. The best and worst are, respectively, the best and worst evaluations of all alternatives for each criterion. The minimal and maximum level positions are determined by the preference direction of the criterion. If the direction is minimization, the minimum value is used as a reference for the category C_3 , and the maximum value of the performance of actions in this indicator is used as a reference for the category C_1. If the direction is maximization, the value of the reference action b_3^2 corresponds to the maximum value of the performance of the alternatives and b_1^1 to the minimum value. To decide the values of the remaining actions, a meeting was held with the expert to try to define them (Gregório, 2022). The reference actions are specified in Table 20.

Table 20: Reference actions established for each criterion and each category.

Reference	$\mathbf{g_1}$	$\mathbf{g_2}$	$\mathbf{g_3}$	$\mathbf{g_4}$	$\mathbf{g_5}$	$\mathbf{g_6}$	$\mathbf{g_7}$	$\mathbf{g_8}$	$\mathbf{g_9}$	$\mathbf{g_{10}}$
$\mathbf{b_1^1}$	-25466.41	17.21	9.61	L1	L1	L1	4.84	L1	L1	1214.48
$\mathbf{b_1^2}$	0	15.00	4.00	L2	L1	L1	5	L1	L1	1220
$\mathbf{b_2^1}$	5000	10.00	3.00	L2	L2	L2	20	L2	L2	1280
$\mathbf{b_2^2}$	7500	8.50	2.20	L2	L2	L2	100	L2	L2	1350
$\mathbf{b_3^1}$	15000	6.50	1.70	L3	L3	L3	259	L2	L3	1500
$\mathbf{b_3^2}$	33924.39	5.48	1.52	L3	L4	L3	732.51	L2	L3	2040.14

5.6.2 Criterion parameters: Preference, indifference, and veto thresholds

During the process of indicator selection, the presence of arbitrariness becomes evident as there is a requirement to pick from a diverse range of possibilities. For that reason, it is necessary to include various components within each criterion, such as the scale, preference direction, and weight. Each criterion is also composed of a preference (p_j), an indifference (q_j), and, in some cases, a veto threshold (v_j). The indifference and preference thresholds serve as a means to integrate imperfect knowledge within the model. In fact, there is not only an element of arbitrariness in the definition of each criterion, but there is also a margin of imprecision surrounding the data used to build them, as well as inherent uncertainty regarding data parameters and ill-determined characteristics resulting from the difficulty of defining the outcomes and consequences of a criterion.

94 https://www.juntacentral.es/sites/default/files/prensa/2020-10/31-10-20_pais.pdf

The indifference threshold between two performances corresponds to the "largest performance difference that is judged compatible with an indifference situation between two actions with different performances," whereas the preference threshold between two performances corresponds to "the smallest performance difference that, when exceeded, is judged significant of a strict preference in favour of the action with the best performance." The concept of the veto threshold is a parameter linked to a particular criterion, serving the purpose of enhancing its strength, "where a discordant difference in favour of one option greater than this value will require the DM to negate any possible outranking relationship indicated by other criteria" (M. A. Pereira & Marques, 2022). Table 21 contains these values, which were determined collaboratively with the expert.

Table 21: Preference, indifference, and veto thresholds per criterion.

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

5.6.3 Method parameters: The credibility level

The credibility level or discrimination threshold denotes the minimum degree of trustworthiness in the validation of outranking relations (M. A. Pereira & Marques, 2022). Hence, it was settled by the expert on $\lambda = 0.7$.

5.6.4 Performance table

The evaluation of each alternative for each criterion is reflected in a performance table, shown in Table 22.

Table 22: 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

6.1 Analysis

The ELECTRE Tri-nC technique classifies each action into either a single category or an interval of categories, depending on the outcome of the ascending and descending rules. If the result of the ascending rule is equivalent to the descending result, the alternative is assigned to a unique category. Table 23 presents the results provided by the software employed.

Table 23: Results of the assignment procedure.

Alternative	Action	Worst	Best	Urgency of action
$\mathbf{a_1}$	PV self-consumption: single-family houses	C_2	C_3	Medium-high
$\mathbf{a_2}$	PV self-consumption: municipal buildings	C_2	C_2	Medium
$\mathbf{a_3}$	Solar street lighting	C_1	C_1	Low
$\mathbf{a_4}$	PV self-consumption: water treatment plant	C_2	C_3	Medium-high
$\mathbf{a_5}$	PV self-consumption: livestock farms	C_2	C_3	Medium-high
$\mathbf{a_6}$	Solar-powered water pumping system	C_2	C_2	Medium
$\mathbf{a_7}$	Local community solar farm	C_3	C_3	High
$\mathbf{a_8}$	PV self-consumption: restaurants and rental houses	C_2	C_3	Medium-high
$\mathbf{a_9}$	Solar-powered electric vehicle charging station	C_1	C_2	Medium-low
$\mathbf{a_{10}}$	Utility-scale solar farm	C_2	C_2	Medium

The analysis reveals that only one measure, a_7, is deemed to possess a sense of immediacy and has been allocated to the category C_3, whereas a significant proportion of 40% of the actions proposed have been assigned between C_2 and C_3. Three actions have been assigned to C_2, corresponding to a medium implementation urgency. There is one alternative, a_9, placed between C_2 and C_1. Lastly, a_3 has been 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 29.

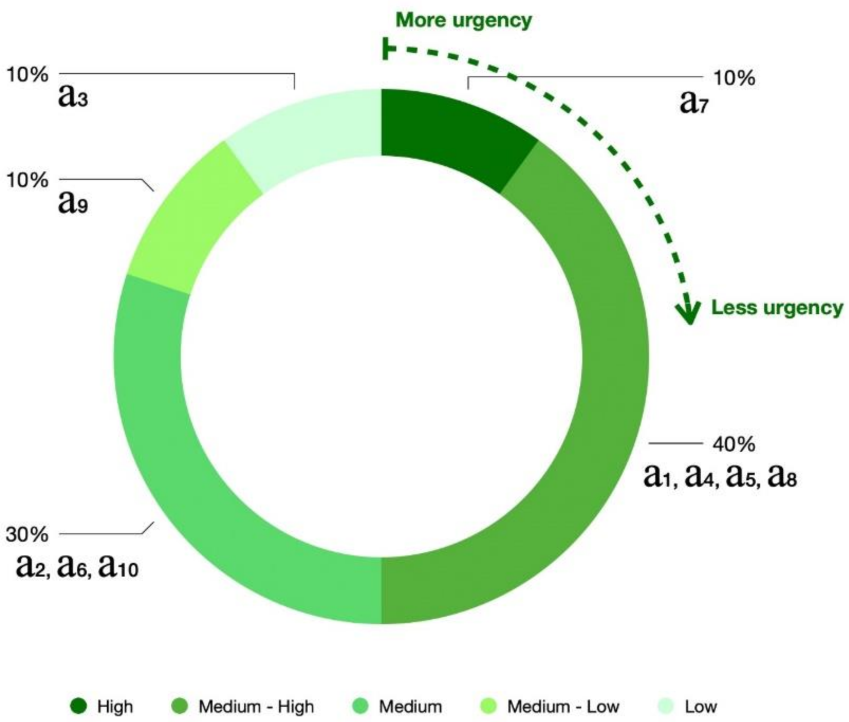

Figure 29: Classification of alternatives according to their urgency of implementation.

Based on the results obtained, the following analysis has been conducted for each category or pair of categories:

High urgency (C_3): The only alternative that has been classified as C_3 is a_7. Action a_7 refers to the establishment of a local energy community based on photovoltaic energy, where half of the energy produced would be used for the municipal buildings' consumption, and the other half would be distributed among the neighbours who wished to join. For example, each participating neighbour could be assigned 1.5 kW_p of power, which would enable approximately thirty homes to join in. On the one hand, 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. As the power generated is minor when compared to domestic consumption, most of the energy produced is directly consumed. Compared to a_1, this implies a 40% increase in self-consumption. In addition, as opposed to a_1 and a_2, this alternative is more energy-efficient when it comes to capturing solar radiation, due to its optimal inclination and orientation. Furthermore, when compared to roof-integrated systems, ground-mounted installations have greater ventilation and heat dissipation. On the other hand, there are certain aspects that, in practice, slow down the development of these proposals. For example, there is administrative complexity and a long timescale for the legalisation of the installation. The social acceptability of ground-mounted PV systems is typically low because of their visual and environmental impact; however, when the public is involved, acceptance increases.

Medium-high urgency (C_3;C_2): 40% of the alternatives have been categorised between C_3 and C_2, which are regarded as calls for a medium-to-high degree of urgency for implementation. Action a_1 involves people installing solar panels on the roofs of their properties with the purpose of using the generated energy for self-consumption. Among the possible alternatives, this action implies the significant involvement of the majority of the population, so there is a great impact on the achievement of the environmental objectives in terms of avoiding the emission of over 200 tonnes of CO_2 annually. Furthermore, it is an economically viable alternative, with a relatively short payback period of 7-8 years for a 25-year installation. The existing regulations that promote individual self-consumption, surplus compensation, and incentives such as property tax bonification contribute to the increased profitability of these systems. Moreover, the administrative simplicity of implementing them has made it a truly attractive option. The measures a_4, a_5, and a_8 include the installation of solar panels for the self-consumption of electricity in the water treatment plan, restaurants, rural tourism accommodations, and some farms. These projects are highly profitable and have a brief payback period, under six years, as they are highly energy-consuming and have competitive installation costs, mainly because they are larger installations than residential ones, and their specific cost is lower. However, they account for only a minor portion of the total energy consumption of the municipality and do not contribute significantly to emissions reduction. Their solar gain is dependent on the orientation and inclination of the roofs on which the solar panels are installed and is thus lower than that of ground-mounted systems. These installations (a_1, a_4, a_5, a_8) are in full expansion throughout the national territory. In 2022, the energy generated for self-consumption by photovoltaic panels on rooftops covered 1.8% of the electricity demand in Spain, with more than 298000 residential installations and 54000 commercial installations having solar panels on their roofs[95].

Medium urgency (C_2): Three actions, namely a_2, a_6, and a_{10}, have been established in this category for different possible reasons. All these alternatives are cost-effective, but they can have certain drawbacks compared to urgent actions. Option a_2 entails the implementation of photovoltaic panels on municipal buildings for self-consumption; therefore, the investor is the local council itself. In contrast to the above options, this action has a comparatively reduced financial impact and a less appealing payback period that exceeds eight years. This is primarily a result of a low rate of self-consumption and higher installation costs. In addition, solar incidence and avoided emissions are low. Regarding a_6, this initiative is also related to photovoltaic self-consumption, but in this case for the very specific application of automatic irrigation. Hence, the proposed system comprises not only the photovoltaic system but also the pumping control and regulation devices. For this reason, and due to the single-axis tracking system, there is an increase in cost. Other disadvantages are the negligible contribution to emissions reduction and the low technological deployment of the system. In contrast, this system has great solar collection efficiency and a rather short payback period. Finally, a_{10} has also been assigned to this category. The proposal to build a utility-scale solar farm has notable benefits but simultaneously implies certain drawbacks.

95 https://elperiodicodelaenergia.com/autoconsumo-genero-espana-18-demanda-electrica-2022/

On the one hand, this alternative has the most favourable solar gain and the greatest impact on reducing CO_2 emissions. Actually, the renewable energy production by this system is related to the national electricity mix and the achievement of national climate goals. In other words, this action does not result in emission reductions in any of the municipal sectors. Nonetheless, it may be argued that the implementation of this installation can counterbalance the emissions produced by other local actors. On the other hand, these systems have a significant visual impact and land usage and are generally rejected by the residents of the municipalities where they are planned to be constructed. In addition, a number of bureaucratic barriers impede the swift development of these initiatives. It has been determined jointly 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. This determination is grounded in the understanding that the success of a project is contingent upon its approval by residents. In the absence of this veto, the assignment of a_{10} would have been designated to C_3.

Medium-low urgency ($C_2; C_1$): The a_9 is assigned to C_1 in the worst-case scenario and C_2 in the best-case scenario. Consequently, this option may be considered to have low-to-medium urgency. This alternative, as opposed to the others, is related to the transportation sector. Certain performances in some criteria are favourable, such as a ratio of 1476.76 kWh/kWp of solar energy collection or a payback period of 7-8 years. However, the system remains in development and does not appear economically profitable, which would discourage private investment. Due to the existence of subsidies for the construction of electric vehicle charging stations, the option that does not include a photovoltaic system appears to be more financially viable.

Low urgency (C_1): The action a_3 is the only one to be placed in the lowest category. Its performance according to several criteria is not satisfactory, such as the fact that the payback period of 17 years is deemed excessively lengthy, a negative economic evaluation, and a highly elevated specific cost.

6.2 Recommendations for policymakers

Following the analysis of the results, a timeline proposition is formulated for the implementation of the proposed projects. The timeframe is shown in Figure 30. Urgent measures should be implemented by 2026, whereas medium-high urgency actions are proposed to be implemented by 2028.

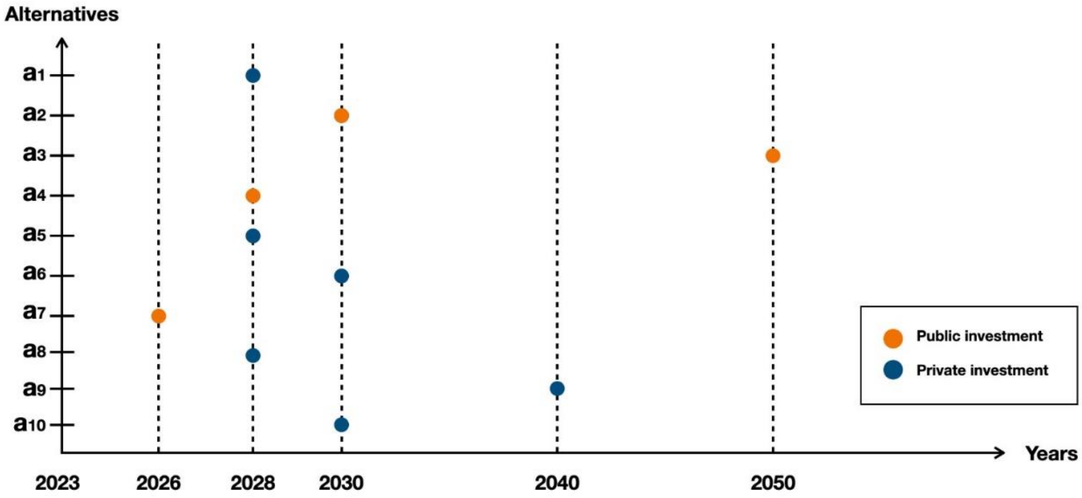

Figure 30: Timeframe of the implementation proposal.

Upon the successful implementation of these proposed alternatives by 2030, it is projected that annual emissions reductions will amount to 392.98 tonnes, excluding the contribution from the photovoltaic power plant. Nevertheless, when incorporating the impact of the solar farm, the estimated emissions savings are expected to reach 1125.39 tonnes. Comparing these results with the environmental goals established by the municipality, it becomes evident how significantly photovoltaic energy contributes to the energy transition. Table 24 and Table 25 provide an illustration of this comparison.

Table 24: Climate goals of Rajadell.

Year	Reduction in emissions	Tonnes of $C0_2$ equivalent emissions	
		Including transport	Excluding transport
2030	55%	1008.51	440
2050	Climate neutrality	1833.66	800

Table 25: Percentage of emissions reduction by the PV projects proposed for 2030.

	Including transport emissions	Not including transport emissions
Without solar farm	21.43%	49.11%
With solar farm	61.37%	140.67%

As can be seen, photovoltaics plays a crucial role in accomplishing environmental goals. Without considering the construction of the solar farm, the proposals made in this study can reduce emissions in the residential and service sectors by 49% by 2030. The following assessment is conducted for each intended action.

Self-consumption in houses (a_1): This measure is essential for the decarbonization of the residential sector, and photovoltaic energy is the primary contributor. It is noteworthy that older residences often rely on gas or butane as a primary source for thermal purposes; consequently, the photovoltaic impact is dependent on the electrification of households. It is recommended that this measure be completed by 2028, but it requires additional efforts from the administration to incentivise these installations. As demonstrated, many residential PV installations are profitable, although citizens are requiring more subsidies and fair regulation. The actual regulation is regarded as indispensable for facilitating the growth of these systems, including measures such as the elimination of self-consumption charges and surplus compensation at a price valued between wholesale and retail prices. To promote citizen investment, municipal tax cuts are also necessary. The 50% reduction of the property tax over five years and the 95% reduction of the construction tax offered by the Rajadell council are currently among the most ambitious in the country. However, it is believed that the administration of the European funds could have been more efficient. Of the €73 million designated for photovoltaic self-consumption, €163 million has been requested, resulting in the exclusion of €90 million[96]. This was the result of both a surplus of demand and ineffective resource management, perhaps due to a lack of demand forecasting. The same fund is dedicated to residential and business consumers, with the majority of the funding allocated to a few applicants. The concern lies in the fact that a small number of receivers exhausted the entire fund, excluding many applicants. It is believed that there should have been two distinct programmes: one for companies and another for residences. The value of the subsidy for each applicant should have been lower to ensure it could be distributed equitably among a greater number. It is suggested to policymakers that they search for a solution to this problem, which may include developing an improved, more efficient funding programme.

Self-consumption in municipal buildings (a_2): Local energy policymaking is essential to realising the energy transition. In essence, this project places special emphasis on the role of municipalities in achieving this transition. Hence, it is advisable for local policymakers to contemplate, as soon as possible, installing solar panels on the roofs of municipal buildings. Based on the model results, this action is of medium urgency, but it is desirable to be implemented well in advance of 2030 since the public administration must serve as a role model, even if the economic benefit is lower than that of private investments. This measure may be executed in conjunction with the creation of a local energy community, or the local council may choose to adopt only one of them.

Solar street lighting (a_3): The reconsideration of the execution of this action seems appropriate, and the allocation of public resources should be redirected towards other initiatives. For instance, replacing antiquated luminaires with new intelligent LED lighting to reduce electricity costs, as has already been done with some municipal streetlights.

96 https://icaen.gencat.cat/es/energia/ajuts/energies-renovables/ajuts-renovables-2022/index.html

The installation of solar luminaires may be considered for new projects requiring illumination, off-grid areas, or very specific applications.

Self-consumption in the water treatment plant (a_4): Nowadays, public organisations are tendering photovoltaic projects at competitive prices. Additionally, it is essential for public entities to serve as precedents and accelerate the completion of such investments. Accordingly, the responsible public agency is urged to install solar panels to cover the consumption of the plant, as it has previously done in other placements, within as little time as feasible. As this measure consists of only a single installation, it can be completed much before 2028.

Self-consumption in livestock farms (a_5): The livestock industry is very prominent in the country and also in the municipality of Rajadell. Due to farms being facilities with high energy consumption, the performance of a self-consumption installation is high. It is an advantageous moment for farmers to install solar panels on the roofs of their farms, given the existence of tax incentives. However, photovoltaic technology alone is insufficient to achieve the decarbonisation of this sector. Since thermal energy constitutes a major part of their overall energy consumption, renewable energy systems, such as solar thermal or biomass, have a relevant role. In addition, many farm roofs are old or cannot support the installation of solar panels, so they must be renovated before adopting a PV system. For this reason, the Catalan government has recently presented an initiative, funded by 40 million euros, to replace asbestos roofing on farms and install photovoltaic panels for self-use[97].

Solar-powered water pumping system (a_6): Agriculture, such as livestock farming, is of high relevance for the national and local economies. The sector is especially vulnerable to climate change and drought, and therefore, urgent solutions are needed. In this example, the impact of the proposed initiative is small. Larger installations, such as those shared by multiple farmers, increase the yield of the system and the value of the land, and they can sell a portion of the energy produced on the energy market. In a meeting with the municipal architect, the technician stated that there are more bureaucratic processes to legalise installations on rural land than those on roofs. In this area, it is suggested to speed up solar installation legalisation on rustic grounds to facilitate rural development.

Local energy community (a_7): This option is an efficient public-private system that has favourable outcomes in terms of self-consumption ratio, solar incidence, and financial criteria. As some municipalities have already done, it is recommended that the town council examine the best way to implement this action by 2026. It can be considered to cover only the buildings closest to the production point, such as the school, the library, and the sports field, allowing more neighbours to participate in the energy community. Then, solar panels could be installed on the roofs of the other buildings for individual use. A power capacity of 100 kW_p is considered adequate, as a higher power level implies many administrative procedures and permits that can impede the progress of the project.

97 https://web.gencat.cat/ca/actualitat/detall/Substituir-lamiant-per-plaques-solars

The participation of several individuals is complex, so it is needed to set well-defined and transparent conditions for inclusion. In general, it is important to improve the regulatory frameworks of energy communities and, above all, simplify the legalization process of these systems. In 2022, there was an extension of the maximum distance between self-consumption points and installations, increasing it from 500 metres to 2 kilometres. This enhancement is positive, but consideration should be given to further broadening the radius to benefit industries and rural populations.

Self-consumption in restaurants and rental houses (a_8): Photovoltaic energy investments provide lower energy costs, stable power pricing, and corporate sustainability. The competitive installation costs for enterprises result in favourable financial outcomes, and due to the current tax incentives, there is an opportune moment for enterprises to implement these systems. Current policies are recognised as advantageous for companies. It is recommended to complete these projects by 2028.

Solar-powered electric vehicle charging station (a_9): This measure is regarded as less urgent than others and is scheduled for 2040. The decarbonisation of transport presents many challenges, with only 0.26%[98] of the cars in Spain being electric. Apart from electric vehicle subsidies and the tax on gasoline, the EU proposed banning the sale of new petrol and diesel cars by 2035[99]. Consequently, the deployment of electric charging stations is indispensable. This proposed measure was intended to analyse the influence of photovoltaics on this area, but it seems to not be financially profitable. It is therefore proposed to install recharge stations without photovoltaic panels, and benefit from the existing subsidies. Public entities can also invest in these systems to foster distribution throughout the entire territory.

Utility-scale solar farm (a_{10}): The distribution of renewable energies in Spain, particularly wind and solar, is mainly concentrated in a few regions. In the region of Catalonia, where Rajadell is located, the renewable sector is not progressing as expected. While there has been a notable increase in the adoption of self-consumption systems, it remains insufficient to meet the energy demand. The deployment of solar energy throughout the territory is needed and must be balanced and structured. Many initiatives were paralysed by bureaucratic procedures and strong social opposition. It is proposed that policymakers develop a strategy to increase the social acceptability of these systems and streamline the permit procurement process. One approach may include engaging the municipalities affected in the implementation of these projects, reducing the environmental impact, providing more benefits to the population affected, and achieving an equilibrium between agricultural activities and solar farms.

98 https://www.newtral.es/coche-electrico-espana/20230404/

99 https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

6.3 Sensitivity and robustness concerns

On the one hand, sensitivity analysis concerns the alteration of discrimination threshold values. Changes in the credibility level influence the assignments made in both ascending and descending order. Indeed, an increase (decrease) in this parameter leads to a tendency to converge (diverge) of both assignment rules towards (away from) a category (M. A. Pereira & Marques, 2022). For this reason, it has been decided to run the model again with $\lambda = 0.65$ and $\lambda = 0.75$ to determine whether a ±0.05 variation in the credibility level affects xthe results. In Table 26, the variations in the attributed categories relative to the base scenario provided by the expert (where $\lambda = 0.70$) are highlighted in light grey. For a 0.05 decrease in the credibility level, there is a single variation in the upper range of a_2. For an increase of 0.05, there are variations in two intervals, with a_1 converging on C_3 and a_4 converging on C_2.

Table 26: Sensitivity analysis for the discrimination threshold.

	λ=0.65		λ=0.70		λ=0.75	
	Worst	**Best**	**Worst**	**Best**	**Worst**	**Best**
$\mathbf{a_1}$	C_2	C_3	C_2	C_3	C_3	C_3
$\mathbf{a_2}$	C_2	C_3	C_2	C_2	C_2	C_2
$\mathbf{a_4}$	C_2	C_3	C_2	C_3	C_2	C_2

On the other hand, robustness analysis consists of the creation of several scenarios distinct from the original setting. This can be accomplished by varying the criteria parameters. It has been analysed three scenarios in relation to the DCM-SRF procedure, focusing on the number of blank cards and the z ratio (M. A. Pereira & Marques, 2022). First, referred to as "scenario one," in light of the inherent uncertainty associated with the placement of blank cards, it has been established that no blank cards have been inserted between levels. Second, two scenarios have been created to examine the impact of the ratio z, which influences the criteria weights. In scenario two, z is set to 5, whereas in scenario three, z is set to 15. Table 27 shows the modifications in the weights associated with each scenario that were included in the MCDA-ULaval software while maintaining the other parameters unchanged.

Table 27: Robustness analysis for the weights

Scenario	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
w_j	8.06	15.83	10.65	5.46	1.58	8.06	10.65	10.65	14.53	14.53
1	7.85	17.07	10.92	4.78	1.71	7.85	10.92	10.92	13.99	13.99
2	8.38	14.85	10.55	6.21	2.97	8.38	10.55	10.55	13.78	13.78
3	7.94	16.17	10.69	5.20	1.08	7.94	10.69	10.69	14.80	14.80

The stability of the criterion weights is clear since any modifications resulting from changes in the number of blank cards and the ratio z. The analysis of the model's behaviour under various credibility indexes and weight ponderations revealed that the findings were generally solid and exhibited few deviations when compared to the first version of the model.

7. Conclusions

7.1 Achievements

The main objective of this dissertation was to assess various initiatives related to solar photovoltaic energy aimed at reducing emissions in municipalities. This evaluation included different types of installations, areas, and investors. As far as could be determined at the time this dissertation was written, the use of ELECTRE Tri-nC in the assessment of photovoltaic installations for local energy policymaking, particularly in Spain, had not been previously explored. Since an MCDA project had never been completed within the scope and objectives of this study, a knowledge gap was identified.

At the beginning of the study, a literature review was conducted to examine the current state of the art related to renewable energies. Among the different technologies available, the application of photovoltaic energy was selected. The study reviewed the fundamentals of photovoltaic systems alongside the current Spanish energy system and the regulations governing solar energy in the country.

Research was carried out on the technique of MCDA and its application in the energy sector, and more specifically, in solar energy. From all the methods analysed, the ELECTRE Tri-nC method was chosen. The foundations of the ELECTRE Tri-nC technique, its parameters and its assumptions were presented.

The methodology was applied to the Spanish municipality of Rajadell. The implementation of the model was co-developed through interactive engagement between the analyst and an expert in the photovoltaics market. The use of preference and indifference thresholds addressed the issue of imperfect knowledge and uncertainty, yielding more accurate results. The inclusion of veto thresholds introduced non-compensatory considerations. The technique allowed for greater flexibility and permitted the assignment of several categories to each action.

Finally, the results were analysed and discussed, some policy recommendations were formulated, and a sensitivity analysis was conducted. 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, but 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.

In the end, it becomes essential to perform an evaluation of each of the objectives set for each section of the project to determine whether they have been successfully attained. Therefore:

- Chapter 1: The problem was identified and described.
- Chapter 2: A comprehensive overview of current renewable energies and a literature review on MCDA applied to the energy sector were developed. A knowledge gap was identified.
- Chapter 3: The study on photovoltaic technology, its relevance, and regulation in the Spanish energy context has been addressed.
- Chapter 4: The multi-criteria problem has been analysed and verified. In particular, the ELECTRE technique has been explored in greater depth.
- Chapter 5: The methodology was applied to the Spanish municipality of Rajadell. Each alternative was evaluated according to the defined criteria.
- Chapter 6: The results were analysed and discussed. A sensitivity analysis and recommendations for policymakers were provided.

7.2 Limitations and future work

The identification of the limitations of the current research and the discussion of possible future work are essential.

Firstly, the model developed has been evaluated in a Spanish municipality, and therefore, the context and regulations of this country were considered. Nevertheless, 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.

Secondly, the ELECTRE Tri-nC approach involves many stages that rely on the knowledge of the experts. This project included the participation of one engineer expert in the renewable energy and photovoltaic sectors. Due to the fact that only the knowledge of an expert was considered, there is a potential bias. Considering the multidimensional character of the topic, it is recommended that further research include the formation of a diverse focus group and the participation of policy decision-makers, as they will provide different viewpoints and perspectives.

Thirdly, the amount of time available for interaction and conversation with the expert was restricted, which limited his ability to fully use his knowledge and expertise.

Lastly, the evaluation of the alternatives based on the selected criteria was not exactly in line with reality since some approximations were made due to a lack of data. Nonetheless, all simplifications are duly justified.

7.3 Personal assessment

My motivation for undertaking this dissertation arose from a strong desire to contribute to the advancement of renewable energies and, by extension, to the huge challenges of energy transition and climate change. I believe I have been able to apply my knowledge and experience to this project.

This work has also been a challenge for me. Using a subject that I had never studied before, such as multi-criteria decision-making, I was provided with opportunities for intellectual growth and development, as well as a significant improvement in my ability to conduct comprehensive literature reviews and critically analyse academic papers. The complexities of the new research topic, the limited time, and the inherent uncertainties and setbacks of the research process led to moments of self-doubt. Nevertheless, this dissertation has been a greatly rewarding experience. Moreover, being able to apply the model to my hometown, Rajadell, has continuously motivated me to seek out the best solutions.

In conclusion, I believe that the following factors contributed to the success of this work: my knowledge of photovoltaics, my interest in energy policy formulation, my esteem for my village, and the challenge of the unknown.

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Appendix A

A.1 Evaluation of alternatives based on the criteria selected.

A.1.1 Evaluation of a_1 based on the criteria selected.

ALTERNATIVE 1

kWh / kWp ratio		
South (0º)	20%	1352.98
Southeast (-35º)	30%	1317.4
Southwest (35º)	30%	1327.48
East-Southeast (-70º)	10%	1233.26
West-Southwest (70º)	10%	1248.07

Values obtained from PVGIS

Data			
Concept	Value	Units	
Module Power	415	Wp	
Modules per installation	10	modules	
Installation DC Power	4.15	kWp	
Total DC Power	859.05	kWp	
kWh / kWp	1312.19	kWh / kWp	
PV Power Loss	0.55%	-	
% Self-Consumption	50%	-	
Cost / Wp	2.05	EUR / Wp	
Installation Cost	1761052.5	EUR	
Surplus compensation	0.1	EUR / kWh	
Average electricity tariff	0.25621	EUR / kWh	
Inflation	1.50%	-	
Grid CO2 equivalent	259	CO2 eq / kWh	
IBI	400	EUR / year	
Houses	207	houses	
IBI bonification	50%	-	*During 5 years*

Concept	Value	Units
Annual CO2 avoided	273.47	*t CO2 eq*
Payback	7.58	*years*
Interest Rate	10%	-
NPV	307933.07	€
Lifespan	25	*years*
EAA	33924.39	€

Calculations		Year 0	1	2	3	4	5	6	7	8
Energy Generated	*kWh*		1127239	1121039.58	1114874	1108742.056	1102644	1096679.433	1090548.246	1084560.231
Energy Self-Consumed	*kWh*		563619.7	560519.79	557436.9	554371.028	551321.99	548289.7164	545274.123	542275.1153
Energy pushed into the grid	*kWh*		563619.7	560519.79	557436.9	554371.028	551321.99	548289.7164	545274.123	542275.1153
Current retail price	*EUR / kWh*		0.25621	0.26005315	0.263954	0.267913256	0.271932	0.276010936	0.280151099	0.284353365
Current price paid by the grid	*EUR / kWh*		0.1	0.1015	0.103023	0.104567838	0.1061364	0.1077284	0.109344326	0.110984491
Investment Analysis										
Savings self consumption	*EUR*		144405	146764.937	147137.7	148623.3474	149922.07	151333.9571	152759.1446	154197.7539
Revenue Grid	*EUR*		56361.97	56892.75868	57428.56	57969.37957	58515.306	59066.3741	59622.63168	60184.12781
Total Revenue	*EUR*		200767	202657.6957	204566.2	206492.727	208437.37	210400.3312	212381.7763	214381.8817
Savings on IBI	*EUR*		41400	41400	41400	41400	41400			
Maintenance	*EUR*		-1761.05	-1787.46829	-1814.28	-1841.494516	-1869.1169	-1897.153688	-1925.610994	-1954.495158
Inverter replacement	*EUR*									
CF	*EUR*		240405.9	242270.2274	244151.9	246051.2325	247968.26	208503.1775	210456.1663	212427.3866
Investment Cost	*EUR*	-1761052.5								
Cumulative CF	*EUR*		-1520647	-1278376.36	-1034224	-788173.1756	-540204.92	-331701.7428	-121245.5775	91181.80899
CO2 saved	*g CO2 eq*		2.92E+08	290349251.2	2.89E+08	287164192.5	285584789	284014073.1	282451995.7	280898509.7

Calculations		9	10	11	12	13	14	15	16	17
Energy Generated	*kWh*	1078586.204	1072652.986	1066753.394	1060886.251	1055051.38	1049248.594	1043477.726	1037738.599	1032031.037
Energy Self-Consumed	*kWh*	539292.6022	536326.4929	533376.6972	530443.1253	527525.688	524624.2969	521738.8632	518869.2995	516015.5183
Energy pushed into the grid	*kWh*	539292.6022	536326.4929	533376.6972	530443.1253	527525.688	524624.2969	521738.8632	518869.2995	516015.5183
Current retail price	*EUR / kWh*	0.288618666	0.292947946	0.297342165	0.301802297	0.30632933	0.310924272	0.315588136	0.320321958	0.325126787
Current price paid by the grid	*EUR / kWh*	0.112649259	0.114338998	0.116054083	0.117794894	0.11956182	0.121356244	0.123175673	0.125023207	0.126898555
Investment Analysis										
Savings self consumption	*EUR*	155649.9112	157115.7443	158596.3818	160088.9538	161596.592	163118.4274	164654.5952	166205.2298	167770.4676
Revenue Grid	*EUR*	60750.91184	61323.03365	61900.54322	62483.49158	63071.9299	63665.90976	64265.48347	64870.70366	65481.62351
Total Revenue	*EUR*	216400.8231	218438.7778	220496.925	222572.4454	224668.521	226784.3372	228920.0787	231075.9335	233252.0911
Savings on IBI	*EUR*									
Maintenance	*EUR*	-1983.812586	-2013.569775	-2043.773321	-2074.429921	-2105.5464	-2137.129565	-2169.186509	-2201.724307	-2234.75017
Inverter replacement	*EUR*						-105663.15			
CF	*EUR*	214417.0105	216425.208	218452.1517	220498.0154	222562.975	118984.0576	226750.8922	228874.2092	231017.3409
Investment Cost	*EUR*									
Cumulative CF	*EUR*	305598.8195	522024.0275	740476.1792	960974.1946	1183537.17	1302521.227	1529272.119	1758146.329	1989163.67
CO2 saved	*g CO2 eq*	279353567.9	277817123.3	276289129.1	274769538.9	273258306	271756386.8	270260731.1	268774297.1	267296038.5

Calculations		18	19	20	21	22	23	24	25
Energy Generated	*kWh*	1026354.866	1020709.914	1015096.01	1009512.98	1003960.66	998438.8766	992947.4628	987486.2517
Energy Self-Consumed	*kWh*	513177.433	510354.9571	507548.0048	504756.491	501980.3301	499219.4383	496473.7314	493743.1259
Energy pushed into the grid	*kWh*	513177.433	510354.9571	507548.0048	504756.491	501980.3301	499219.4383	496473.7314	493743.1259
Current retail price	*EUR / kWh*	0.330003689	0.334953744	0.33997805	0.34507772	0.350253887	0.355507696	0.360840311	0.366252915
Current price paid by the grid	*EUR / kWh*	0.128802033	0.130734064	0.132695075	0.1346856	0.136705783	0.13875637	0.140837715	0.142950281
Investment Analysis									
Savings self consumption	*EUR*	169350.446	170946.3038	172556.1812	174180.22	175820.5618	177476.352	179147.7356	180834.8593
Revenue Grid	*EUR*	66098.2967	66720.77741	67349.12033	67983.3807	68623.61416	69269.87705	69922.22611	70580.71868
Total Revenue	*EUR*	235448.7427	237666.0812	239904.3015	242163.6	244444.176	246746.229	249069.9616	251415.578
Savings on IBI	*EUR*								
Maintenance	*EUR*	-2268.271424	-2302.2956	-2336.829928	-2371.88238	-2407.460612	-2443.572521	-2480.226109	-2517.429501
Inverter replacement	*EUR*								
CF	*EUR*	233180.4713	235363.7857	237567.4716	239791.718	242036.7154	244302.6565	246589.7355	248898.1486
Investment Cost	*EUR*								
Cumulative CF	*EUR*	2222344.141	2457707.926	2695275.398	2935067.12	3177103.831	3421406.488	3667996.223	3916894.372
CO2 saved	*g CO2 eq*	265825910.3	264363867.8	262909866.5	261463862	260025811	258595669	257173392.9	255758939.2

A.1.2 Evaluation of a_2 based on the criteria selected.

ALTERNATIVE 2

Data		
Concept	**Value**	**Units**
Module Power	415	Wp
PV Power Loss	0.55%	-
Average electricity tariff	0.25621	EUR/kWh
Inflation	1.50%	-
Surplus compensation	0.1	EUR / kWh
Total DC Power	50.215	kWp
Cost / Wp	**1.88**	EUR / Wp
kWh / kWp	**1280.62**	kWh / kWp
Grid CO2 equivalent	259	g CO2 eq / kWh

		Electricity Consumption													
		January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Novembe**	**December**	**Total**	**%**
Town Hall	kWh	1109.12	820.87	1166.40	982.26	564.57	1616.49	1849.50	1250.10	816.75	1034.37	1080.81	1166.40	13457.64	27%
Medical Centre	kWh	369.71	273.62	388.80	327.42	188.19	538.83	616.50	416.70	272.25	344.79	360.27	388.80	4485.88	9%
Train Station - Tourist Office	kWh	492.94	364.83	518.40	436.56	250.92	718.44	822.00	555.60	363.00	459.72	480.36	518.40	5981.17	12%
School - Library - Sports Field	kWh	1314.51	972.88	1382.40	1164.16	669.12	1915.84	2192.00	1481.60	968.00	1225.92	1280.96	1382.40	15949.79	32%
Cultural Centre	kWh	821.57	608.05	864.00	727.60	418.20	1197.40	1370.00	926.00	605.00	766.20	800.60	864.00	9968.62	20%
Total	kWh	4108	3040	4320	3638	2091	5987	6850	4630	3025	3831	4003	4320	49843	100%

	kWp	**kWh/kWp**	**kWh Generated**	**Self-Use**	**kWh consumed**	**Cost EUR**
Town Hall	6.225	1213.81	7555.97	85%	6422.57	12325.50
Medical Office	4.980	1214.54	6048.41	45%	2721.78	9860.40
Train Station - Tourist Office	6.640	1304.92	8664.69	40%	3465.88	13147.20
School & Library	21.580	1316.65	28413.31	40%	11365.32	38628.20
Cultural Space	10.790	1262.63	13623.78	45%	6130.70	20393.10

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Concept	**Value**	**Units**
Payback	**8.26**	years
Interest Rate	10%	-
NPV	11763.87	EUR
Lifespan	25	years
EAA	**1296.00**	EUR
Annual C02 avoidec	**15.60**	t CO2 eq

		Year								
Calculations		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Energy Generated	kWh		64306.15	63952.47	63600.73	63250.92	62903.04	62557.08	62213.01	61870.84
Energy Self-Consumed	kWh		30106.25	29940.67	29776.00	29612.23	29449.36	29287.39	29126.31	28966.11
Energy pushed into the grid	kWh		34199.90	34011.80	33824.73	33638.70	33453.68	33269.69	33086.70	32904.73
Current retail price	EUR/kWh		0.25621	0.2600532	0.2639539	0.267913256	0.271932	0.276010935	0.280151099	0.28435337
Current price paid by the grid	EUR/kWh		0.1	0.1015	0.1030225	0.104567838	0.106136	0.1077284	0.109344326	0.11098449
Investment Analysis										
Savings self consumption	EUR		7713.5236	7786.1657	7859.4919	7933.508653	8008.222	8083.639906	8159.767585	8236.6122
Revenue Grid	EUR		3419.9896	3452.1973	3484.7084	3517.525643	3550.652	3584.090205	3617.843375	3651.91441
Total Revenue	EUR		11133.513	11238.363	11344.2	11451.0343	11558.87	11667.73011	11777.61096	11888.5266
Maintenance	EUR		-94.3544	-95.76972	-97.20626	-98.66435567	-100.144	-101.6464858	-103.1711831	-104.718751
Inverter replacement	EUR									
CF			11039.159	11142.593	11246.994	11352.36994	11458.73	11566.08363	11674.43978	11783.8079
Investment Cost	EUR	-94354.40								
Cumulative CF			-83315.24	-72172.65	-60925.65	-49573.28	-38114.55	-26548.47	-14874.03	-3090.22
CO2 saved	g CO2 eq		16655293	16563689	16472589	16381989.39	16291888	16202283.06	16113170.51	16024548.1

		Year								
Calculations		**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Energy Generated	kWh	61530.55	61192.13	60855.58	60520.87	60188.01	59856.97	59527.76	59200.36	58874.76
Energy Self-Consumed	kWh	28806.80	28648.36	28490.80	28334.10	28178.26	28023.28	27869.15	27715.87	27563.43
Energy pushed into the grid	kWh	32723.75	32543.77	32364.78	32186.77	32009.75	31833.69	31658.61	31484.49	31311.32
Current retail price	EUR/kWh	0.288618666	0.292947946	0.2973422	0.301802297	0.306329332	0.31092427	0.3155881	0.320322	0.325126787
Current price paid by the grid	EUR/kWh	0.112649259	0.114338998	0.1160541	0.117794894	0.119561817	0.12135524	0.1231756	0.125023	0.126898555
Investment Analysis										
Savings self consumption	EUR	8314.180491	8392.479286	8471.5155	8551.295957	8631.827786	8713.11802	8795.1738	8878.002	8961.61095
Revenue Grid	EUR	3686.306319	3721.022109	3756.0648	3791.437575	3827.143438	3863.18556	3899.5671	3936.291	3973.361308
Total Revenue	EUR	12000.48681	12113.50139	12227.58	12342.73353	12458.97122	12576.3036	12694.741	12814.29	12934.97226
Maintenance	EUR	-106.2895321	-107.8838751	-109.5021	-111.144665	-112.811835	-114.50401	-116.2216	-117.9649	-119.73437
Inverter replacement	EUR						-5661.264			
CF		11894.19728	12005.61752	12118.078	12231.58887	12346.15939	6800.53557	12578.519	12696.33	12815.23789
Investment Cost	EUR									
Cumulative CF		8803.97	20809.59	32927.67	45159.26	57505.42	64305.95	76884.47	89580.80	102396.04
CO2 saved	g CO2 eq	15936413.06	15848762.78	15761595	15674905.82	15588693.84	15502956	15417690	15332892	15248561.56

		Year							
Calculations		**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Energy Generated	kWh	58550.94	58228.91	57908.65	57590.16	57273.41	56958.41	56645.14	56333.59
Energy Self-Consumed	kWh	27411.84	27261.07	27111.13	26962.02	26813.73	26666.26	26519.59	26373.73
Energy pushed into the grid	kWh	31139.11	30967.84	30797.52	30628.13	30459.68	30292.15	30125.54	29959.85
Current retail price	EUR/kWh	0.330003689	0.3349537	0.3399781	0.345077721	0.350253887	0.355507695	0.360840311	0.366252915
Current price paid by the grid	EUR/kWh	0.128802033	0.1307341	0.1326951	0.134685501	0.136705783	0.13875637	0.140837715	0.142950281
Investment Analysis									
Savings self consumption	EUR	9046.006921	9131.1977	9217.1907	9303.993639	9391.614	9480.059524	9569.337985	9659.457225
Revenue Grid	EUR	4010.780438	4048.552	4086.6792	4125.165502	4164.014248	4203.228853	4242.81276	4282.76945
Total Revenue	EUR	13056.78736	13179.75	13303.87	13429.15914	13555.62825	13683.28838	13812.15075	13942.22667
Maintenance	EUR	-121.530386	-123.35334	-125.2036	-127.081696	-128.987921	-130.92274	-132.886581	-134.87988
Inverter replacement	EUR								
CF		12935.25697	13056.396	13178.666	13302.07745	13426.64033	13552.36564	13679.26416	13807.34679
Investment Cost	EUR								
Cumulative CF		115331.30	128387.69	141566.36	154868.44	168295.08	181847.44	195526.71	209334.05
CO2 saved	g CO2 eq	15164694.47	15081289	14998342	14915850.69	14833813.51	14752227.53	14671090.28	14590399.28

A.1.3 Evaluation of a_3 based on the criteria selected.

ALTERNATIVE 3

Data		
Concept	**Value**	**Units**
Luminaire Power *	50	*W*
Module Power	150	*Wp*
Total Power	46.5	*kWp*
Operating hours	12	*h/ day*
Montlhy Energy	18600	*Wh*
Monthly Energy Consumption	5758	*kWh*
Luminaires needed	310	*Luminaires*
Luminaire Unit Cost	1309.83	*EUR*
Investment Cost	446652.03	*EUR*
Annual Cost of Street Lighting	30250	*EUR*
Inflation	1.50%	-
Grid CO2 equivalent	259	g CO2 eq / kWh
Cost / Wp	**9.61**	*EUR / Wp*
kWh / kWp	**1531.39**	*kWh / kWp*

Plus 10% for the reeplacement task

Concept	Value	Units
Annual CO2 avoided	**17.90**	*t CO2 eq*
Payback	**17.21**	*years*
Interest Rate	10%	-
NPV	-216809.91	*EUR*
Lifespan	20	*years*
EAA	**-25466.41**	*EUR*

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Investment analysis		Year 0	1	2	3	4	5	6	7	8	9	10
Costs Saved	*EUR*		30250	30703.75	31164.306	31631.77084	32106.24741	32587.84112	33076.66	33572.81	34076.4	34587.55
LED and battery replacement	*EUR*											-142117
CF	*EUR*		30250	30703.75	31164.306	31631.77084	32106.24741	32587.84112	33076.66	33572.81	34076.4	-107529
Invesment Cost	*EUR*	-446652.03										
Cumulative CF	*EUR*		-416402	-385698	-354534	-322902.2029	-290795.9555	-258208.1144	-225131	-191559	-157482	-265011
CO2 saved	g CO2 eq / kWh		17895864	17895864	17895864	17895864	17895864	17895864	17895864	17895864	17895864	17895864

Investment analysis		Year 11	12	13	14	15	16	17	18	19	20
Costs Saved	*EUR*	35106.36	35632.96	36167.45	36709.96	37260.6	37819.5	38386.8	38962.6	39547.1	40140.3
LED and battery replacement	*EUR*										
CF	*EUR*	35106.36	35632.96	36167.45	36709.96	37260.6	37819.5	38386.8	38962.6	39547.1	40140.3
Invesment Cost	*EUR*										
Cumulative CF	*EUR*	-229905	-194272	-158104	-121395	-84133.9	-46314.4	-7927.58	31035	70582.1	110722
CO2 saved	g CO2 eq / kWh	17895864	17895864	17895864	17895864	1.8E+07	1.8E+07	1.8E+07	1.8E+07	1.8E+07	1.8E+07

A.1.4 Evaluation of a_4 based on the criteria selected.

ALTERNATIVE 4		
Data		
Concept	**Value**	**Units**
Module Power	415	*Wp*
Modules	102	*Modules*
DC Power	42.33	*kWp*
kWh/kWp Ratio	**1214.48**	*kWh/kWp*
PV Power Loss	0.55%	-
% Self-Consumption	100%	-
Cost (including VAT)	73230.9	*EUR*
Average electricity price	0.25621	*EUR/kWh*
Inflation	1.50%	-
Grid CO2 equivalent	259	*g CO2 eq / kWh*
Cost / Wp	**1.73**	*EUR / Wp*

Concept	Value	Units
Annual CO2 avoided	**12.47**	*t CO2 eq*
Payback	**5.48**	*years*
Interest Rate	10%	-
NPV	53309.99	*€*
Lifespan	25	*years*
EAA	**5873.06**	*€*

		Year												
Calculations		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Energy Generated	*kWh*		51408.94	51126.189	50844.995	50565.348	50287.238	50010.6585	49735.6	49462.054	49190.013	48919.468	48650.4	48382.833
Energy Self-Consumed	*kWh*		51408.94	51126.189	50844.995	50565.348	50287.238	50010.6585	49735.6	49462.054	49190.013	48919.468	48650.4	48382.833
Current retail price	*EUR / kWh*		0.25621	0.2600532	0.2639539	0.2679133	0.271932	0.27601093	0.2801511	0.2843534	0.2886187	0.2929479	0.29734	0.3018023
Investment analysis														
Savings self consumption	*EUR*		13171.48	13295.527	13420.737	13547.127	13674.707	13803.4886	13933.483	14064.702	14197.156	14330.858	14465.8	14602.05
Maintenance	*EUR*		-73.2309	-74.32936	-75.4443	-76.57597	-77.72461	-78.890477	-80.07383	-81.27494	-82.49407	-83.73148	-84.987	-86.26226
Inverter replacement														
CF	*EUR*		13098.25	13221.197	13345.293	13470.551	13596.982	13724.5981	13853.409	13983.427	14114.662	14247.126	14380.8	14515.788
Investment Cost	*EUR*	-73230.9												
Cumulative CF	*EUR*		-60132.6	-46911.45	-33566.16	-20095.61	-6498.623	7225.97483	21079.384	35062.811	49177.472	63424.598	77805.4	92321.217
CO2 saved (g CO2)	*g CO2 eq*		13314915	13241683	13168854	13096425	13024395	12952760.6	12881520	12810672	12740213	12670142	1.3E+07	12531154

		Year												
Calculations		**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Energy Generated	*kWh*	48116.728	47852.086	47588.899	47327.16	47066.861	46807.993	46550.549	46294.5213	46039.901	45786.682	45534.855	45284.413	45035
Energy Self-Consumed	*kWh*	48116.728	47852.086	47588.899	47327.16	47066.861	46807.993	46550.549	46294.5213	46039.901	45786.682	45534.855	45284.413	45035
Current retail price	*EUR / kWh*	0.3063293	0.3109243	0.3155881	0.320322	0.3251268	0.3300037	0.3349537	0.33997805	0.3450777	0.3502539	0.3555077	0.3608403	0.3663
Investment analysis														
Savings self consumption	*EUR*	14739.565	14878.375	15018.492	15159.929	15302.697	15446.81	15592.281	15739.1211	15887.344	16036.963	16187.991	16340.442	16494
Maintenance	*EUR*	-87.55619	-88.86954	-90.20258	-91.55562	-92.92895	-94.32289	-95.73773	-97.173797	-98.6314	-100.1109	-101.6125	-103.1367	-104.7
Inverter replacement			-4393.854											
CF	*EUR*	14652.009	10395.651	14928.289	15068.373	15209.768	15352.488	15496.543	15641.9473	15788.713	15936.852	16086.379	16237.305	16390
Investment Cost	*EUR*													
Cumulative CF	*EUR*	106973.23	117368.88	132297.17	147365.54	162575.31	177927.8	193424.34	209066.286	224855	240791.85	256878.23	273115.54	289505
CO2 saved (g CO2)	*g CO2 eq*	12462232	12393690	12325525	12257735	12190317	12123270	12056592	11990281	11924334	11858751	11793527	11728663	1E+07

A.1.5 Evaluation of a_5 based on the criteria selected.

ALTERNATIVE 5

Data		
Concept	Value	Units
kWh / kWp	1310.3	kWh/kWp
% Self-consumption	95%	-
Module Power	415	Wp
Total DC Power	70.17	kWp
Cost / Wp	1.69	EUR / Wp
Installation Cost	118886	
Surplus compensation	0.1	EUR / kWh
Average electricity tariff	0.21174	EUR / kWh
Inflation	1.50%	-
Grid CO2 equivalent	259	g CO2 eq / kWh
IBI	550	EUR
Farms	6	farms
IBI bonification	50%	-
PV Power Loss	0.55%	-

	Farms Data					
	Number	Units	kWh per unit		kWh annual	
Poultry Farm	282386	kg	0.0921	kWh / kg	26007.71	kWh
Porcine	3007	animals	7.8000	kWh / animal	23454.60	kWh

Concept	Value	Units
Annual CO2 avoidec	22.31	t CO2 eq
Payback	5.69	years
Interest Rate	10%	-
NPV	69121.66	€
Lifespan	25	years
EAA	7615.00	€

		Month												
		January	February	March	April	May	June	July	August	ieptembe	October	Novembe	December	
	% electricity	8%	8%	7%	7%	7%	10%	11%	10%	8%	8%	8%	8%	
Consumption	Poultry Farm	2081	2080.6	1820.54	1820.54	1820.539963	2600.77	2860.85	2600.77	2080.62	2080.62	2080.62	2080.62	kWh
	Porcine	1876	1876.4	1641.82	1641.82	1641.822	2345.46	2580.01	2345.46	1876.37	1876.37	1876.37	1876.37	kWh
Production	Poultry Farm	62.04	78.1	112.86	126.32	149.63	155.74	163.15	143.8	111.98	86.65	63.64	56.39	kWh
Data from PVGIS	Porcine	62.04	78.1	112.86	126.32	149.63	155.74	163.15	143.8	111.98	86.65	63.64	56.39	kWh
kWp	Poultry Farm	33.54	26.64	16.13	14.41	12.17	16.70	17.54	18.09	18.58	24.01	32.69	36.90	kWp
	Porcine	30.24	24.03	14.55	13.00	10.97	15.06	15.81	16.31	16.76	21.65	29.48	33.27	kWp

Year														
Calculations		0	1	2	3	4	5	6	7	8	9	10	11	12
Energy Generated	kWh		91946.05	91440.34	90937.42	90437.27	89939.86	######	#######	88464.00	87977.45	87493.57	87012.36	86533.79
Energy Self-Consumed	kWh		87348.744	86868.33	86390.6	85915.4	85442.868	84973	84505.6	84040.8	83578.58	83118.89364	82661.74	82207.1
Energy pushed into the grid	kWh		4597.30	4572.02	4546.87	4521.86	4496.99	4472.26	4447.66	4423.20	4398.87	4374.68	4350.62	4326.69
Current retail price	€ / kWh		0.21174	0.214916	0.21814	0.221412	0.2247331	0.2281	0.23153	0.234999	0.238524	0.242101393	0.245733	0.249419
Current price paid by the grid	€ / kWh		0.1	0.1015	0.10302	0.104568	0.1061364	0.1077	0.10934	0.110984	0.112649	0.114338998	0.116054	0.117795
Investment Analysis														
Savings self consumption	EUR		18495.223	18669.4	18845.2	19022.7	19201.842	19383	19565.2	19749.47	19935.46	20123.19997	20312.71	20504.01
Revenue Grid	EUR		459.73023	464.0597	468.43	472.8415	477.29445	481.79	486.327	490.9066	495.5297	500.1963671	504.907	509.6619
Total Revenue	EUR		18954.953	19133.46	19313.7	19495.54	19679.137	19864	20051.5	20240.37	20430.99	20623.39633	20817.62	21013.67
Savings on IBI	EUR		1650	1650	1650	1650	1650							
Maintenance	EUR		-118.886	-120.669	-122.48	-124.317	-126.1813	-128.1	-130	-131.945	-133.924	-135.9330907	-137.972	-140.042
Inverter replacement	EUR													
CF	EUR		20486.067	20662.79	20841.2	21021.22	21202.955	19736	19921.5	20108.43	20297.06	20487.46324	20679.65	20873.63
Investment Cost	EUR	-118886.03												
Cumulative CF	EUR		-98400.0	-77737.2	-56896.0	-35874.8	-14671.8	5064.6	24986.1	45094.5	65391.6	85879.1	106558.7	127432.3
CO2 saved	g CO2 eq		23814026	23683049	2.4E+07	23423252	23294424	2E+07	2.3E+07	22912176	22786159	22660835.21	22536201	22412252

Year														
Calculations		13	14	15	16	17	18	19	20	21	22	23	24	25
Energy Generated	kWh	86057.85	85584.54	85113.82	84645.69	84180.14	83717.15	83256.71	82798.80	82343.40	81890.51	81440.12	80992.20	80546.74
Energy Self-Consumed	kWh	81754.96	81305.31	80858.13	80413.41	79971.14	79531.29	79093.9	78658.86	78226.23	77795.988	77368.1106	76942.59	76519.4
Energy pushed into the grid	kWh	4302.89	4279.23	4255.69	4232.28	4209.01	4185.86	4162.84	4139.94	4117.17	4094.53	4072.01	4049.61	4027.34
Current retail price	€ / kWh	0.25316	0.256958	0.260812	0.264724	0.268695	0.272725	0.27682	0.280969	0.285183	0.2894608	0.29380274	0.29821	0.302683
Current price paid by the grid	€ / kWh	0.119562	0.121355	0.123176	0.125023	0.126899	0.128802	0.13073	0.132695	0.134686	0.1367058	0.13875637	0.140838	0.14295
Investment Analysis														
Savings self consumption	EUR	20697.1	20892.02	21088.77	21287.37	21487.84	21690.21	21894.5	22100.66	22308.8	22518.891	22730.9627	22945.03	23161.12
Revenue Grid	EUR	514.4617	519.3066	524.1972	529.1338	534.1169	539.147	544.224	549.3496	554.5231	559.74534	565.016746	570.3378	575.7089
Total Revenue	EUR	21211.56	21411.32	21612.96	21816.5	22021.96	22229.35	22438.7	22650.01	22863.32	23078.636	23295.9794	23515.37	23736.83
Savings on IBI	EUR													
Maintenance	EUR	-142.142	-144.274	-146.439	-148.635	-150.865	-153.128	-155.42	-157.756	-160.122	-162.5241	-164.96193	-167.436	-169.948
Inverter replacement	EUR		-7133.16											
CF	EUR	21069.42	14133.89	21466.53	21667.87	21871.1	22076.23	22283.3	22492.26	22703.2	22916.112	23131.0175	23347.93	23566.88
Investment Cost	EUR													
Cumulative CF	EUR	148501.8	162635.6	184102.2	205770.0	227641.1	249717.4	272000.6	294492.9	317196.1	340112.2	363243.2	386591.2	410158.0
CO2 saved	g CO2 eq	22288984	22166395	22044480	21923235	21802657	21682743	2.2E+07	21444888	21326941	21209643	21092990.1	20976979	20861605

A.1.6 Evaluation of a_6 based on the criteria selected.

ALTERNATIVE 6

Data		
Concept	**Value**	**Units**
DC Power	13.695	kWp
kWh/kWp Ratio	**1983.58**	kWh/kWp
PV Power Loss	0.55%	-
Electricity Tariff	0.21174	EUR / kWh
Capacity	10700	m3
Water Pumps	3	-
Power (Pump)	2.2	kW
Water Flow	5	m3 / h
Cost PV system	2.06	EUR / Wp
Installation Cost	32731.25	EUR
Inflation	1.50%	-
Grid CO2 equivalent	259	g CO2 eq / kWh
Cost / Wp	**2.39**	EUR / Wp
Other savings	0.6803296	EUR / day

Pumping details		
Month	**HSP**	**m3**
January	118.89	-
February	135.75	-
March	172.56	-
April	177.27	2659.05
May	202.97	3044.55
June	209.96	3149.4
July	225.96	3389.4
August	203.39	3050.85
Septembe	165.18	No need
October	138.7	-
November	117.7	-
December	115.23	-

Data from PVGIS

Control items			
Item	**Power**	**Quantity**	**Unit price**
Variable-frequency drive	3kW	3	1005.631
Installation costs	-	1	1297

Concept	Value	Units
Annual CO2 avoided	**4.84**	t CO2 eq
Payback	**7.67**	years
Interest Rate	10%	-
NPV	6928.59	/
Lifespan	25	years
EAA	**763.31**	/

Calculations	Units	January	February	March	April	May	June	July	August	eptembe	October	November	December	Total
Energy Generated	kWh	1628.19855	1859.096	2363.2092	1169.98	1339.602	1385.736	1491.336	1342.374	2262.1	1899.497	1611.902	1578.075	19931.15
Electricity Tariff	EUR / kWh	0.220605	0.216195	0.309225	0.21315	0.20559	0.213465	0.227325	0.26334	0.227	0.16905	0.13881	0.15309	0.212
Energy savings	EUR	359.1887411	401.9273	730.76336	249.382	275.4088	295.8061	339.018	353.5008	513.53	321.1099	223.748	241.5875	4304.969
Other savings	EUR	21.0902176	19.04923	21.090218	20.4099	21.09022	20.40989	21.09022	21.09022	20.41	21.09022	20.40989	21.09022	248.3203

		Year								
Investment Analysis	Units	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Energy Generated	kWh		19931.15	19821.526	19712.5	19604.09	19496.27	19389.04	19282.4	19176
Electricity Tariff	EUR / kWh		0.21174	0.2149161	0.21814	0.221412	0.224733	0.228104	0.231526	0.235
Other savings	EUR		248.3203	252.04511	255.826	259.6632	263.5581	267.5115	271.5242	275.6
Energy Savings	EUR		4220.221	4259.965	4300.08	4340.579	4381.457	4422.719	4464.37	4506.4
Total savings	EUR		4468.541	4512.0101	4555.91	4600.242	4645.015	4690.231	4735.894	4782
OPEX	EUR		-327.313	-332.2222	-337.21	-342.264	-347.398	-352.609	-357.898	-363.27
Replacement	EUR									
CF	EUR		4141.229	4179.7879	4218.7	4257.979	4297.617	4337.622	4377.996	4418.7
Investment Cost		-32731.25								
Cumulative CF		-32731.25	-28590.03	-24410.24	-20191.53	-15933.56	-11635.94	-7298.32	-2920.32	1498.42
CO2 saved	g CO2 eq		5162167	5133775.1	5105539	5077459	5049533	5021760	4994141	5E+06

Investment Analysis	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Energy Generated	19070.87	18965.98	18861.67	18757.93	18654.8	18552.162	18450.13	18348.64943
Electricity Tariff	0.238524	0.242101	0.245733	0.249419	0.25316	0.2569576	0.260812	0.264724138
Other savings	279.731	283.9269	288.1859	292.5086	296.896	301.34971	305.87	310.4580069
Energy Savings	4548.852	4591.691	4634.933	4678.583	4722.64	4767.1189	4812.013	4857.3304
Total savings	4828.583	4875.618	4923.119	4971.092	5019.54	5068.4686	5117.883	5167.788407
OPEX	-368.715	-374.246	-379.86	-385.557	-391.34	-397.2109	-403.169	-409.2166383
Replacement						-2618.5		
CF	4459.868	4501.372	4543.26	4585.534	4628.2	2052.7573	4714.714	4758.571768
Investment Cost								
Cumulative CF	5958.29	10459.66	15002.92	19588.46	24216.66	26269.41	30984.13	35742.70
CO2 saved	4939356	4912190	4885173	4858304	4831584	4805010	4778582	4752300.202

Investment Analysis	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Energy Generated	18247.73	18147.37	18047.56	17948.297	17849.58	17751.41	17653.776	17556.68	17460.12
Electricity Tariff	0.268695	0.272725	0.276816	0.2809686	0.285183	0.289461	0.2938027	0.29821	0.302683
Other savings	315.1149	319.8416	324.6392	329.50881	334.4514	339.4682	344.56024	349.7286	354.9746
Energy Savings	4903.074	4949.249	4995.859	5042.9071	5090.399	5138.337	5186.7278	5235.574	5284.88
Total savings	5218.189	5269.091	5320.498	5372.4159	5424.85	5477.806	5531.288	5585.302	5639.854
OPEX	-415.355	-421.585	-427.909	-434.3276	-440.843	-447.455	-454.167	-460.98	-467.894
Replacement									
CF	4802.834	4847.505	4892.589	4938.0882	4984.008	5030.351	5077.121	5124.323	5171.96
Investment Cost									
Cumulative CF	40545.53	45393.04	50285.63	55223.72	60207.72	65238.08	70315.20	75439.52	80611.48
CO2 saved	4726163	4700169	4674318	4648609	4623042	4597615	4572328	4547180	4522171

A.1.7 Evaluation of a_7 based on the criteria selected.

ALTERNATIVE 7		
Data		
Concept	**Value**	**Units**
DC Power	100	kWp
Cost / Wp	**2.05**	I / Wp
Installation Cost	205000	EUR
kwH/kWp	**1531.39**	kWh / kWp
PV Power Loss	0.55%	-
Self-consumption	70.00%	-
Surplus compensation	0.1	EUR / kWh
Electricity tariff	0.25621	EUR / kWh
Inflation	1.50%	-
Grid CO2 equivalent	2.59	g CO2 eq / kWh

Concept	Value	Units
Annual CO2 avoided	**37.15**	t CO2 eq
Payback	**6.66**	years
Interest Rate	10%	-
NPV	83504.07	I
Lifespan	25	years
EAA	**9199.48**	I

Year

		0	1	2	3	4	5	6	7	8	9	10	11	12
Calculations	Units													
Energy Generated	kWh		153139	152296.7	151459.1	150626.1	149797.6	148973.7	148154.392	147339.5	146529.2	145723.3	144921.8	144124.7
Energy Self-Consumed	kWh		107197	106607.7	106021.4	105438.3	104858.3	104281.6	103708.075	103137.7	102570.4	102006.3	101445.3	100887.3
Energy pushed into the grid	kWh		45941.7	45689.02	45437.73	45187.82	44939.29	44692.12	44446.3177	44201.86	43958.75	43716.98	43476.54	43237.42
Current retail price	EUR / kWh		0.25621	0.260053	0.263954	0.267913	0.271932	0.276011	0.2801511	0.284353	0.288619	0.292948	0.297342	0.301802
Current price paid by the grid	EUR / kWh		0.1	0.1015	0.103023	0.104568	0.106136	0.107728	0.10934433	0.110984	0.112649	0.114339	0.116054	0.117795
Investment Analysis														
Savings self consumption	EUR		27465	27723.67	27984.76	28248.31	28514.33	28782.87	29053.9311	29327.55	29603.74	29882.53	30163.95	30448.02
Revenue Grid	EUR		4594.17	4637.436	4681.109	4725.193	4769.692	4814.611	4859.95267	4905.721	4951.921	4998.556	5045.63	5093.147
Total Revenue	EUR		32059.2	32361.11	32665.87	32973.5	33284.03	33597.48	33913.8837	34233.27	34555.66	34881.09	35209.58	35541.17
OPEX	EUR		-2050	-2080.75	-2111.96	-2143.64	-2175.8	-2208.43	-2241.5587	-2275.18	-2309.31	-2343.95	-2379.11	-2414.8
Components replacement	EUR													
CF			30009.2	30280.36	30553.91	30829.86	31108.23	31389.05	31672.325	31958.09	32246.35	32537.14	32830.47	33126.37
Installation Cost		-205000												
Cumulative CF			-174991	-144710	-114157	-83326.7	-52218.5	-20829.4	10842.9177	42801	75047.35	107584.5	140415	173541.3
CO2 saved	g CO2 eq		4E+07	39444854	39227908	39012154	38797587	38584201	38371987.6	38160942	37951057	37742326	37534743	37328302

		13	14	15	16	17	18	19	20	21	22	23	24	25
Calculations	Units													
Energy Generated	kWh	143332	142543.7	141759.7	140980	140204.6	139433.5	138666.6	137904	137145	136391.2	135641.05	134895	134153.1
Energy Self-Consumed	kWh	100332.4	99780.59	99231.8	98686.03	98143.25	97603.46	97066.65	96532.78	96001.8	95473.84	94948.732	94426.51	93907.17
Energy pushed into the grid	kWh	42999.61	42763.11	42527.91	42294.01	42061.39	41830.06	41599.99	41371.19	41143.6	40917.36	40692.314	40468.51	40245.93
Current retail price	EUR / kWh	0.306329	0.310924	0.315588	0.320322	0.325127	0.330004	0.334954	0.339978	0.34508	0.350254	0.3555077	0.36084	0.366253
Current price paid by the grid	EUR / kWh	0.119562	0.121355	0.123176	0.125023	0.126899	0.128802	0.130734	0.132695	0.13469	0.136706	0.1387564	0.140838	0.14295
Investment Analysis														
Savings self consumption	EUR	30734.76	31024.21	31316.38	31611.3	31909	32209.5	32512.84	32819.03	33128.1	33440.08	33755.005	34072.89	34393.77
Revenue Grid	EUR	5141.111	5189.528	5238.4	5287.733	5337.53	5387.796	5438.536	5489.753	5541.45	5593.64	5646.3178	5699.492	5753.167
Total Revenue	EUR	35875.88	36213.74	36554.78	36899.03	37246.53	37597.3	37951.37	38308.78	38669.6	39033.72	39401.323	39772.38	40146.94
OPEX	EUR	-2451.02	-2487.78	-2525.1	-2562.98	-2601.42	-2640.44	-2680.05	-2720.25	-2761.1	-2802.47	-2844.506	-2887.17	-2930.48
Components replacement	EUR		-12300											
CF		33424.86	21425.95	34029.68	34336.06	34645.11	34956.86	35271.32	35588.53	35908.5	36231.25	36556.817	36885.21	37216.46
Installation Cost														
Cumulative CF		206966.2	228392.1	262421.8	296757.9	331403	366359.9	401631.2	437219.7	473128	509359.5	545916.28	582801.5	620017.9
CO2 saved	g CO2 eq	37122996	36918820	36715766	36513829	36313003	36113282	35914659	35717128	3.6E+07	35325320	35131031	34937810	34745652

A.1.8 Evaluation of a_8 based on the criteria selected.

ALTERNATIVE 8		
Data		
Concept	Value	Units
Module Power	415	Wp
PV Power Loss	0.55%	-
Average electricity tariff	0.21174	EUR/kWh
Inflation	1.50%	-
Surplus compensation	0.1	EUR/kWh
% Self-Consumption	85%	-
Total DC Power	88.395	kWp
Installation Cost	134784.11	EUR / kWh
Cost / Wp	1.52	EUR / Wp
kWh / kWp	1260.75	kWh / kWp
Grid CO2 equivalent	259	g CO2 eq / kWh
IBI	550	EUR
IBI bonification	50%	-

	Modules	kWp	kWh/kWp
Restaurant 1	77	31.955	1230.78
Restaurant 2	59	24.485	1209.64
Rural Rental Home 1	22	9.13	1214.74
Rural Rental Home 2	26	10.79	1353.96
Rural Rental Home 3	29	12.035	1395.63
Total	213	88.395	1260.75

Concept	Value	Units
Annual CO2 avoided	27.04	t CO2 eq
Payback	5.79	years
Interest Rate	10%	-
NPV	78608.93	€
Lifespan	25	years
EAA	8660.19	€

		Year								
		0	1	2	3	4	5	6	7	8
Calculations										
Energy Generated	kWh		111444	110831.0614	110221.49	109615.3	109012.39	108412.8202	107816.55	107223.559
Energy Self-Consumed	kWh		94727.403	94206.4022	93688.267	93172.98	92660.53	92150.8972	91644.067	91140.0249
Energy pushed into the grid	kWh		16716.601	16624.65921	16533.224	16442.29	16351.858	16261.92304	16172.482	16083.5338
Current retail price	EUR / kWh		0.21174	0.2149161	0.2181398	0.221412	0.2247331	0.228104115	0.2315257	0.23499856
Current price paid by the grid	EUR / kWh		0.1	0.1015	0.1030225	0.104568	0.1061364	0.1077284	0.1093443	0.11098449
Investment Analysis										
Savings self consumption	EUR		20057.58	20246.47256	20437.144	20629.61	20823.89	21019.99885	21217.955	21417.7748
Revenue Grid	EUR		1671.6601	1687.40291	1703.294	1719.335	1735.5266	1751.870956	1768.3692	1785.02282
Total Revenue	EUR		21729.24	21933.87547	22140.438	22348.95	22559.417	22771.86981	22986.324	23202.7976
Savings on IBI	EUR		1375	1375	1375	1375	1375			
Maintenance	EUR		-134.7841	-136.805873	-138.858	-140.941	-143.0549	-145.200767	-147.3788	-149.58946
Inverter replacement	EUR									
CF			22969.456	23172.06959	23376.58	23583	23791.362	22626.66904	22838.945	23053.2081
Cost	EUR	-134784.11								
Cumulative CF	EUR		-111814.7	-88642.5857	-65266.01	-41683	-17891.64	4735.029111	27573.974	50627.1824
GHG saved	g CO2 eq		28863997	28705244.91	28547366	28390356	28234209	28078920.44	27924486	27770901.7

		9	10	11	12	13	14	15	16	17
Energy Generated	kWh	106633.83	106047.3431	105464.08	104884.03	104307.17	103733.48	103162.94	102595.55	102031.27
Energy Self-Consumed	kWh	90638.755	90140.24161	89644.47	89151.426	88661.093	88173.457	87688.503	87206.216	86726.582
Energy pushed into the grid	kWh	15995.074	15907.10146	15819.612	15732.605	15646.075	15560.022	15474.442	15389.332	15304.691
Current retail price	EUR / kWh	0.2385235	0.242101393	0.2457329	0.2494189	0.2531602	0.2569576	0.260812	0.2647241	0.268695
Current price paid by the grid	EUR / kWh	0.1126493	0.114338998	0.1160541	0.1177949	0.1195618	0.1213552	0.1231756	0.1250232	0.1268986
Savings self consumption	EUR	21619.477	21823.07809	22028.597	22236.051	22445.459	22656.839	22870.21	23085.59	23302.999
Revenue Grid	EUR	1801.8333	1818.802035	1835.9306	1853.2205	1870.6732	1888.2902	1906.0732	1924.0237	1942.1432
Total Revenue	EUR	23421.31	23641.88013	23864.528	24089.272	24316.132	24545.13	24776.283	25009.614	25245.142
Savings on IBI	EUR									
Maintenance	EUR	-151.8333	-154.110802	-156.4225	-158.7688	-161.1503	-163.5676	-166.0211	-168.5114	-171.0391
Inverter replacement	EUR					-8087.047				
CF		23269.477	23487.76933	23708.105	23930.503	16067.935	24381.562	24610.262	24841.103	25074.103
Cost	EUR									
Cumulative CF	EUR	73896.659	97384.42833	121092.53	145023.04	161090.97	185472.53	210082.8	234923.9	259998
GHG saved	g CO2 eq	27618162	27466261.86	27315197	27164964	27015557	26866971	26719203	26572247	26426100

		18	19	20	21	22	23	24	25
Energy Generated	kWh	101470.1	100912.02	100357	99805.036	99256.108	98710.199	98167.293	97627.373
Energy Self-Consumed	kWh	86249.586	85775.213	85303.449	84834.28	84367.692	83903.669	83442.199	82983.267
Energy pushed into the grid	kWh	15220.515	15136.802	15053.55	14970.755	14888.416	14806.53	14725.094	14644.106
Current retail price	EUR / kWh	0.2727254	0.2768163	0.2809686	0.2851831	0.2894608	0.2938027	0.2982098	0.3026829
Current price paid by the grid	EUR / kWh	0.128802	0.1307341	0.1326951	0.1346855	0.1367058	0.1387564	0.1408377	0.1429503
Savings self consumption	EUR	23522.455	23743.978	23967.587	24193.301	24421.142	24651.128	24883.28	25117.618
Revenue Grid	EUR	1960.4333	1978.8957	1997.5319	2016.3437	2035.3326	2054.5003	2073.8486	2093.3791
Total Revenue	EUR	25482.888	25722.873	25965.118	26209.645	26456.474	26705.628	26957.128	27210.997
Savings on IBI	EUR								
Maintenance	EUR	-173.6047	-176.2087	-178.8519	-181.5347	-184.2577	-187.0215	-189.8269	-192.6743
Inverter replacement	EUR								
CF		25309.284	25546.665	25786.267	26028.11	26272.217	26518.607	26767.302	27018.323
Cost	EUR								
Cumulative CF	EUR	285307.29	310853.95	336640.22	362668.33	388940.54	415459.15	442226.45	469244.77
GHG saved	g CO2 eq	26280756	26136212	25992463	25849504	25707332	25565942	25425329	25285490

A.1.9 Evaluation of a_9 based on the criteria selected.

ALTERNATIVE 9		
Data		
Concept	**Value**	**Units**
DC Power of PV system	23.4	*kWp*
kWh / kWp Ratio	**1476.76**	*kWh/kWp*
% PV Power Loss	0.55%	-
% Energy sold	45%	-
Expected Initial Demand	7	*Recharges per day*
Investment Cost	82800	*EUR*
Annual demand increase	3%	-
Surplus compensation	0.1	*EUR / kWh*
Inflation	1.50%	-
Average vehicle load	40	*kWh*
Total Annual Charges	102200	*kWh*
Average electricity price	0.21174	*EUR / kWh*
Recharge price	0.35	*EUR / kWh*
Subsidies	40%	-
Grid CO2 equivalent	259	*g CO2 eq / kWh*
Cost / Wp	**3.54**	*//Wp*

OPEX cost includes the power term, electricity tax, equipment rental, human resources, maintenance, as calculated in (Galvarro Cano, 2020)

Inclination of 20º and azimuth of 0º

Concept	**Value**	**Units**
Annual CO2 avoided	**8.73**	*t CO2 eq*
Payback	**7.62**	*years*
Interest Rate	10%	-
NPV	-14791.00	/
Lifespan	10	*years*
EAA	**-2407.17**	/

		Year										
Calculations		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Energy Generated PV	*kWh*		34556.2	34366.12	34177.11	33989.14	33802.2	33616.28485	33431.4	33247.52	33064.66	32882.8056
Energy sold from PV	*kWh*		15550.3	15464.76	15379.7	15295.11	15210.99	15127.32818	15044.13	14961.39	14879.1	14797.26252
Energy pushed into the grid	*kWh*		19005.9	18901.37	18797.41	18694.03	18591.21	18488.95667	18387.27	18286.14	18185.56	18085.54308
Total Annual Charges	*kWh*		102200	105266	108424	111676.7	115027	118477.8104	122032.1	125693.1	129463.9	133347.8194
Energy sold from the grid	*kWh*		86649.7	89801.24	93044.28	96381.59	99816.01	103350.4822	106988	110731.7	114584.8	118550.5569
Average electricity price	*EUR / kWh*		0.21174	0.214916	0.21814	0.221412	0.224733	0.228104115	0.231526	0.234999	0.238524	0.242101393
Surplus compensation	*EUR / kWh*		0.1	0.1015	0.103023	0.104568	0.106136	0.1077284	0.109344	0.110984	0.112649	0.114338998
Recharge price	*EUR / kWh*		0.35	0.35525	0.360579	0.365987	0.371477	0.377049401	0.382705	0.388446	0.394272	0.400186491
Investment analysis												
Revenue: Energy sold from PV	*EUR*		5442.6	5493.855	5545.593	5597.819	5650.536	5703.750036	5757.465	5811.686	5866.418	5921.66457
Revenue: Energy sold from the grid	*EUR*		13880.8	14049.19	14205.39	14348.32	14476.84	14589.78422	14685.88	14763.79	14822.1	14859.32276
Total Revenue	*EUR*		19323.4	19543.05	19750.98	19946.13	20127.38	20293.53426	20443.34	20575.47	20688.52	20780.98733
OPEX	*EUR*		-9796	-9942.94	-10092.1	-10243.5	-10397.1	-10553.0741	-10711.4	-10872	-11035.1	-11200.6482
Depreciation	*EUR*		-7495	-7495	-7495	-7495	-7495	-7495	-7495	-7495	-7495	-7495
Subsidies	*EUR*		17600									
EBT	*EUR*		19632.4	2105.106	2163.899	2207.669	2235.262	2245.460156	2236.971	2208.43	2158.395	2085.339135
Corprate Tax (25%)	*EUR*		-4908.09	-526.276	-540.975	-551.917	-558.816	-561.365039	-559.243	-552.108	-539.599	-521.3347838
Net Profit	*EUR*		14724.3	1578.829	1622.924	1655.751	1676.447	1684.095117	1677.728	1656.323	1618.796	1564.004352
Cash Flow	*EUR*		22219.3	9073.829	9117.924	9150.751	9171.447	9179.095117	9172.728	9151.323	9113.796	9059.004352
Investment Cost	*EUR*	-82800										
Cumulative CF	*EUR*		-60580.7	-51506.9	-42389	-33238.2	-24066.8	-14887.669	-5714.94	3436.382	12550.18	21609.18266
C02 saved	*g CO2 eq*		8950052	8900826	8851872	8803187	8754769	8706617.776	8658731	8611108	8563747	8516646.65

Considering the surplus compensation

A.1.10 Evaluation of a_{10} based on the criteria selected.

ALTERNATIVE 10		
	Data	
Concept	Value	Units
DC Power	1500	kWp
kWh / kWp Ratio	2040.14	kWh/kWp
PV Power Loss	0.55%	-
CAPEX	1.70	EUR / Wp
Investment Cost	2553000.00	EUR
OPEX	0.03875	EUR / Wp year
Inflation	1.50%	-
Electricity Price	0.128	EUR / kWh
ha	11.25	ha
Land Rental Pric	1350	EUR / ha year
Grid CO2 equivale	259	g CO2 eq / kWh
Cost / Wp	1.70	/ / Wp

Concept	Value	Units
Annual CO2 avoided	732.51	t CO2 eq
Payback	9.51	years
Interest Rate	10%	-
NPV	24956.80	/
Lifespan	30	years
EAA	2647.40	/

Year

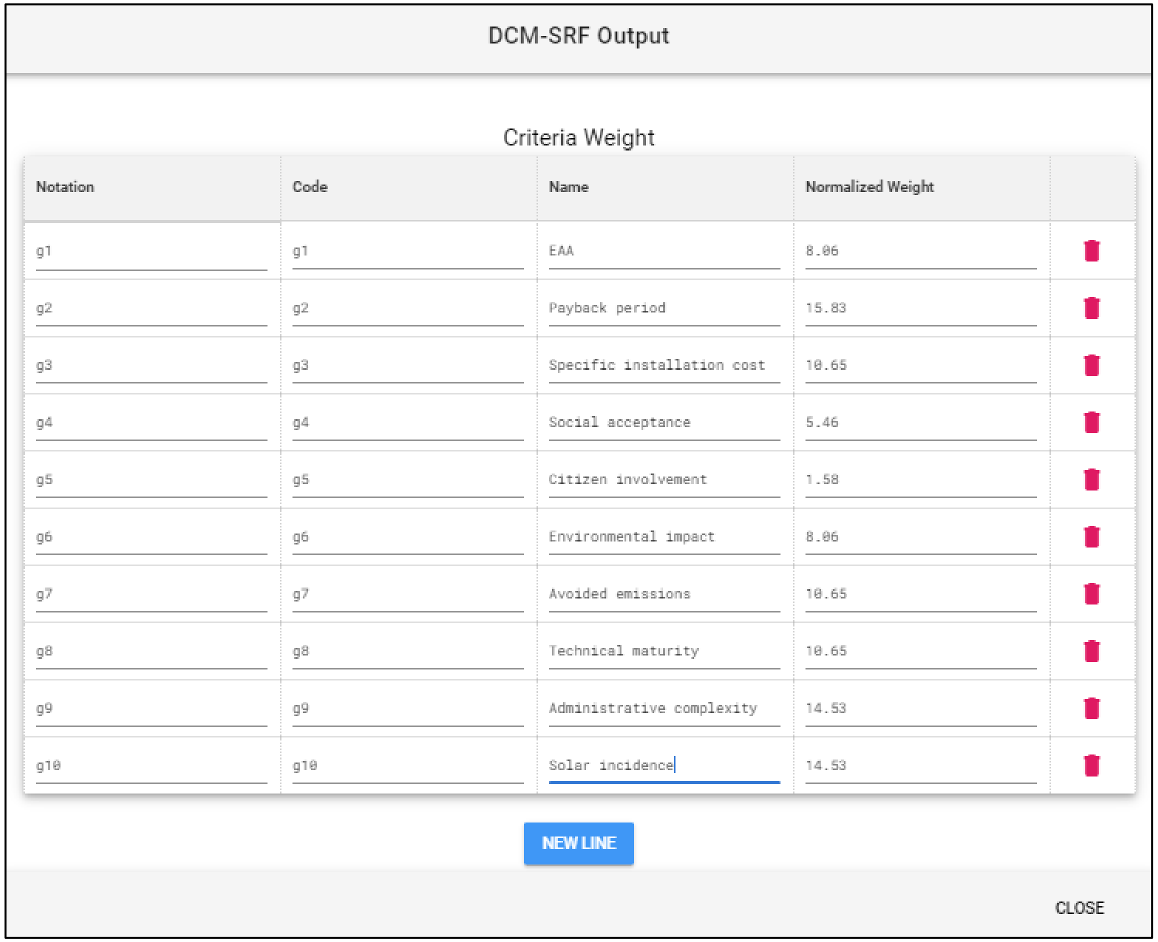
Investment Analys	Units	0	1	2	3	4	5	6	7	8	9	10
Energy generated	kWh		3060210	3E+06	3026640	3009994	2993439	2976974.86	2960601	2944318.19	2928124.44	2912019.8
OPEX	EUR		-58125	-58997	-59881.83	-60780.06	-61691.76	-62617.133	-63556.4	-64509.736	-65477.382	-66459.542
Electricity Price	EUR / kWh		0.128	0.1299	0.131869	0.133847	0.135855	0.13789235	0.139961	0.14206015	0.14419105	0.1463539
Revenue	EUR		391706.88	395396	399119.4	402878.1	406672.2	410502.067	414368	418270.28	422209.341	426185.5
Replacement	EUR											-76590
Land rental	EUR		-15187.5	-15415	-15646.54	-15881.24	-16119.46	-16361.251	-16606.7	-16855.77	-17108.606	-17365.235
Depreciation	EUR		-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100
BAI	EUR		233294.38	235884	238491	241116.8	243761	246423.683	249104.9	251804.775	254523.353	180670.72
CIT Rate (25%)	EUR		-58323.6	-58971	-59622.76	-60279.21	-60940.25	-61605.921	-62276.2	-62951.194	-63630.838	-45167.68
Net Profit			174970.79	176913	178868.3	180837.6	182820.8	184817.763	186828.7	188853.581	190892.515	135503.04
CF	EUR		260070.79	262013	263968.3	265937.6	267920.8	269917.763	271928.7	273953.581	275992.515	220603.04
Investment Cost	EUR	-2553000										
Cumulative CF	EUR		-2292929	-2E+06	-1766948	-1501011	-1233090	-963172.09	-691243	-417289.82	-141297.31	79305.732
CO2 saved	g CO2 eq		792594390	8E+08	7.84E+08	7.8E+08	7.75E+08	771036489	7.67E+08	762578411	758384230	754213117

Investment Analys	11	12	13	14	15	16	17	18	19	20
Energy generated	2896003.6	2880075.6	2864235.2	2848481.9	2832815.3	2817234.8	2801740	2786330.4	2771005.6	2755765.1
OPEX	-67456.435	-68468.282	-69495.306	-70537.736	-71595.802	-72669.739	-73759.785	-74866.182	-75989.174	-77129.012
Electricity Price	0.1485492	0.1507775	0.1530391	0.1553347	0.1576647	0.1600297	0.1624302	0.1648666	0.1673396	0.1698497
Revenue	430199.1	434250.5	438340.05	442468.12	446635.06	450841.25	455087.05	459372.83	463698.97	468065.86
Replacement										-76590
Land rental	-17625.714	-17890.099	-18158.451	-18430.828	-18707.29	-18987.9	-19272.718	-19561.809	-19855.236	-20153.064
Depreciation	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100
BAI	260016.95	262792.12	265586.3	268399.56	271231.97	274083.61	276954.54	279844.84	282754.56	209093.78
CIT Rate (25%)	-65004.238	-65698.029	-66396.574	-67099.889	-67807.993	-68520.903	-69238.636	-69961.21	-70688.641	-52273.445
Net Profit	195012.71	197094.09	199189.72	201299.67	203423.98	205562.71	207715.91	209883.63	212065.92	156820.34
CF	280112.71	282194.09	284289.72	286399.67	288523.98	290662.71	292815.91	294983.63	297165.92	241920.34
Investment Cost										
Cumulative CF	359418.44	641612.53	925902.26	1212301.9	1500825.9	1791488.6	2084304.5	2379288.1	2676454.1	2918374.4
CO2 saved	750064945	745939588	741836920	737756817	733699154	729663809	725650658	721659579	717690452	713743154

Investment Analys	21	22	23	24	25	26	27	28	29	30
Energy generated	2740608.4	2725535	2710544.6	2695636.6	2680810.6	2666066.1	2651402.8	2636820	2622317.5	2607894.8
OPEX	-78285.947	-79460.236	-80652.14	-81861.922	-83089.851	-84336.199	-85601.242	-86885.26	-88188.539	-89511.367
Electricity Price	0.1723974	0.1749834	0.1776082	0.1802723	0.1829764	0.185721	0.1885068	0.1913344	0.1942044	0.1971175
Revenue	472473.87	476923.39	481414.82	485948.54	490524.96	495144.48	499807.5	504514.44	509265.71	514061.72
Replacement										
Land rental	-20455.36	-20762.191	-21073.624	-21389.728	-21710.574	-22036.233	-22366.776	-22702.278	-23042.812	-23388.454
Depreciation	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100	-85100
BAI	288632.56	291600.96	294589.05	297596.89	300624.54	303672.05	306739.49	309826.9	312934.35	316061.89
CIT Rate (25%)	-72158.14	-72900.241	-73647.263	-74399.223	-75156.134	-75918.012	-76684.872	-77456.726	-78233.589	-79015.474
Net Profit	216474.42	218700.72	220941.79	223197.67	225468.4	227754.04	230054.61	232370.18	234700.77	237046.42
CF	301574.42	303800.72	306041.79	308297.67	310568.4	312854.04	315154.61	317470.18	319800.77	322146.42
Investment Cost										
Cumulative CF	3219948.8	3523749.6	3829791.3	4138089	4448657.4	4761511.5	5076666.1	5394136.2	5713937	6036083.4
CO2 saved	709817567	705913570	702031046	698169875	694329941	690511126	686713315	682936391	679180241	675444750

A.2 Software implementation of the model

A.2.1 DCM-SFR output


DCM-SRF Output

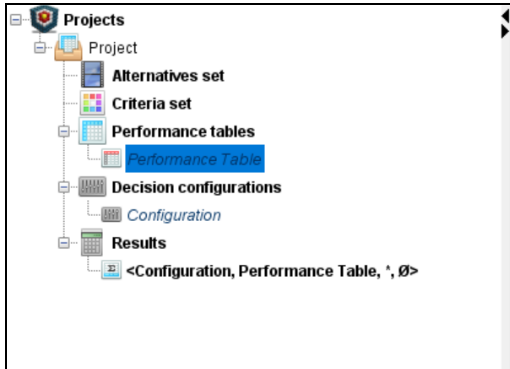
Criteria Weight

Notation	Code	Name	Normalized Weight
g1	g1	EAA	8.06
g2	g2	Payback period	15.83
g3	g3	Specific installation cost	10.65
g4	g4	Social acceptance	5.46
g5	g5	Citizen involvement	1.58
g6	g6	Environmental impact	8.06
g7	g7	Avoided emissions	10.65
g8	g8	Technical maturity	10.65
g9	g9	Administrative complexity	14.53
g10	g10	Solar incidence	14.53

NEW LINE

CLOSE

A.2.2 Performance table



Project : Project - Performance table : Performance Table

[Alternative]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9	Criterion10
Extent	59390.80078...	11.729999542	8.090000153	2	3	2	727.6699829...	1	2	825.6600341...
Alternative1	33924.39062...	7.579999924	2.049999952	L3	L4	L2	273.4700012...	L2	L3	1312.189941...
Alternative2	1296.000000...	8.260000229	1.879999995	L3	L2	L3	15.600000381	L2	L3	1280.619995...
Alternative3	-25466.4101...	17.209999084	9.609999657	L3	L2	L2	17.899999619	L2	L3	1531.390014...
Alternative4	5873.060058...	5.480000019	1.730000019	L3	L1	L3	12.470000267	L2	L3	1214.479980...
Alternative5	7615.000000...	5.690000057	1.690000057	L3	L3	L3	22.309999466	L2	L3	1310.300048...
Alternative6	763.3099975...	7.670000076	2.390000105	L2	L1	L2	4.840000153	L1	L2	1983.579956...
Alternative7	9199.480468...	6.659999847	2.049999952	L2	L3	L1	37.150001526	L1	L1	1531.390014...
Alternative8	8660.190429...	5.789999962	1.519999981	L3	L3	L3	27.040000916	L2	L3	1260.750000...
Alternative9	-2407.16992...	7.619999886	3.539999962	L2	L2	L2	8.729999542	L1	L2	1476.760009...
Alternative10	2647.399902...	9.510000229	1.700000048	L1	L2	L1	732.5100097...	L2	L1	2040.140014...

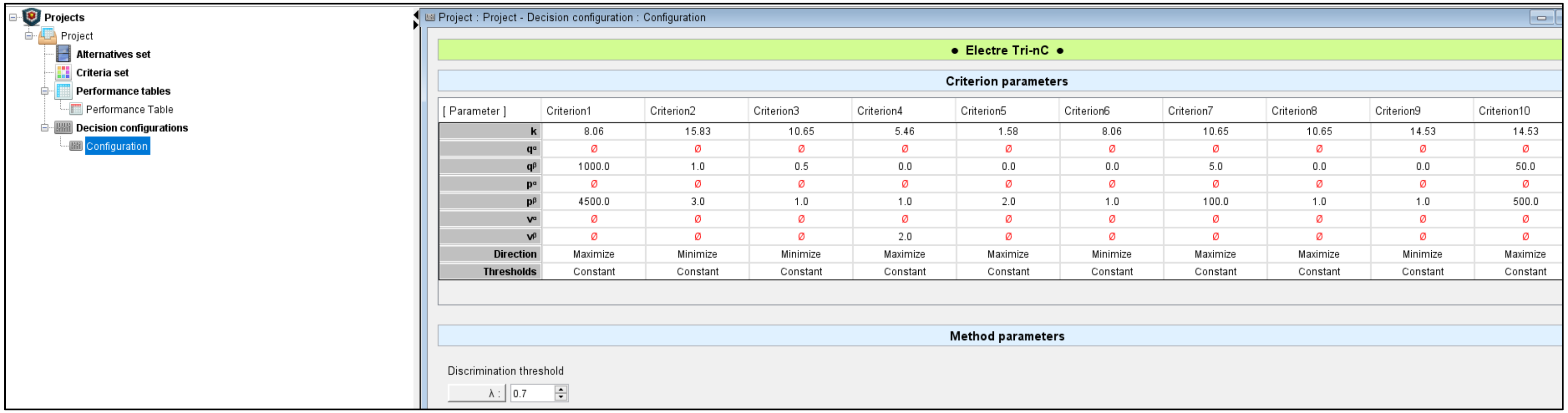
A.2.3 Performance table of the reference alternatives

Performance table of the reference alternatives

Import CSV

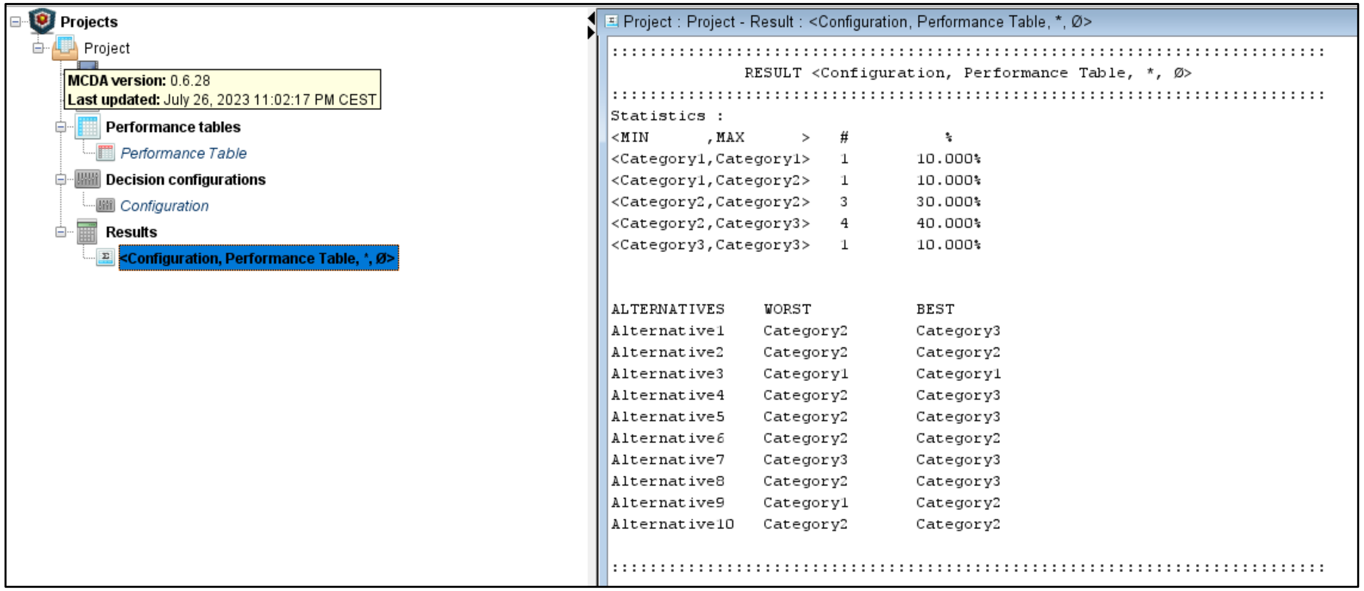
[Alternative]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9	Criterion10
Extent	59390.800781250	11.729999542	8.090000153	2	3	2	718.669982910	1	2	825.660034180
Alternative11	-25466.410156250	17.209999084	9.609999657	L1	L1	L1	4.840000153	L1	L1	1214.479980469
Alternative12	0.000000000	15.000000000	4.000000000	L2	L1	L1	5.000000000	L1	L1	1220.000000000
Alternative21	5000.000000000	10.000000000	3.000000000	L2	L2	L2	20.000000000	L2	L2	1280.000000000
Alternative22	7500.000000000	8.500000000	2.200000048	L2	L2	L2	100.000000000	L2	L2	1350.000000000
Alternative31	15000.000000000	6.500000000	1.700000048	L3	L3	L3	259.000000000	L2	L3	1500.000000000
Alternative32	33924.390625000	5.480000019	1.519999981	L3	L4	L3	723.510009766	L2	L3	2040.140014648

A.2.4 Parameters



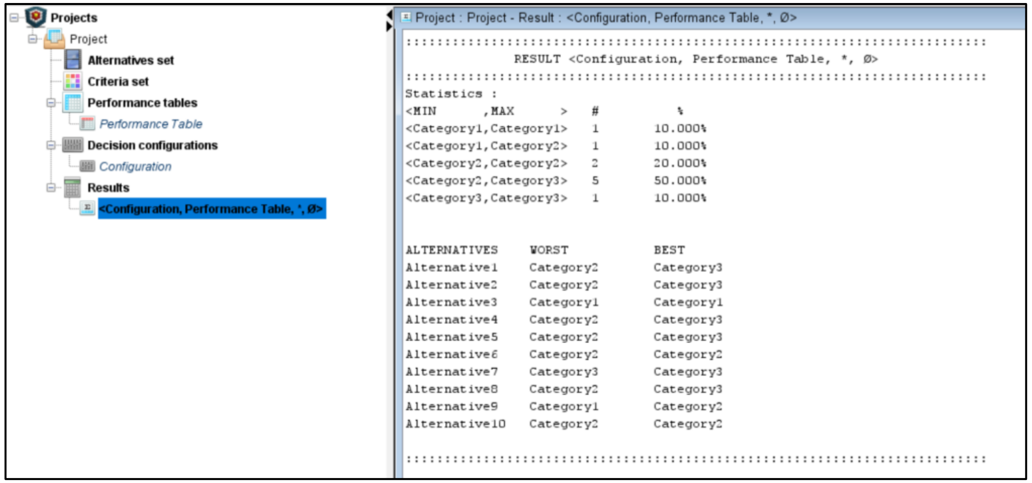
[Parameter]	Criterion1	Criterion2	Criterion3	Criterion4	Criterion5	Criterion6	Criterion7	Criterion8	Criterion9	Criterion10
k	8.06	15.83	10.65	5.46	1.58	8.06	10.65	10.65	14.53	14.53
q^{α}	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø
q^{β}	1000.0	1.0	0.5	0.0	0.0	0.0	5.0	0.0	0.0	50.0
p^{α}	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø
p^{β}	4500.0	3.0	1.0	1.0	2.0	1.0	100.0	1.0	1.0	500.0
v^{α}	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø	Ø
v^{β}	Ø	Ø	Ø	2.0	Ø	Ø	Ø	Ø	Ø	Ø
Direction	Maximize	Minimize	Minimize	Maximize	Maximize	Minimize	Maximize	Maximize	Minimize	Maximize
Thresholds	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant

A.2.5 Results considering λ=0.7

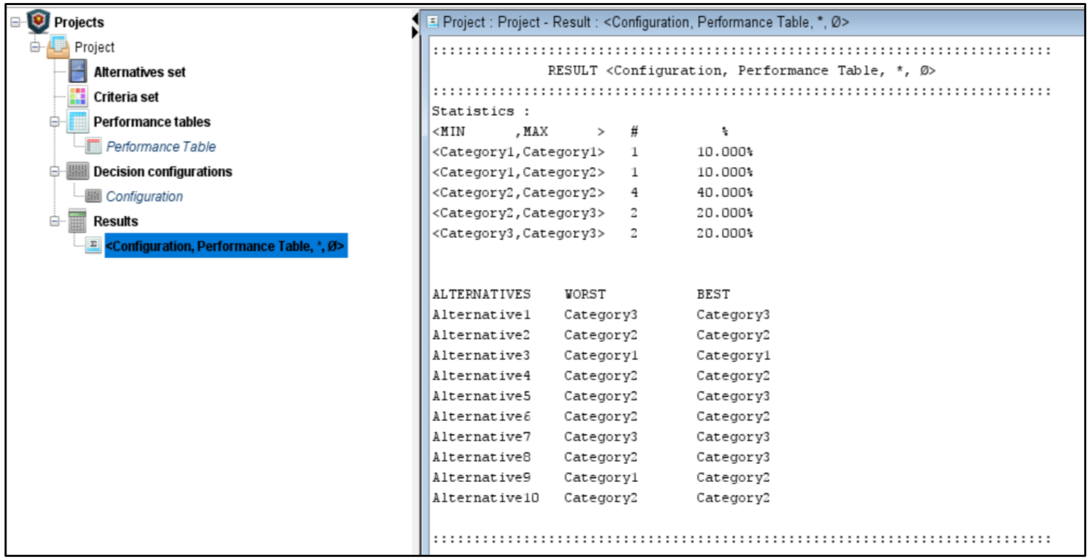



```
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
              RESULT <Configuration, Performance Table, *, Ø>
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
Statistics :
<MIN      ,MAX      >   #          %
<Category1,Category1>   1       10.000%
<Category1,Category2>   1       10.000%
<Category2,Category2>   3       30.000%
<Category2,Category3>   4       40.000%
<Category3,Category3>   1       10.000%


ALTERNATIVES    WORST          BEST
Alternative1    Category2      Category3
Alternative2    Category2      Category2
Alternative3    Category1      Category1
Alternative4    Category2      Category3
Alternative5    Category2      Category3
Alternative6    Category2      Category2
Alternative7    Category3      Category3
Alternative8    Category2      Category3
Alternative9    Category1      Category2
Alternative10   Category2      Category2

::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
```

A.2.6 Results considering λ=0.65



A.2.6 Results considering λ=0.75



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A case study concerning photovoltaics in Rajadell, Spain

Alex Harillo Antolinez